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12th IWACP

"WAYS FORWARD TO PROMOTE RESOURCES EQUITY:
THE ROLE OF CLEANER PRODUCTION
AND CIRCULAR ECONOMY AS MODERATOR.
ACTION OR REACTION TO SAVE THE PLANET?"

Advances in Cleaner Production

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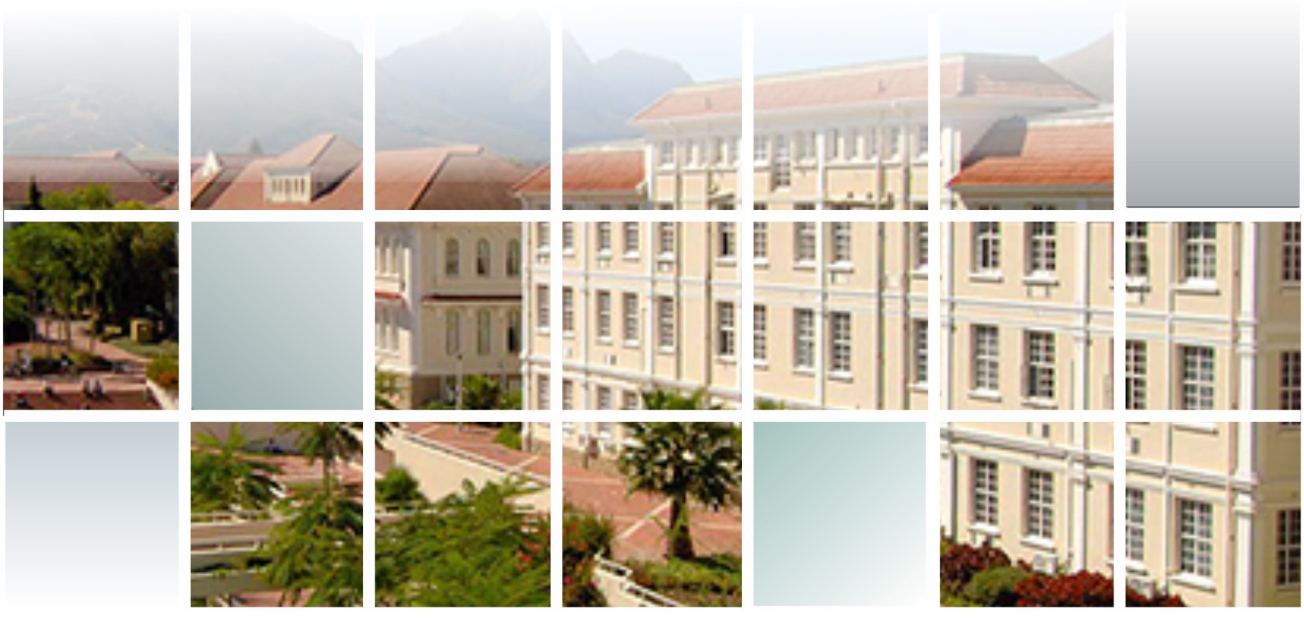
Stellenbosch - South Africa

November, 23rd and 24th - 2023



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Lund University
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Nanjing University
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National Institute of Industrial Engineering
National University of Colombia
Nord University Business School
Northwest Green Chemistry
Northwestern Polytechnical University
Nottingham Trent University
Nueva Granada Military University
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Journal Manager of Frontiers in Sustainable Cities

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The Organizing Committee also extends its gratitude to all the authors and participants who have contributed to making this event possible. Special thanks are given to the support committees of Universidade Paulista and the University of Stellenbosch.

We would like to acknowledge and thank all the staff members of the University of Stellenbosch who have contributed to the preparation of this event, with a special mention to **Prof. Joubert van Eeden**, Head of the Department of Industrial Engineering at Stellenbosch University, **Prof. Wikus van Niekerk**, Dean of Engineering, and **Prof. Cornelius S. L. Schutte**, Chair of the Department of Industrial Engineering. We would also like to express our gratitude to **Prof. Anton Basson**, **Prof. Imke De Kock**, and the entire team.

Special thanks go to **Prof. Sandra Rejane Gomes Miessa**, the Rector of Universidade Paulista, Prof. **Dr. Marina Soligo**, Vice-Rector of Post Graduation and Research of Universidade Paulista, and **Prof. Dr. Marília Ancona-Lopez**, the Vice-Rector of Graduation of Universidade Paulista, for their unwavering support since the first event in 2007.

General Chair and Founder of ACPN
Biagio F. Giannetti (Paulista University-UNIP, Brazil)

Special Welcome Message

On behalf of the Organizing Committee, it is a true honor to warmly welcome all participants and express our profound gratitude to the researchers for the significant work presented in this edition of the International Workshop on Advances in Cleaner Production.

It is worth noting that the International Workshops on Advances in Cleaner Production, held from 2007 to 2019, were in-person events. During this period, eight gatherings took place in different locations such as Brazil, Colombia, and China. In 2020 and 2021, the challenging global health conditions stemming from the COVID-19 pandemic presented our academic community with a new landscape. Faced with this scenario, in 2020 and 2021, the events were held virtually (a combination of synchronous and asynchronous formats), with Australia and Italy as the hosting locations.

In 2022, the 11th IWACP took place in Italy, marking the first experience of a hybrid event, reinstating the possibility of in-person meetings among scientists, which had been disrupted by the pandemic. Now, in 2023, the 12th IWACP maintains the hybrid format, solidifying this new dynamic of participation.

With this event, we conclude a series of gatherings that spanned across five continents. Today, we find ourselves on the African continent, aiming to strengthen research ties to address sustainability in a more comprehensive manner. We are immensely delighted to be in South Africa, a country that imparts valuable lessons through its recent history.

The exciting program and the quality of the conferences and contributions elevate this event to the status of an academic success. This is the result of the dedicated work of colleagues over several years in various academic, business, and governmental institutions.

To all of you actively participating in this event, credit is due for the quality of the International Workshop on Advances in Cleaner Production.

I extend my gratitude to Prof Joubert van Eeden, Head of the Department of Industrial Engineering at Stellenbosch University, Prof. Wikus van Niekerk, Dean of Engineering, and Prof. Cornelius S. L. Schutte, Chair of the Department of Industrial Engineering. A special thanks to Prof. Anton Basson, and Prof. Imke De Kock and the team. Without the exceptional and competent support of the professors and staff at Stellenbosch University, this event would not have been possible.

I sincerely hope that you will continue to contribute to the advancement of cleaner production and sustainable development.

Welcome, everyone!

General Chair and Founder
Biagio F. Giannetti – Paulista University (UNIP) - Brazil

Presentation

The **"International Workshop on Advances in Cleaner Production"** is a multi/interdisciplinary forum for the exchange of information and research results on technologies, concepts and policies based on Cleaner Production and conceived to assist the desired transition to a sustainable society.

Cleaner Production is a concept that goes far beyond the simple pollution control. It includes research and development of new processes, materials and products directed to promote the efficient use of resources and energy. Prevention must be the first approach of governments and corporations concerning sustainable development, and for this, environmental friendly strategies allied to economical robustness of products and services must be assured.

The adoption of Cleaner Production by governments, companies, and universities is getting speed with technical assistance and training programs, but it is worthy of attention that all these initiatives, even if implemented by all governments and corporations, do not guarantee the achievement of sustainable development. There is still a lack of a science, and consequently of a consolidated engineering devoted to the sustainable development.

Objectives

The **"12th International Workshop on Advances in Cleaner Production"** is an international forum to be held in November 23rd and 24th, 2023 in Stellenbosch, South Africa. The "12th International Workshop: Advances in Cleaner Production" aims to promote:

1. The exchange of academic information;

2. The presentation of recent achievements;

3. The discussion of common problems and their possible solutions;

4. The contact among academic knowledge and corporative experiences;

5. The discussion of the event's theme **"Ways forward to promote resource equity: The role of cleaner production and circular economy as moderator. Action or reaction to save the planet?".**

Researchers interested on Cleaner Production and Sustainable Development are invited to submit papers. Authors devoted to correlated themes are also welcome

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Program

Time (GMT +2)	November 23rd, 2023 Industrial Engineering Building
08:00 to 10:00	**Reception**
10:00 to 10:30	**Opening Ceremony** **Anton Basson** **Joubert van Eeden** **Imke de Koch** **Biagio F. Giannetti**
10:30 to 12:00	**Opening Conference** **Mark Swilling** *Chair: Imke de Koch* *(Stellenbosch University - South Africa)* **Official Picture**
12:00 to 13:30	**Lunch**
13:30 to 15:00	**Plenary Presentations** *Ecoinnovation to Achieve a Sustainable Planet* **Massimiliano Mazzanti** **Ubiratã Tortato** *Chair: Philani Zincume* *(Stellenbosch University - South Africa)*
15:00 to 16:30	**Oral Presentations**
16:30 to 16:50	**Coffee Break**
16:50 to 18:30	**Roundtable** *Action or Reaction to Save the Planet?* *Africa as a New Player on Strategies for Ecological and Societal Transition* **Jana Breedt** **Thinus Booysen** *Chair: Feni Agostinho* *(Paulista University-UNIP - Brazil)*
18:30 to 19:30	**Cocktail**

Time (GMT +2)	November 24th, 2023 STIAS Wallenberg Research Centre
09:00 to 10:40	**Oral Presentations**
10:40 to 11:00	**Coffee Break**
11:00 to 11:30	**Special Session** *Frontiers in Sustainable Cities: High Quality Research to Inform and Promote Urban Sustainability* **Clare Brown** *Chair: Feni Agostinho* *(Paulista University-UNIP - Brazil)*
11:30 to 12:30	**Workshop for Collaborative Projects** **Nayeli Naidee Majia Rivera** **Mario Canever** **Bankole Awuzie** **Gengyuan Liu** *Chair: Cecília Almeida* *(Paulista University-UNIP - Brazil)*
12:30 to 13:30	**Closing Conference** **Alan Brent** *Chair: Ubiratã Tortato* *(PUC-PR - Brazil)*
13:30 to 14:30	**Lunch and Closing Ceremony**

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Abstracts

A Study of Mixed Plastic Waste Pyrolysis under Low-Pressure

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Abstract

The increasing volumes of mixed plastic waste worldwide have become a global issue, as such waste cannot be easily recycled and usually ends life at landfill and waterways. The chemical inertness and extremely low biodegradability of this class of materials have forced researchers to find more sustainable means of treating this waste. One of the proposed solutions is the recovery of hydrocarbons used in the synthesis of plastics for use in other applications such as fuels and lubrication.

A promising approach for this process is the low-pressure pyrolysis of the mixed plastic waste in the presence of the catalyst. This reaction usually occurs in a semi-batch or continuous reactor vessel. The decreased pressure allows for easier and more effective transport of the pyrolysis product outside the reactor. This benefits the process because the decomposition reaction equilibrium shifts towards the products. Lower pressure also decreases the boiling points of the hydrocarbons. At the same time catalyst used in the reactor decreases the energy requirements of the C-C bonds cracking reaction allowing for increased creation of the shorter-chain pyrolysis products. A combination of those factors reduces the overall cost of the unit operation and helps obtain higher amounts of hydrocarbons valuable for the chemical industry.

The gaseous emissions from the pyrolysis process are not well documented in the literature. It is known that these gases contain significant quantities of volatile organic compounds (VOC). Most commercial pyrolysis processes do not integrate any form of gaseous cleaning but dilute gaseous emissions with fresh air before exhausting. Flaring is also an environmentally impactful alternative. Catalytic pyrolysis can aid in reducing VOCs by increasing the rate of conversion of cracked plastic to liquids and wax with shorter residence times. It is imperative that the gaseous emissions from mixed plastic waste pyrolysis are properly characterized for cleaner management of plastic waste that is less impactful on the environment.

Low-density polyethylene (LDPE), high-density polyethylene (HDPE), and polypropylene (PP) were chosen as feedstocks in this study as they are the most common types of plastic utilized currently by global industries and households. Each type of the abovementioned materials was subjected to three pyrolysis processes in a lab-scale semi-batch reactor under lower pressure using a different catalyst-to-feed ratio (uncatalyzed, 1:20, and 1:10). Zinc oxide (ZnO) was chosen as a catalyst based on previous literature showing its effectiveness as a catalyst in the plastic pyrolysis process and its relatively low price, in comparison to other available catalysts. Experiments were conducted at a temperature of 450°C and pressures within 41 to 42 kPa. It was observed that an increase in the catalyst-to-feed ratio significantly decreased the time of the process for each studied plastic.

Additionally, three mixtures of various compositions of the abovementioned plastics were prepared to simulate plastic streams from different sources. Experiments with each feed sample were studied three times with varying catalyst-to-feed ratios (no catalyst, 1:20, and 1:10 ZnO to plastic), utilizing the same conditions (T = 450°C, P=41-42 kPa) as the individual plastic experiments. A similar trend was observed as an increase in the catalyst-to-feed ratio allowed to decrease in the time required to finalize the process.

Liquid and wax products with carbon chain lengths between C11 and C25 were recognized as hydrocarbons viable for industrial applications. ZnO catalyst was proven as a sufficient choice for this process as its presence increased the overall amount of the liquid and wax products obtained compared with the uncatalyzed processes. This applies to both pure and mixed plastic waste experiments. Additionally, obtained data shows that in terms of the studied process, a catalyst-to-feed ratio of 1:20 is preferred over the catalyst-to-feed ratio of 1:10, as a higher amount of catalyst promotes the creation of the gaseous products, which should be avoided.

The highest yield of total liquid and wax products for experiments involving individual plastic feeds was achieved for the thermal pyrolysis of HDPE (85.4 wt% of total product). The highest yield of combined liquid and wax products (81.7 of total product wt%) for the experiments with mixed plastic feeds was obtained for a mixture containing 15 wt% of LDPE, 45 wt% of HDPE, and 40 wt% of PP. The analysis of gaseous products showed that the lowest emissions of the compounds from the VOC group were observed for the experiment with LDPE using a 1:10 catalyst-to-feed ratio (32.6volume % of gas sample) in terms of individual plastic experiments. For the experiments with mixed plastic feed, the lowest concentration of the VOCs (65.8 volume % of gas sample) was observed for thermal pyrolysis of a mixture containing 32.3 wt% of LDPE, 34.5 wt% of HDPE, and 33.2 wt% of PP.

Keywords: *Plastic waste, plastic pyrolysis, LDPE, HDPE, pyrolysis fuel oil*

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A Systematic Review of the Barriers and Drivers of Implementing Industrial Symbiosis

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Abstract
Nowadays, enhancing the sustainability of production processes is one of the keys to supporting the transition towards the circular economy. An important issue concerns reducing the amounts of industrial wastes and by-products disposed of in landfill and the amounts of virgin inputs used by production processes. In this regard, industrial symbiosis (IS) deals with the exploitation of wastes produced by one production process as a substitute for the primary inputs required by other production processes; these processes can belong to the same company or, conversely, to different companies. IS is recognised as a win-win strategy since it can create environmental benefits while producing economic advantages for the involved companies at the same time, in the form of lower waste disposal costs and input purchase costs. Hence, policymakers of several countries have strongly recommended the implementation of IS.
Nevertheless, IS is scantly implemented compared to its theoretical potential. The case studies described by the literature so far highlight that several barriers might hamper the establishment of IS relationships among companies. However, the literature is highly fragmented in this sense, and a general and comprehensive framework about barriers and drivers to IS is lacking.
This paper is aimed at developing a general framework for drivers and barriers for IS by conducting a systematic literature review. In particular, this paper involves both empirical and theoretical papers on IS in general, which mention at least one barrier or one driver for IS, by contextualising the best practices and the failures described in the literature. 760 papers were part of the final database, considering only papers published in peer-reviewed journals in Scopus and Web of Science databases until the 20th of July 2023. The investigation focused on the full text of each paper to extract information about drivers and barriers. The output of this investigation is a theoretical framework based on the classification of the drivers and the barriers identified.
Barriers and drivers are classified into four macro-sectors by combining two factors: the internal or external origin of the drivers and barriers with respect to the company and whether they impact the stand-alone company or the network (or a subpart of it). This classification in four macro-sectors helps to delineate the type of IS that can be established and the companies that can be involved under a specific set of external policies.
Moreover, as IS develops along four readiness levels, the classification of the drivers and barriers into the macro-sectors must be focused on each level: willingness, assessment, implementation, and operation. This further classification allows decision-makers and companies to develop implementation plans and policies by also considering future drivers and barriers and the potential side effects of plans, specific for a readiness level, on the others.
Beyond the development of the framework, this paper reports the advances in IS research over the last three decades, the progressive reduction of some barriers and the emergence of others, the impacts of national policies, and the fields that are progressively interested in IS establishment. This sort of history of barriers and drivers of IS can provide insights for those countries starting to introduce IS in their industrial policies right now. At the same time, new technologies, business models, industrial sectors, and development strategies arose and have been involved worldwide around the IS concept, and simultaneously visualising them helps to understand the pivotal role of the local context in IS that the framework tries to highlight.
The theoretical framework can be useful for companies, policymakers, scholars, practitioners, and Eco-Industrial Parks (EIPs) managers. From the managerial perspective, companies can be aware in advance of which drivers they can exploit and which barriers they need to tackle. Policymakers can use the results from this literature review to better design incentives to adopt industrial symbiosis and promote measures to reduce the perception of IS barriers. Scholars and practitioners can compare the best practices diffused in the literature for specific resource streams, particular local areas, and production processes and identify more clearly the research gaps. The focus on the internal and external drivers and barriers of IS can help the managers of the Eco-Industrial Parks to define plans for extending IS within the parks without contrasting the IS sustainability from the internal point of view of the companies.
The development of this framework started from the analised papers. However, often the papers do not report crucial information regarding national policies, social and cultural contexts, and business information. In other cases, the papers have more technical scopes and the barriers and drivers have been inferred from the authors' experience. Therefore, the framework is a valid starting point that must have been read, interpreted, and used by considering all those case-dependent factors that can impact the performance of the companies involved in an IS.
Keywords: *industrial symbiosis, driver, barrier, systematic literature review, theoretical framework.*

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Adoption of Autonomous Guided Vehicles in the Automotive Industry contributes to the micro-level Circular Economy

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Abstract

The production system of automobile manufacturers generates significant environmental impacts, including excessive consumption of natural resources such as water and energy, considerable greenhouse gas emissions during vehicle manufacturing, and the generation of solid and liquid waste from production stages (Montemayor and Chanda, 2023; Ravina et al., 2023). However, automakers are adopting Industry 4.0 technologies in production, aiming to improve operational performance through waste reduction, cost reduction, quality improvement, and reduced byproduct consumption (Montemayor and Chanda, 2023; Bankar and Nandurkar, 2023; Daly, 1996, 2008).

The implementation of Industry 4.0 technologies in production has been found to be a relevant aspect that contributes to the circular economy at the micro-level, where cleaner production is considered a strategic tool (Amjad et al., 2021). This has led to an increased concern for the use of renewable and regenerative resources, seeking to balance resource consumption and extraction (Beltrami et al., 2021), as well as promote equity in resource utilization (Bal and Satoglu, 2018; Delai and Takahashi, 2013).

Thus, the objective of this study is to evaluate the benefits of adopting Autonomous Guided Vehicles in the Automotive Industry, examining their contributions to the micro-level circular economy. The study aims to analyze the gains achieved through the implementation of these technologies, highlighting the economic benefits such as cost reduction and increased operational efficiency, social benefits such as improved working conditions and employee safety, and environmental benefits such as resource optimization and waste reduction. Additionally, it aims to provide insights that drive the transition towards a more sustainable and circular automotive production model.

The adopted method was a case study using interviews, direct observation, and document analysis. It was concluded that the adoption of Industry 4.0 technologies in the material receiving sector resulted in several benefits. Autonomous Guided Vehicles (AGVs) are intelligent devices that can collect materials from the receiving or warehouse area and transport them to the production line or storage. This technology utilizes cyber-physical systems with interconnected network sensors, such as optical, laser, and radiofrequency sensors, providing greater safety in the factory environment.

The AGV can be controlled by programmed guided rails or through an antenna that detects the magnetic field generated by embedded electrical conductors in the floor, following a predefined route. The implementation of the AGV system in material transport resulted in a significant increase in productivity by replacing manual operations with an efficient autonomous system.

Economically, the adoption of AGVs reduced company costs, saving $48,800.00 annually. The return on investment was 46.8% per year, with a capital payback period of 2.72 years. Regarding environmental impact, the adoption of AGV technology contributed to the reduction of natural resource usage. In the case at hand, replacing two natural gas-powered forklifts with AGVs resulted in a reduction of 10,560 kg of natural gas per year. This reduction is significant considering that natural gas is a non-renewable fossil fuel. Furthermore, the implementation of AGVs also brought environmental benefits related to waste reduction.

By avoiding the generation of waste materials that would have been produced without the adoption of AGV technology, a negative environmental impact was avoided. Another relevant aspect is the contribution to sustainability, with a reduction in the total compartment mass intensity (MIT) due to the elimination of natural gas usage. This reduction in mass intensity amounted to 103 kg of materials. Regarding safety, the use of forklifts presented significant risks due to direct employee contact with the flammable product. However, the implementation of AGVs contributed to safety by reducing the risk priority number (RPN) from 320, which is considered high risk.

Additionally, the elimination of forklift use in the material receiving and storage process also benefited operator safety and well-being since sharp turns and obstructions in the path were eliminated, resulting in a safer work environment. In summary, the adoption of AGV technology in the material receiving sector provided significant gains in economic, environmental, and social terms.

Therefore, it was found that the adoption of Industry 4.0 technologies in automotive production has been a key factor in driving the circular economy at the micro-level, with a focus on cleaner production as a crucial strategic tool. These technologies play a significant role in reducing environmental impacts and promoting social equity by emphasizing the regeneration and utilization of renewable resources.

Keywords: *Circular Economy, Cleaner Production, Industry 4.0, Automotive Industry, Resources Equity*

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An analysis of Waste Management in Italian cities: Performance Measurements and policy Implications

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Abstract

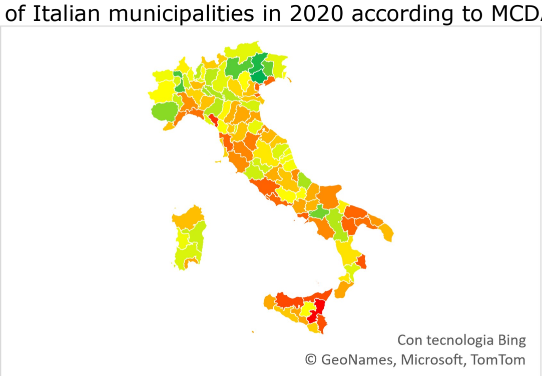
Municipal solid waste (MSW) accounts for approximately 10% of the total waste generated in the European Union - EU27 (Eurostat, 2018). Their management is a pivotal issue in EU environmental policies, not only because of the aspects related to environmental and human health impacts, but also because the responsibility for the collection service is generally entrusted to local authorities (public or private operator), and because the sector requires significant investments. Managing municipal waste is also a complex activity, because of the heterogeneity of waste itself, the existence of different sources of production (60% to 90% comes from households, the rest from commercial activities) and because of the close link that the sector has with social behaviour and consumption trends (Romano *et al.* 2022). From this point of view, the most important challenges for the world of waste are twofold: reducing production and aligning management objectives with the principles of the circular economy in order to orient the waste cycle more towards efficiency and sustainability. The performance of municipal waste generation in 2020 was strongly influenced by the Covid-19, which, due to the closure of many businesses, resulted in a decrease of more than one million tonnes of municipal waste generated. In 2020, municipal solid waste generation in Italy stands at 28.9 million tonnes (Table 1), down from 2019 (-3.6%).

Table 1. municipal solid waste generation in Italy (2016-2020), 1000 tonnes

	2016	2017	2018	2019	2020
North	14152	13955	14338	14399	13910
Center	6614	6474	6582	6510	6161
South	9346	9143	9244	9114	8874
Italy	30112	29572	30164	30023	28945

The Sustainable Development Goals (SDGs) 11 and 12 aim to achieve a more inclusive, resilient, safe and sustainable society and cities. In this pattern, policy makers, together with entrepreneurs and citizens, are called to a great challenge to optimize waste management. This work, through a multi-criteria decision analysis (MCDA), aims at comparing the sustainability of 110 Italian cities through the evaluation of technical and economic indicators, ranking cities on the base of their economic, environmental and social performance (D'Adamo *et al.*, 2022; Lombardi *et al.*, 2021) in a triple bottom line perspective, using cost data (economic), separate collection and mixed waste generation data (environmental) and average tariff paid by citizens (social). Results in Figure 1 show strong disparities across Italy with three northern cities at the top of the ranking (green areas) and many southern cities at the bottom (red areas), clearly indicating best and worst performers. The analysis would facilitate the development of a future sustainability urban waste management plan that can improve our cities and quality of life for citizens.

Figure 1. Ranking of Italian municipalities in 2020 according to MCDA sustainable index



Keywords: circular economy; sustainability, waste management, MCDA
JEL: O18; Q53

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Comprehensive Evaluation of Urban Greenspace Value through the Spatial Relationship between Housing price and Ecosystem Services

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Abstract

Urban greenspace provides a variety of ecosystem services. A reasonable evaluation of such services, both from an environmental and from an economic point of view, can deliver a more comprehensive and accurate assessment of urban greenspace value and might be helpful for possible future market transactions. There seems to be a spatial correlation between housing price and ecosystem services. The hedonic price model takes into account also the greenspace around the residences. This study proposed a methodological framework combining the emergy accounting method and statistical model, taking Beijing as a case study. The relationship between housing prices and ecosystem services is explored, and the different types of urban ecosystem service are evaluated, taking into account the heterogeneity of different size, distance and perception of greenspaces. Ecological thermodynamics was applied to the housing price characteristic model, accounting for the ecological value embedded in the housing price, and provided a theoretical basis for the ecological value monetization evaluation and urban ecological planning. The results show that the improvement of each unit of ecosystem services value measured by means of the emergy accounting method will increase the housing price by 806.28 yuan per square meter. Small and micro parks have a more positive impact on housing prices than medium and large parks; The positive impact of grassland on housing price is greater than that of woodland, wetland and shrubs; Carbon sequestration has the largest positive impact on housing prices of other kind of ecosystem services.

Two important inspirations can be obtained from this research: (1) The current real estate market does not reflect the part of ES provided by urban greenspace that can be passively acquired by residents. Accessibility is still a key issue to be considered in the pricing of urban greenspace. This also shows that: (2) The value reflected in the current housing price does not represent the full value of ecosystem services provided by urban greenspace. As many ecologists believe, the value of an ecosystem is enormous and incalculable, because it is not only "valuable" to human beings, but also to other species and future generations, and even to the homeostasis of the ecosystem itself. For this reason, it is "anthropocentrism" to equate only the part of the ecosystem that serves humans with its intrinsic value. The methodological framework proposed in this study is helpful to further explore the ecosystem services provided by urban greenspace. The quantitative pricing results of different ecosystem services can be used as reference for relevant ecological trading and compensation policies. Qualitative analysis of parks and different ecosystems can provide value for urban greenspace planning.

Keywords: *housing prices; emergy; ecosystem services; urban greenspace*

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Determinants of Sustainable Footwear Consumption: A Cross-Country Comparison

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Abstract

Unsustainable production and consumption patterns lead to climate change, biodiversity loss, and pollution globally (UN, 2022). The fashion industry belongs to the most impactful sectors, together with the food, energy, and mobility industries. These sectors' impacts are linked to the increase in consumption, driven by fast fashion and the growing population, the high resources consumption, the use of polluting substances, the exploitation of labour, and the early disposal of enormous quantities of clothing (Dissanayake and Sinha, 2015). Footwear production has grown dramatically in recent decades. On average, more than three pairs of shoes are purchased worldwide per person per year (Jacques and Guimarães, 2012). This amplifies the previously mentioned problems and sheds light on the need to carry out an in-depth analysis of this subset of the fashion industry from the sustainability point of view.

Literature about footwear and consumer behaviour is scant. Most studies approach the topic by focusing on the technical characteristics of shoes (e.g., robustness, fit, performance) and their link to consumer health (e.g., Willems et al., 2019; Bishop et al., 2020). Few studies investigate the footwear consumption process, some from the company's perspective (e.g., Juárez-Varón et al., 2023) and others from the consumer's one (e.g., Falahat et al., 2017). Research on sustainable footwear consumption is rare. For instance, Achabou (2020) evaluated the impact of perceived corporate social responsibility efforts on consumer preference; Jacques and Guimarães (2012) studied the innovation in green footwear composition by focusing on the disclosure practices used by companies. Only one study investigates consumers' consumption behaviours in the sustainable footwear context, giving insights related to the purchase behaviour of recycled shoes (Yadav et al., 2022). Furthermore, no studies compare sustainable footwear purchase behaviour of consumers belonging to two or more countries. Literature encourages research on consumers' sustainable footwear purchase behaviour in different contexts (Yadav et al., 2022) and on how cultural values influence sustainable consumer behaviours (Chwialkowska et al., 2020).

In this study, we focused on Italy and the Netherlands. Although Italy and the Netherlands belong to the European Union, distinct characteristics distinguish these countries at economic, structural, and cultural levels (Ali et al., 2021; Passaretta et al., 2018). This study explores the determinants of sustainable footwear purchase behaviour in these two contexts by extending the Theory of Planned Behavior (TPB) (Ajzen, 1991). Specifically, two constructs (ascription of responsibility and perceived marketplace influence) were added to the model. Hofstede's (2001) cultural dimensions were used to evaluate differences between Italian and Dutch consumers. This study's novelties are threefold: the focus on footwear - so far an under investigated industry under the sustainable consumer behaviour perspective, the cross-country comparison between Italy and the Netherlands, and the extension of the TPB model through the inclusion of two new variables.

An online survey was developed to reach the study goals. Constructs' scales were based on previous studies and modified to adapt them to the sustainable footwear context. The survey was distributed in English (in the Netherlands) and Italian (in Italy). The questionnaire was spread between December 2022 and May 2023. As a result, a sample of 724 respondents was obtained, composed of 430 Italian and 294 Dutch consumers. Confirmatory factor analysis (CFA) and structural equation modelling (SEM) techniques were used for the data analysis. SPSS 26 and AMOS 26 programs were used for CFA and SEM.

CFA results show a good model fit and the validity and reliability of the scales. The SEM technique was used to test the hypotheses. Preliminary results show that 8 out of 9 hypotheses are confirmed. Concerning the three main determinants in the TPB, only attitude was found to positively affect purchase intention, while subjective norms and behavioural control showed no significant effects. Ascription of responsibility has a positive influence on purchase intention, attitude, subjective norms and behavioural control. Perceived marketplace influence has a positive impact on attitude, whereas it displays a not significant impact on purchase intention. Furthermore, the multi-group analysis showed significant differences between the behaviour of Italian and Dutch consumers.

This study has several implications. From a theoretical perspective, it extends the TPB model by including three constructs; future studies could test this framework in other contexts. Further, it sheds light on consumption behaviour towards sustainable footwear (a so far under investigated product); and future studies should further investigate this product. Finally, it compares consumer behaviour in two European countries; future studies could be devoted to further investigate the country's influence, for instance, comparing emerging economies and mature ones. From a managerial point of view, it offers several insights for marketers to promote sustainable footwear consumption. It emerges that ascription of responsibility is a strong predictor of sustainable footwear consumption. Thus, marketers could develop marketing strategies highlighting the reduction of the environmental impacts generated by the consumption of sustainable footwear. Further, the differences that emerged between the two countries make it possible to formulate specific strategies for the two analysed markets.

Keywords: *Sustainable footwear, consumer behaviour, cross country, Italy, The Netherlands.*

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Emergy-Based Sustainability Assessment of Beef Cow-Calf Operation System

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Abstract

Emergy analysis offers a comprehensive assessment of resources utilization in livestock systems allowing the identification of hotspots of resource consumption and environmental stress, as well as comparisons between different production systems. This information can support decision-making processes for environmental cleaner production. Therefore, the aim of this study was to evaluate the impact of beef cow-calf operation phase on an extensive system by employing emergy analysis-based sustainability indicators. To achieve this, an inventory of activities and inputs used during the 2019 breeding season and subsequent rearing phase (calves born in 2020 and weaned in 2021) of Nellore animals belonging to the Animal Science Institute (IZ), located in Sertãozinho, São Paulo, Brazil, was constructed. The cow-calf operation system comprises 266.95 hectares of pasture, with a livestock capacity of 303.51 LU. The production system is considered extensive, relied on *Urochloa sp*. pastures, with a mineral supplementation of 0.100 kg/head/day for 180 days of the year and protein-mineral supplementation of 0.250 kg/head/day during the dry periods (180 days) of the year. The climate in the region is considered tropical, with the rainy season concentrated in the summer. The herd consists of 199 cows, 9 bulls, and 120 calves with natural mating being adopted. Data regarding pasture production and consumption, facility usage, input consumption, and zootechnical indicators (weight gain, mortality, pregnancy rate, number of animals) were collected. Outputs were measured in kilograms (live body weight) and comprised animals sold as steer and animals for feedlot and slaughter. The collected data were organized in an emergy table, categorized according to their origin: nature (I) or economy (F). The sum of these inputs represented emergy value produced in the productive system. Emergy indicators were calculated to estimate emergy efficiency, environmental load, and production system sustainability. Solar transformity was determined as the ratio between total emergy and the energy of good or services. The environmental load ratio was calculated as the ratio between input emergy flows and renewable and non-renewable inputs. The yield emergy ratio was calculated as the ratio between total emergy and non-renewable inputs form economy. Lastly, the emergy sustainability index was determined as the ratio between net emergy and the environmental load ratio of the system. The transformity of livestock was calculated to be 6.77E+05 sej/J, indicating a good energy efficiency in comparison to other livestock systems. The environmental load ratio (ELR) of 1.47 suggests a low environmental impact of this system. ELR ~ 2 suggest low environmental impact, 3<ELR<10 indicate moderate environmental impact, and ELR >10 indicate environmental impact relatively concentrated. However, the yield emergy ratio of 1.68 indicates that the system does not significantly increase emergy production. The emergy sustainability index (ESI) was found to be 1.14, reflecting medium-term sustainability (1<ESI<5). Notably, fuel and consumption of protein-mineral supplement were identified as the inputs with the most significant impact on emergy indicators. Based on these results, it is suggested that the extensive production system of beef cattle cow-calf operation exhibits good energy efficiency with low environmental impacts, reflecting medium-term sustainability. Therefore, the pasture-based production system can serve as a viable alternative for raising beef cattle. However, it is important to focus on producing supplemental feed within the farm's boundaries to minimize fuel and supplement inputs. To gain a deeper comprehension of the influence of animal feeding on production sustainability, it becomes necessary to conduct regional or national studies on the subject. As the spatial scale expands, this will ensure the proper involvement of all stakeholders within the production chain.

Keywords: *cattle breeding, environment pressure, efficiency, nellore.*

Enhanced Hexavalent Chromium Removal using Nanocomposite PANI-NSA@Ni0: Mechanisms and Kinetic Insights

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Abstract

This study focuses on the utilization of a novel adsorbent, PANI-NSA@Ni0, comprised of 2-naphthalenesulfonic acid doped-polyaniline adorned with zero valent nickel nanoparticles, for the efficient removal of hexavalent chromium from synthetic wastewater. The investigation delves into the optimization of critical adsorption parameters and the subsequent design insights for PANI-NSA@Ni0-based adsorption systems.

Through rigorous batch adsorption experiments, the optimal adsorption conditions, encompassing pH and adsorbent dosage, were systematically refined. The remarkable performance of PANI-NSA@Ni0 in achieving complete hexavalent chromium elimination at a dosage of 0.6 g/L within the pH range of 2 to 3 was unveiled. The adsorbent's monolayer capacity was quantified at an impressive 820.5 mg/g, and its equilibrium adsorption behavior was aptly characterized by a modified dual-site Langmuir isotherm model.

Furthermore, the adsorbent exhibited exceptional selectivity for hexavalent chromium, with negligible interference from competing ions. The efficient recovery of 95.5% of adsorbed chromium was successfully accomplished using regenerants 0.5 M HNO_3 followed by 0.5 M NaOH. The removal mechanism involves an adsorption-coupled reduction process, followed by the precipitation of $Cr(OH)_3$.

Intriguingly, a novel Langmuir-type kinetic model, derived from the proposed mechanism, yielded kinetic parameters unaffected by operational conditions. This innovative model precisely captured both adsorption kinetics and equilibrium using identical rate constants. Moreover, congruence between thermodynamic parameters, derived from the optimal isotherm and the novel kinetic model, underscored the spontaneous and endothermic nature of the adsorption process. This process was also associated with heightened interfacial randomness and potential structural modifications within the adsorbent/adsorbate system.

This comprehensive exploration not only offers a pioneering approach to hexavalent chromium removal utilizing PANI-NSA@Ni0 but also presents a breakthrough kinetic model that decouples kinetic constants from operational variances. The findings pave the way for the design of advanced, efficient, and adaptable adsorption systems for the treatment of hexavalent chromium-contaminated waters.

Keywords: *Polyaniline nanotubes; Zero-valent nickel nanoparticles; Nanocomposite; Adsorption coupled reduction; Langmuir kinetics.*

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Environmental, Economic, and Social Assessment of the Adoption of Industry 4.0 Technologies in Automotive Production: Contributions to Circular Economy and Cleaner Production

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Abstract

Automakers generate environmental impacts in the production system, including excessive consumption of natural resources such as water and energy, considerable emissions of greenhouse gases during the vehicle manufacturing process, and the generation of solid and liquid waste resulting from production stages (Montemayor and Chanda, 2023; Ravina et al., 2023). However, automakers are implementing Industry 4.0 technologies in production to improve operational performance in terms of waste reduction, cost reduction, quality improvement, and reduction in byproduct consumption (Montemayor and Chanda, 2023; Bankar and Nandurkar, 2023; Daly, 1996, 2008).
Another relevant aspect observed in practice is that the adoption of Industry 4.0 technologies in production has contributed to the micro-level circular economy, which considers cleaner production as a strategic tool (Amjad et al., 2021). Consequently, there is an increasing concern for the use of renewable and regenerative resources, aiming to balance resource consumption and extraction (Beltrami et al., 2021) and promote resource equity (Bal and Satoglu, 2018; Delai and Takahashi, 2013).
Thus, the objective of this article is to evaluate the environmental, economic, and social gains from the adoption of Industry 4.0 technologies in automotive production, contributing to the micro-level circular economy that considers cleaner production as a strategic tool. This approach seeks not only to mitigate the environmental impacts but also to establish sustainable practices that consider cleaner production as a strategic tool to achieve resource efficiency, waste reduction, and maximization of material utilization throughout the lifecycle of automobiles.
The method adopted for this study was a case study using interviews, direct observation, and document analysis. It was concluded that the incorporation of Industry 4.0 technologies such as big data, the Internet of Things, cyber-physical systems, and autonomous robots in the production system had positive impacts on the economic, environmental, and social spheres. The company utilizes Industry 4.0 technologies in conjunction with Cleaner Production approaches to promote environmental sustainability and resource efficiency in industrial activities, contributing to the circular economy. Notable practices include the use of state-of-the-art machines, devices, tools, and computer programs for vehicle manufacturing.
Additionally, the company invests in traceability systems that allow tracking the process from raw material acquisition to production, consumption, and disposal, thereby identifying relevant product information. The company also employs 3D printing for complex prototyping, intelligent robots with integrated network communication and autonomous management to assist in decision-making, as well as intelligent logistics through autonomous guided vehicles (AGVs) for autonomous process replenishment.
These technologies contribute to production optimization, waste reduction, efficient supply chain monitoring, and resource utilization maximization, thereby driving the circular economy. In terms of economic aspects, the company achieved significant benefits by reducing costs by $41,121.50 annually through the elimination of non-specialized jobs. Moreover, thanks to improved decision-making and real-time data access, there was a total saving of $211,000.00 per year and a return on investment (ROI) of 37.9% per year. The capital return time for investment was 3.15 years or 38 months.
Regarding the environment, the implementation of these technologies brought improvements in cleaner production. The reduction of 7,680 liters of water per year, decreased consumption of natural resources, and savings of 0.5233 GW of energy annually demonstrated greater energy efficiency in the process. Furthermore, real-time analysis performed by robots resulted in a reduction of 1,965 kg of inputs, contributing to a decrease in material waste. There was also a reduction of 1,198.1 kg of waste annually, thanks to an increased electrode lifecycle.
In the social aspect, while the elimination of non-specialized jobs brought economic benefits, it is crucial to consider the impact on affected workers and seek solutions for their training and reallocation. In conclusion, the adoption of these Industry 4.0 technologies in production has resulted in economic, environmental, and social advantages, emphasizing their importance for companies and society.
Therefore, it has been observed that the adoption of Industry 4.0 technologies in production has contributed to the micro-level circular economy, which considers cleaner production as a strategic tool, playing an important role in reducing environmental impacts and promoting social equity, with a focus on regeneration and the use of renewable resources.

Keywords: *Circular Economy, Cleaner Production, Industry 4.0, Automotive Industry, Resources Equity*

Exploring Cleaner Production and Circular Economy patterns within the Civil Economy paradigm, to address global and local challenges

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Abstract

The emergence of the concept of cleaner production (CP) expresses the will and the efforts of producers in rendering the life cycle of their products more environmentally friendly in terms of lower resources' use and reduced use of harmful substances for the environment and people. Clearly, the concept of CP is preparatory to the introduction of the CE model in production and services activities and aligns with the milestones of CE model of economy that emphasize the elimination of waste and pollution, the circulation of products and materials at their highest level, the capacity of production activities of regenerating the natural environment (Ellen Mac Arthur Foundation, 2023). Recently, CP also widen its attention beyond the relations of production processes with the natural environment to include that with the stakeholders of the company or the industry complementing the corporate social responsibility framework (Hens et al., 2018). This orientation contributes to the implementation of sustainable development patterns that are more environmentally just and socially inclusive and participative (Ghisellini et al., 2018).

Several authors point out that the current ecological-social crisis require to rethink radically the dominant economic and social paradigm based on the neoliberals' approach and propose alternative models such as that of the civil economy (Bruni and Zamagni, 2015). This school of thought, born in Italy in the eighteen century, was focused on a different idea of economic subjects and activities as well as of market and wellbeing. In particular, the economic actors are moved beyond the maximization of the profits or the consumption of goods since they take most care to the relations with the other economic subjects and their happiness contributing actively to the achievement of the happiness of society as a whole. According to Antonio Genovesi (1756) one of the major scholars of this school of thought, economic subjects by carrying out the economic activity in a "civil" way, the latter becomes a mean for achieving public happiness: individual happiness depends on the ability to create happiness in others and therefore we cannot be happy if others are not happy too.

Nowadays, being "civil" means that economic subjects such es entrepreneurs create good jobs, respects the environment, their workers and the society, improves the quality of goods and services. On the contrary, if they do not act in this way, they are not civil (Bruni, 2013).

On the basis of these premises, it is relevant and urgent to promote a shift of the current economic and social paradigm towards an alternative one where economic subjects recognize that their well-being also depends on goods that are not private but are public or common such as the quality of the environment (Nogueira et al., 2023). Such a shift has the potential to contribute to reduce the exploitation of natural resources and the exports of environmental and social impacts (Bocken and Short, 2021) since these aspects are taken into account in the decisions of the economic subjects (Bruni, 2013).

This study aims to evaluate by means of a literature review and case studies of application of CP and CE, embedded in the values of civil economy, their potential in contributing to tackle the current environmental-social crisis and promote the decline of the dominant economic and social paradigm based on the neoliberalism.

Keywords: *Cleaner Production, Circular Economy, Civil Economy, Resource equity, Environmental Work (font verdana, italic, 8-point)*

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From Ghost Gears to Green Solutions: Innovating Against Plastic Fishing Gear Loss

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Abstract

Marine pollution from plastic waste has emerged as a critical environmental concern, exerting profound and wide-ranging impacts on marine ecosystems and human societies. Plastic pollution in marine ecosystems results from the pervasive use of plastics in modern society, compounded by inadequate waste management systems and human behaviour. Plastic fishing gear, including nets, lines, traps, and floats, constitutes a substantial portion of marine debris due to accidental loss or deliberate discarding. These ghost gears persist in oceans and seas due to their longevity, entangling marine life and deteriorating into microplastics through physical degradation and sunlight exposure. A recent survey estimated that 2% of all fishing gear was lost annually, comprising 78,230 km2 of nets, 739,583 km of longlines, and more than 25 million pots and traps.

Furthermore, the economic toll is substantial, affecting fishing industries, coastal tourism, and coastal communities that depend on marine resources for livelihoods. The responsibility for such pollution belongs not to one particular entity but to an entire supply chain. The upstream stakeholders experience economic benefits, while the downstream stakeholder is left with environmental and economic costs. Recycling and retrieving fishing gear may create social and economic benefits for downstream communities. However, it is highly dependent on local infrastructures and market accessibility by those communities involved in this practice.

Novel material development, such as biodegradable polymers, can be vital in replacing petrol-based plastic in this area. Studies demonstrated that bio-blends can reach similar mechanical properties to nylon and other plastics. Their biodegradation in marine environments is effective on long-term exposure to marine environments, making it a compromised solution for lost fishing gear. The catch efficiency of such bio-blends also demonstrated no differences in some cases. But in some net applications, the actual biomaterial tested had a reduced efficiency ranging from 10% to 30%. In those cases, continual engineering in those bio-blends can occur to improve the efficiency results. Natural fibres can also be used to produce fishing traps. Cotton or jute has been assessed with an adequate degradation ratio in marine environments after long-time exposure, similar to the ghost-gear scenario. Natural material can be sourced from textile recycling schemes or local agriculture activities and replace petrol-based material.

In conclusion, addressing the issue of plastic fishing gear loss requires collaborative efforts across sectors and stakeholders. Implementing stringent regulations and guidelines for responsible fishing practices, incentive schemes to facilitate integration and acceptance, gear maintenance, and disposal can mitigate gear loss. Technological advancements, such as biodegradable fishing gear, promise to reduce lost gear's impact.

Keywords: *Resource Equity; Sustainable Development; Bio-based Materials; Environmental Conservation; Fishing gear*

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Hyperspectral Imaging for Sustainable Space Debris Recycling

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Abstract

Recycling plastics and other materials in space is becoming a significant focus for international space agencies to help prevent waste by allowing the use of ordinarily discarded materials. Metals, nonmetals (i.e. plastic, foams, packaging materials, etc.), and liquids (i.e., water, drinks, and chemicals) are usually waste produced during space missions. Plastics account up a significant amount of this solid waste. Reusing and/or recycling provides a viable alternative between financial gain and technological growth. Material identification and categorization are essential to implement a correct procedure for material recycling and/or to select manufacturing facilities (i.e. shredder, classifiers, separators, extruder, etc.) to be involved in outer space. An in-depth assessment of space materials may result in an *ad hoc* recycling technique decreasing resource loss and saving money. The possibility to implement a whole recycling process and/or a portion of it directly in the space environment can thus represent and interesting and viable option. In this perspective, the "*Hyperspectral based sensing architectures for resource circularity"* project was started and is actually running. The project belongs to the Spoke 5 - Closed-loop, sustainable, inclusive factories and processes of the Extended Partnership "MADE IN ITALY CIRCOLARE E SOSTENIBILE" (MICS) in the framework of the Italian PNRR - Missione 4 "Istruzione e ricerca" – Componente 2 "Dalla ricerca all'impresa" Investimento 1.3, financed by the EU – NextGenerationEU - PE0000004 - CUP: B53C22004130001 This project is specifically dedicated to the development and performance study of HyperSpectral Point (HSP) and Imaging (HSI) devices in order to design and set up sensing architectures and analytical procedures for the collection of information concerning waste materials resulting from space activities in order to identify and classify them recover and recycle them in a circular economy perspective. Recent advances in the waste recycling industry have given rise to HSI based sensing architectures, enabling the identification of various materials based on their distinctive spectral signatures. HSI is a non-destructive method for collecting spectral data from a large portion of the electromagnetic spectrum and storing it in a hypercube: a three-dimensional data structure with two spatial and one spectral dimension.

In order to define the sample spectral and spatial properties, HSI analysis aims to compress the chemical information present in these generally high dimensional datasets to a small number of components. The HSI-based approach is particularly successful when control actions have to be implemented, allowing the monitoring of recycled material quality and guaranteeing that it complies with industry standards. Through automating the identification and selection of waste materials and increasing the purity of recycled materials (i.e., removing contaminants that may have a negative impact on the quality of recycled products), the use of HSI in the waste sector may also improve the efficiency of sorting processes. In addition, when HSI is used instead of conventional manual sorting techniques, labor costs can be decreased, and throughput rates can be raised. The possibility to classify space debris by HSI sensors to recognize the presence of different materials for sorting/classification purposes was thus investigated in this work (Figure 1).

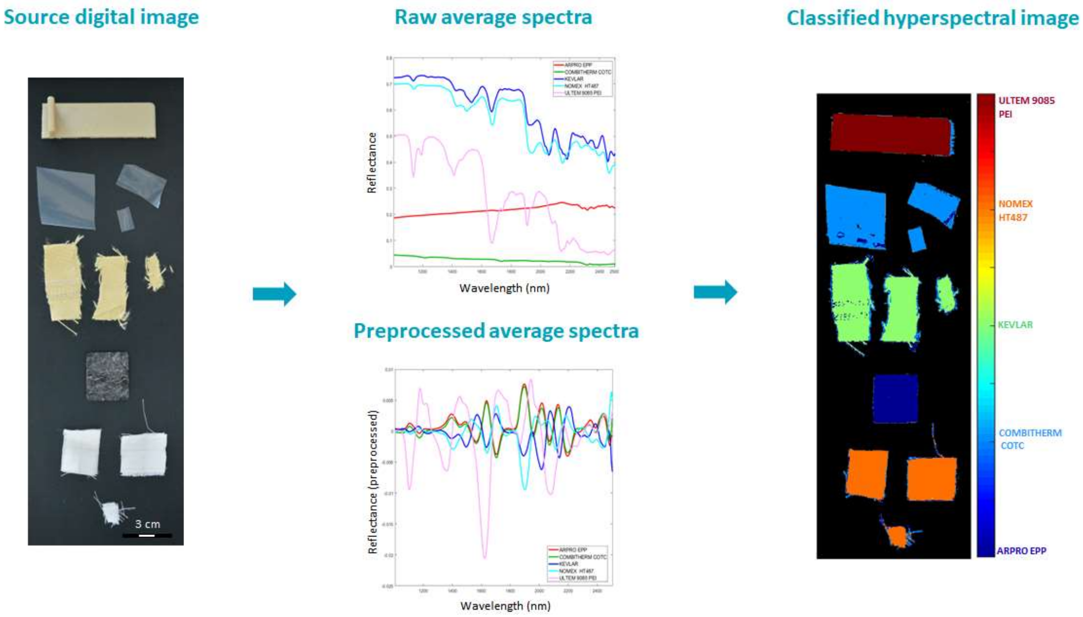

Figure 1 Procedure adopted to implement Hyperspectral Imaging analysis.

Two different acquisition platforms were used to acquire hyperspectral images:

- SisuCHEMA XL™ Chemical Imaging workstation (SPECIM Ltd, Finland) operating in the SWIR (1000-2500 nm) range (1000-2500 nm), equipped with Chemadaq™ software for spectra acquisition and collection;
- NIR Spectral Camera™ (Specim, Finland) equipped with an ImSpector N17E™ (SPECIM Ltd, Finland) imaging spectrograph working in the spectral NIR field (1000-1700 nm).

The adopted two HSI platforms, working in different spectral ranges, were tested and results analyzed. Analyses were performed using a set of samples provided by THALES ALENIA SPACE composed by materials linked to the most used family in space application: foam, technical textiles, multilayer, technopolymers Results showed as the adopted HSI approach can be profitably utilized to identify, recognize, and classify the different material categories. Finally, it is possible to state that good findings were obtained with these initial investigations and further studies will be carried out to improve the classification performance, widen the materials to be studied and reducing the number of wavelengths involved in the analysis to increase analytical speed and reduce instrumental costs.

Keywords: space debris, hyperspectral imaging, classification, waste, recycling

Acknowledgements - This study was carried out within the MICS (Made in Italy—Circular and Sustainable) Extended Partnership and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR)—MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.3—D.D. 1551.11-10-2022, PE00000004) PE 11 (CUP B53C22004130001). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

Innovative Antimicrobial Composites for Sustainable Infrastructure Enhancement

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Abstract

In the realm of engineering, the synergy between advanced materials and sustainable practices has ushered in a new era of research and development. This study delves into the promising realm of material fusion, resulting in the creation of reliable and cost-effective composites. The primary objective is to contribute to the principles of a circular economy by enhancing the adsorption of silver nanoparticles and silver nitrate onto repurposed chicken eggshell membranes. This novel approach has led to the formation of high-performance anti-microbial silver/eggshell membrane composites.

Key parameters, including pH, time, concentration, and temperatures, were optimized to achieve the desired outcomes. Through a comprehensive array of characterization techniques such as spectrophotometry, AAS, SEM, and XPS, the intricate properties of these composites were systematically explored.

Crucially, this research underscores the pressing issue of infrastructure budgets disproportionately allocated to maintenance, thereby impeding novel development. By addressing the pertinent challenge of microbial-induced concrete deterioration, this study innovatively proposes the incorporation of nano metals and waste materials into cement mortar. The focal point of this approach lies in the use of the eggshell membrane adsorbed silver nitrate and silver nanoparticles as this incorporation medium.

Results of exhaustive characterization and testing unveil a striking balance between antimicrobial effectiveness and structural integrity. The optimal conditions for synthesis were determined to be a pH of 6, a temperature of 25°C, and an agitation duration of 48 hours. The implications are substantial, as these engineered composites showcased remarkable antimicrobial attributes against specific microbial cultures.

In summary, this research demonstrated to the potential of material fusion in revolutionizing sustainable engineering solutions. Beyond its technical significance, the study highlights the urgent need to recalibrate infrastructure budget allocation. By harnessing the power of innovative antimicrobial composites, we stand at the precipice of a paradigm shift where infrastructure sustainability and development can harmoniously coexist. This presentation encapsulates the journey from concept to practical application, epitomizing the strides made in reshaping the engineering landscape for a resilient and ecologically conscious future.

Keywords: *Concrete; Bactericide; Silver Nanoparticles; Egg shell Membrane; Nanocomposite*

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Life in Plastic is not Fantastic: Preliminary Results of A Review on the Solutions for Marine Plastic Pollution

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Abstract

Plastic debris account for 80% of the total marine litter pollution, which poses a global threat to ocean biodiversity and human health. Solutions for preventing plastics to reach the coastal ecosystems or to remove it from the ocean are vast and have been a hotspot in the scientific literature. Nevertheless, a systemic approach for assessing the effectiveness of such solutions and identifying bottlenecks is lacking. This study aims to review the current available scientific literature on the solutions proposed for the problem of plastic pollution in the marine environment. We searched for original articles and reviews in the Scopus database using the search terms: ocean OR marine AND litter; AND plastic; AND solution OR policy OR management, presented in the title or abstract. Then, we selected articles that either propose or assess a solution by analyzing the content of the abstracts. Subsequently, the articles were categorized into "preventive solution" or "mitigative solution". "Preventive", represents a type of solution that proposes to reduce the amount of plastics that ends up at the ocean. On the other hand, "mitigative" represents a type of solution that proposes to remove the plastic from the ocean. Finally, a sample of 10 articles from each category was selected for a preliminary full text evaluation. The search resulted in a total of 706 documents, published from 1983 to 2023, of which 95% (671) were published in the last 10 years. Original articles and reviews account for 615 documents. The top 3 journals in number of articles published are Marine Pollution Bulletin (176), Science of the Total Environment (50) and Environmental Pollution (38). Countries that are more representative in number of articles are Italy (118), UK (97), US (72). At this point, 44 articles were trialed and categorized. Articles that propose a preventive solution are 75% of the total found. Among the preventive solutions, 67% propose improvements on the management of solid waste, strategies for reducing leakage of plastics from the production systems, and public policies for reducing plastic consumption and waste. Technological solutions are found in 9% of the articles and correspond to technological innovations, such as tools for monitoring the waste generated and its impacts on the marine environment, and innovative products to replace plastic such as bio-degradable materials. Public awareness is a preventive solution proposed by 6% of the articles found and comprises educative projects. Among the mitigative solutions (25%), technological proposals are 64% of the articles while management solutions correspond to 36%. Technological solutions in the mitigative category comprise the development of tools for collecting and recycling the marine litter, such as the "Seabin" device and the reuse of marine plastic waste enabled by 3D printing. Management solutions include strategies to engage the population in actions to remove the marine litter, such as programs of payments for environmental services. Results indicate a predominance in scientific-based solutions designed to prevent the plastic pollution via management strategies. This type of solution, as well as public awareness solutions, are mainly comprised of strategies that can be very effective on the long term. Nevertheless, short term solutions are urgently needed to cope with the magnitude of the impacts caused by plastic pollution. On the other hand, preventive technological solutions could be effective on the short term. Yet, the innovative products designed to replace plastic can cause undesirable side effects, such as the release of chemical contaminants. Mitigative solutions are underrepresented in the scientific literature. Both technological and management solutions in this category are applicable at a local scale, which indicates a limited effectiveness. Marine plastic pollution is a systemic problem, with multiple causes and effects. Solutions should cover different aspects of the system and be combined to effectively cope with such complexity. Moreover, multiple solutions should be designed to be applied in the short and long term. A systemic approach for assessing the solutions proposed to the problem of marine plastic pollution is a useful strategy for identifying pros and cons and pointing out research gaps.

Keywords: *marine litter; environmental solutions; systemic approach.*

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Methodological Model to Evaluate Eco-efficiency in Photovoltaic Systems

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Abstract

Eco-efficiency is considered a tool for the analysis of sustainability that indicates the empirical relationship between economic activities, cost, and environmental impacts (Zhang et al., 2008; Huppes and Ishikawa, 2005, cited by Caetano et al., 2012). In Colombia, the municipality of Uribía located in the department of La Guajira, has a great tourist and energy potential through renewable sources, however, this municipality presents conditions of dispersion and lack of interconnection infrastructure to the National Interconnected System, therefore, photovoltaic systems become an alternative solution for the supply of electricity, essential to satisfy the needs of the tourism sector. In this sense, this work shows part of the results obtained from a doctoral research work carried out, with the objective of proposing a methodological model of eco-efficient technological solutions for the installation of photovoltaic systems in Non-Interconnected Zones, specifically in the tourist districts of Nazaret, Punta Gallinas, and Cabo de la Vela. It should be noted that Nazareth has five accommodations and lodging establishments and its source of electricity comes from a hybrid polygeneration system (diesel-photovoltaic) and electric plants (gasoline and diesel). On the other hand, Punta Gallinas has three accommodations and lodging establishments and their source of electricity comes from electric plants (gasoline-diesel). Finally, Cabo de la Vela has fifty accommodations and lodging establishments, and their source of generation comes from photovoltaic systems and electric plants (gasoline-diesel). Likewise, this research includes a mixed experimental approach, so for the collection of information a questionnaire of 58 items was designed and applied to the 58 accommodation and lodging establishments.

In this order of ideas, for the construction of the methodological model, the Colombian Technical Standard NTC-ISO 14045:2012 was used, which addresses environmental management through the evaluation of eco-efficiency, a practical tool that quantitatively evaluates the environmental impacts of the life cycle of a product system in relation to the value of the complete product system, not only the product itself. Empirically, the development of the research started from the environmental evaluation, identifying the energy sources available in the study area; subsequently the technological evaluation through the sizing of the photovoltaic system that met the energy demand of the accommodation and lodging establishments in the study area. This allowed to advance towards the Life Cycle Analysis of the sized system applying the ISO 14040 and ISO 14044 standards, with the help of SIMAPRO software and supported by the impact assessment, in the ILCD 2011 environmental impact method, through which environmental loads were evaluated by impact category; then the economic evaluation using HOMER PRO software, in which different scenarios for electricity generation (photovoltaic system, diesel system and hybrid) were simulated and the economically eco-efficient alternative with the highest return rate of investment was chosen; finally, Standard NTC-ISO 14045:2012 was applied with the results obtained from each evaluation to obtain the Eco-efficiency Indicator of each technological alternative for electricity generation. The results of the research show that at least two technological alternatives are required to evaluate eco-efficiency in electricity generation through the proposed methodological model. Likewise, regarding the eco-efficient technological alternative for accommodation and lodging establishments, located in Alta Guajira such as Nazaret, Punta Gallinas and Cabo de la Vela, it is concluded that environmentally photovoltaic technology is more eco-efficient than the current technology used in accommodation and lodging establishments (diesel), but neither of the two options is economically eco-efficient (because it is not economically viable, since the rate of return on investment is equal to zero), however a hybrid system (photovoltaic - diesel) can be an eco-efficient option. However, the results obtained from the eco-efficient indicator for each technology indicate that the eco-efficient indicator of photovoltaic technology (IEFV) is lower than that obtained by the eco-efficient indicator of current technology - diesel (IEA) and it is difficult to conclude if there is in this scenario a totally more eco-efficient technology than the other.

Keywords: *Eco-efficiency, Cycle Analysis of Life, SIMAPRO software, HOMER PRO Software, ISO 14045:2012 (font verdana, italic, 8-point)*

Methodological Proposition to the Broiler Farmers Payment Considering Local Socioenvironmental Services Perspective

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Abstract

It is notable the efficiency gains that the current organizational form (vertical integration) set to the broiler production system, such as increasing chicken production with lower costs. Features like this moved broiler production from a farm sideline to a highly developed agribusiness. In this sense, production contract adoption was central to this system and providing a formal link between the broiler farmers and the processing firm. Commonly, broiler farmers receive a guaranteed payment based on the feed conversion ratio and the number of birds to slaughter. However, several times, the received payment is not enough to cover the production costs under their responsibility. Simultaneously, received payment does not consider the broiler farmers' capacity and ability that was passed on generation from to generation. Thus, this study aims to propose a methodological approach using Emergy theory as a pathway to suggest the most equitable monetary exchange between agroindustry and broiler farmers. For this, an Economic and Emergy-based mathematical model was developed for broiler production and broiler farming. To the mathematical model development, data from 2018 were obtained based on technical report data from broiler production systems and interview with experts in broiler production from region of Corcórdia, Brazil. Information regarding input consumption, price per input, and the price paid per broiler to the broiler farmers were considered. By evidencing the broiler farmers, a labor Transformity was calculated considering its social welfare according to Odum (1996). For this, landscape beauties (local natural resources), material consumption (food and fuel), and educational information acquisition, plus generational knowledge were considered. The Emergy Exchange Ratio (EER) indicator was proposed as a pathway to suggest an equitable price for the payment of broiler farmers by the processing firms. Thus, using the Solver tool from MS-Excel to their definition, the exchange equitable price was considered when EER =1. The results highlighted a gap between the price received by the broiler producers and the economic cost to their production (BRL 0.19; BRL to USD exchange rate = 3.65). Also, it was observed a gap between the price received by the broiler producers and the suggested equitable price. The suggestion of price paid per broiler for the broiler farmers was BRL 4.43 against BRL 0.88 practiced price. In conclusion, the methodological approach based on Emergy theory was effective in demonstrating an inequitable monetary exchange between agroindustry and broiler farmers. Thus, public policies must be targeted to become fairer in the monetary exchange between processing firms and broiler farmers avoiding chicken market price rises for consumers.

Keywords: *maximum of five. (font verdana, italic, 8-point) broiler production systems, broiler producer, emergy, environmental assessment*

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Pb(II) Adsorption Utilizing Untreated Mining Influenced Water (MIW) Sludge

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Abstract

The contamination of water by heavy metals, notably Pb(II), is a major environmental issue posing ecological and environmental concerns. Pb(II) is considered a priority pollutant and is widely used in various industrial activities. To ensure Pb(II) removal from wastewater before releasing to the environment an environmentally conscious solution is proposed in this study – the utilization of mining influenced water (MIW) sludge as a potential adsorbent for effective Pb(II) removal from aqueous solutions. This study's main aim is to determine whether the adsorbent is a feasible, economical, and environmentally suitable solution. In order to prepare for future applications in continuous flow (column) studies and conceivably prevent back pressure issues, adsorbent particles with a diameter of approximately 3 mm are used. Adsorbent performance is determined by optimizing parameters such as pH, adsorbent dosage, and initial adsorbate concentration. Optimal conditions are observed at an initial concentration of 350 ppm and an adsorbent dosage of 0.1 g. pH is not found to have a strong influence in the selected range. At the pH of the solution (approximately 5.3) and the stated optimal conditions a removal efficiency of more than 98 % and an adsorption capacity of 166 mg/g is observed. Furthermore, kinetic and isotherm studies are conducted to determine suitable models to describe the mechanism involved in the process. Equilibrium is reached at 90 minutes. This research aligns with the conference by showcasing the significance of waste valorization in promoting sustainable environmental practices as is demonstrated by conversion of a waste product into a valuable adsorbent.

Keywords: *sludge-based adsorbent; Pb(II) adsorption; sustainable water treatment; kinetics.*

SDGs and Material Footprint: The Challenges of a Full Circular Economy in EU

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Abstract

Rising inequalities and environmental degradation are major threats to the long-term prosperity of modern economic systems. Significant attention has thus been placed on sustainable transition in European policymaking, as seen by the Next Generation EU and European Green Deal and the rise in tools for monitoring transitions. The pursuit of sustainable development necessitates addressing environmental, social, and economic challenges while minimizing resource consumption.
In 2015, the United Nations introduced the Sustainable Development Goals (SDGs) to provide a comprehensive framework for guiding sustainable development efforts. Concurrently, material footprint has emerged as a vital indicator for assessing resource use and environmental impacts associated with consumption while circular economy has emerged as a promising approach to reducing dependence on external resources for European Union countries. In particular, in the context of sustainable consumption and production (SDG 12), the concept of the circular economy has gained prominence. The circular economy aims to minimize resource extraction, waste generation, and environmental degradation by promoting the reuse, repair, and recycling of materials. By shifting from a linear "take-make-dispose" model to a circular approach, economies can reduce their dependency on external resources and create more sustainable production and consumption patterns.
This paper investigates the challenges, interconnections, and feasibility of integrating the SDGs, material footprint, and circular economy within the European Union (EU) context. Specifically, it focuses on the current and anticipated EU's dependency on materials from the rest of the world[1] in the context of a low-carbon energy transition. Indeed, although the EU is striving to implement a net-zero carbon transition in the next decade, this passage requires rare materials sourced mostly from Africa and China. This context raises important questions regarding the feasibility and implications of circular economy practices in reducing the EU's dependency on external resources while simultaneously pursuing the energy transition. Therefore, the study examines the complexities, trade-offs, and opportunities associated with circular economy practices.
In addition, this research compares current trends with a hypothetical "resource equity scenario", in which the net EU material footprint is zero. This counterfactual analysis provides a measure of the potential increase in the volume and speed of circular economy practices and compares the performance of the SDGs under this scenario. Hence, this research aims to provide insights into sustainable development policymaking and decision-making processes within the EU and beyond.

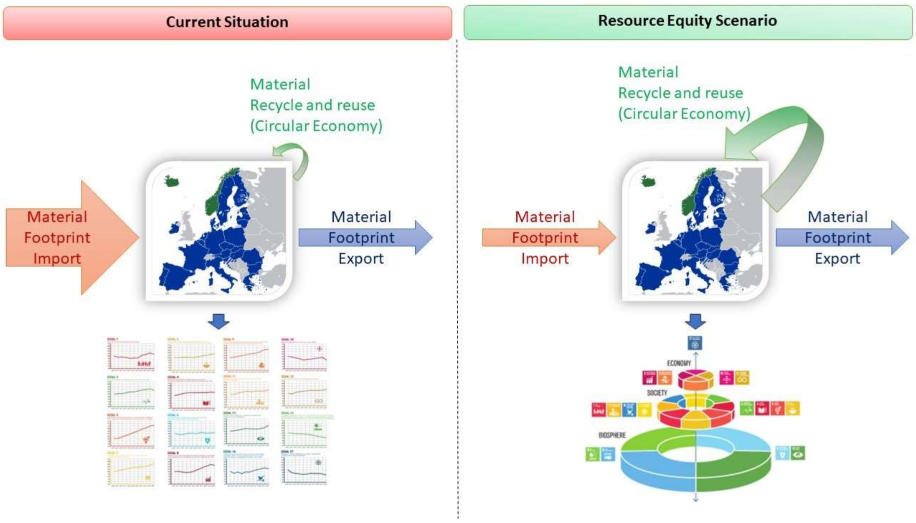

Figure 1: Macroview. EU's material dependency.

Left-hand side: current EU's material dependency from the rest of the world and its possible linkage with SGDs performances. Right-hand side: challenges related to resource equity
Note: SDGs trends' picture from (Asvis, 2022, see pag. 36-37). SDGs' picture from https://www.beyond-growth-2023.eu/).

Figure 1 illustrates the transition from the current situation towards a hypothetical "resource equity" scenario, where the total volume of materials embedded in imported and exported goods is balanced. This scenario

[1] see the Vox column https://cepr.org/voxeu/columns/eus-strategic-dependencies-unveiled

serves as a basis for discussing the expected increase in sectors involved in the circular economy and exploring potential interventions, such as product design for longer product life and material reduction and reuse. Additionally, we will address the challenges posed by the energy transition, considering that the infrastructure to convert renewable energy flows into available energy often requires the use of specific minerals (e.g., lithium, cobalt, etc.) and rare earth elements which are abundant outside the EU. This highlights potential limitations to simultaneously achieving all SDGs in the EU under a more equitable resource scenario, as it may restrict mining activities required to supply minerals for constructing solar plants, electric cars, wind farms, and more within the EU. The pursuit of an equitable resource distribution with low ecological impact necessitates rethinking the structure, connections, and prioritization of the SDGs.
The data used in our analysis are mainly from the "Material Flows and Resource Productivity" from EUROSTAT[2]. This allows us to inspect interconnections through bilateral trade flows in raw material between EU27 and around 200 partners (EU and extra EUR) from 2004 to 2021. Moreover, the other datasets in the "Material flow accounts" contain information on consumption, extraction and the amount involved in the production, and indicators of the circular material use rate. The other relevant data sources are the SDG indicators[3] and bilateral information on geographical, institutional, cultural and economic features from the CEPII (Conte, Cotterlaz and Mayer (2022))
We employ network analysis (De Benedictis, Taglioli, 2011) to understand central and peripherical countries and which are the main actors that foster the integration of the SDGs, material footprint, and circular economy. The network analysis integrates traditional input-output methods, this extends and complements the evidence on material footprint from Wiedmann (2015) and the nexuses with SDG as Lenzen et al. (2022)[4] (which focuses on 8.4 'resource efficiency improvements' and 12.2 'sustainable management of natural resources).

Keywords: *Circular Economy, Resource Equity, Sustainable Development Goals*

[2] https://ec.europa.eu/eurostat/data/database?node_code=env_mrp
[3] Links: https://unstats.un.org/sdgs/indicators/database/archive & https://www.sdgindex.org/reports/
[4] Data provided at https://ielab.info/resources/datasets from this article would be useful to validate our results.

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Solar Panel Recycling

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Abstract

South Africa has seen a tremendous increase in the installations of solar panels over recent years, due to numerous reasons, the main being the pro-longed loadshedding practice. This rate will be further amplified with the transition to renewable energy generation. The volumes of solar panel waste is expected to increase exponentially once solar panels, currently in service, become obsolete. Such trends are seen in many European countries with a push for waste treatment facilities for this electronic waste fraction. As of 2021, South African Legislature declared that decommissioned solar panels can no longer be disposed of in landfills, in fact any electronic waste. The overall aim of this study was to propose a sustainable recycling process for silicon photovoltaic panels that is suitable within a South African context. Experimental tests were conducted on the frame disassembly and delamination phases of the proposed recycling process to determine what percentage of the total initial silicon photovoltaic panel weight can be recovered as the aluminium frame, junction box, and glass. Furthermore, a life cycle analysis was conducted to compare the environmental impacts of the proposed recycling process to that of the production process of the virgin raw materials. In the frame disassembly experimental work, the aluminium frame and junction box were manually recovered. The frameless panel was fed into a crusher and separated into three size fractions: fines ($d < 0.075$ mm), intermediate ($0.075 < d < 1.180$ mm) and coarse ($1.180 < d$ mm). A thermal delamination method was proposed with the coarse fraction undergoing further thermal treatment to disintegrate the encapsulating layer. Thermogravimetric analysis showed that the encapsulating layer was completely disintegrated during thermal treatment. After thermal treatment, the overall average recovery yield of the junction box, aluminium frame, fines, and glass as a percentage weight of the total initial panel was 1.8 ± 0.33%, 12.1 ± 0.0%, 0.94 ± 0.15%, 70.1 ± 2.3%, and 15.1 ± 2.7%, respectively. The remaining 15.1 ± 2.7% of the panel weight was lost due to handing and treatment. The X-Ray Diffraction analysis results showed that the intermediate fraction contained metallic impurities hence cannot be classified as directly recoverable clean glass. Furthermore, the analysis showed that the fines fraction contained a significant amount of metals which can be valorised through the metal recovery phase. The life cycle analysis results showed that the environmental footprint of the proposed recycling process was predominately due to thermal treatment since it comprised 80.5% of the total environmental impact. The proposed recycling process is sustainable since its environmental footprint is significantly lower than that of the production process of the virgin raw materials.

Keywords: *solar panel recycling, silicon, thermal delamination*

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Strategies for Carbon Footprint Reduction of Wine Production

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Abstract

In a world with ever growing population and where climatic change affects all aspects of the day-to-day activities, agroindustries need to continue to improve the efficiency of their production. Nowadays, there is a general increase in the costs of energy and materials, to which is added a growing pressure for sustainable production from increasingly restrictive laws and from consumers themselves. Companies aiming to survive need to face this challenge and find ways to identify and minimize the impact of their products. In this context, life cycle assessment (LCA) approach (ISO 14040 and ISO 14044), based on multi-year analysis, presents itself as a powerful tool to identify the hotspots and help evaluate better production alternatives.

World wine production is around 260 Mhl/year and in the past few years, it became clearer that the wine agroindustry is facing the pressing need to focus on the sustainability of resource use, reducing the dependence on natural resources as well as production costs. Considering the great economic and social importance of wine production in many countries, in this work the wine production chain was studied with a four-year data acquisition in order to include the natural variability present in the crop production. A medium-size winery (production capacity of 6100 hL), located in the south of Portugal was selected for the study, with a cradle-to-gate approach, including all production stages from vineyard installation to wine packaging. The life cycle inventory was carried out by direct measurement and through a questionnaire, taking into account the consumption of energy, materials and natural resources, as well as emissions and residues in the three main production phases: viticulture, vinification and bottling/packaging. Global warming potential (GWP) was the indicator chosen for the assessment of the environmental impact of wine production, with the SimaPro software V.9.0.0.49 PHD, and IPCC 2013 GWP 100a method. Whenever necessary, the Ecoinvent database were used and an uncertainty analysis was carried out using Monte Carlo simulation, aiming to improve results quality. Additionally, the functional unit (FU) chosen represents the traditional bottle of wine (0.75 L), and all the inputs, outputs and identified impacts are therefore converted to this FU.

The overall results revealed that the winery phase accounts for most of the impact with an overall impact of about 80% from the 0.392 Kg CO_2eq/FU. The packaging materials constitute the highest contributor for this impact, mainly resulting from the glass bottles used. In order to help wine producers to make informed choices, different scenarios were evaluated in order to identify the best strategies aiming at carbon footprint reduction. The scenarios evaluated accounted for different levels of implementation difficulty, in order to give some immediate and easily applicable alternatives and some more medium to long term alternatives. Regarding the most impactful input, the glass bottle, an easily implemented alternative was identified accounting for about 19% impact reduction, while a long-term alternative has been identified with an impact reduction of more than 70%.

The importance of the multi-year analysis is revealed when the year-by-year analysis of the data is evaluated. Here, the results show a fluctuation that could be significant and, so, the multi-year analysis revealed to be more representative of the environmental impact of the agro industry than the result of a single random year since it eliminates annual weather variability, corroborating other results found in literature.

This study allowed for the identification of the most impactful production processes of the specified agroindustry, allowing to the identification of hotspots and improvement opportunities, with emphasis to the selection of the bottle of wine that can significantly affect the carbon footprint results and positively contribute to the improvement of the sector environmental and cost efficiency. Considering this, further studies should be conducted, with different environmental impact indicator, in order to have a more comprehensive analysis of the wine production chain impacts.

Keywords*: Agro industry circularity; Hotspots; Resource efficiency; Simapro; Winery;*

Sustainable Brick Production: Harnessing Recycled Aggregates and Bio-based Materials for Equitable Resource Utilisation

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Abstract

When anchored in resource equity principles, brick production can transform the construction industry into a bastion of sustainable development and equitable resource utilisation. For instance, incorporating recycled aggregates or industrial by-products like fly ash conserves virgin raw materials and prevents landfill waste. Similarly, sourcing bio-based materials such as hemp or bamboo for brick production can promote the sustainable use of rapidly renewable resources, thus ensuring that brick manufacturing draws from and contributes to a more balanced and equitable resource pool.

With its extensive reach and immense resource consumption, the construction industry stands at the crossroads of significant environmental impacts and potential sustainability achievements. As one of the fundamental building blocks, bricks play a pivotal role in this narrative. Addressing resource equity in brick production can serve as a microcosm for broader industry shifts towards sustainability. Brick production, long regarded as a traditional facet of the construction sector, finds itself poised to spearhead a transformation. At its core is the notion of resource equity – a principle that promises environmental conservation, sustainable development, and equitable distribution of resources. When anchored in these principles, brick manufacturing is not merely about shaping clay but also reshaping the very foundations of sustainable development in construction.

Traditionally, the raw materials used in brick manufacturing, chiefly clay and shale, are mined extensively. This practice, over time, has led to the depletion of prime natural resources and raised concerns about the ecological footprint of brick production. Yet, the evolution of the industry shows promising shifts. Integrating recycled aggregates and fly ash, by-products often earmarked for landfills, into the brick-making process is more than just innovative. It signifies a transition from wasteful to waste-less, from exhaustive to sustainable. For instance, fly ash, a combustion residue, often accumulates in landfills, contributing to environmental degradation. However, when integrated into brick manufacturing, it not only replaces virgin raw materials, effectively reducing the demand for mining but also results in bricks that are often lighter and more insulating. Yet, the innovation continues beyond recycled aggregates or fly ash. The exploration of bio-based materials, such as hemp and bamboo, in brick production carries the potential to revolutionise the sector. These rapidly renewable resources serve dual purposes. On the one hand, they act as carbon sinks during their growth phase, sequestering carbon dioxide and playing a crucial role in climate change mitigation. On the other, when employed in brick manufacturing, they contribute to durable, environmentally friendly, and resource-equitable bricks.

Beyond the obvious environmental implications, the shift towards resource equity in brick production carries significant economic and societal connotations. Adopting sustainable materials and practices might entail initial investments. Still, the long-term benefits, from reduced resource expenditures to tapping into the expanding market of green products, promise not just recovery but potential profitability. Furthermore, the positive brand image from sustainable practices can enhance the industry's reputation, opening avenues for further investments and partnerships.

While industry innovation and collaboration are pivotal, the role of regulatory bodies is undeniable. By offering incentives, establishing sustainability benchmarks, and providing infrastructural and research support, governments can facilitate the transition. Establishing green building codes, tax incentives for sustainable practices, and grants for research can create an environment where resource equity is encouraged and becomes the industry standard. Consumer awareness, however, remains the linchpin. As consumers become more informed about the environmental impacts of their choices, their demand for sustainable products grows. This demand-pull can justify and propel industry investments in sustainable brick production, making it a norm rather than an exception.

In conclusion, when viewed through the lens of resource equity, brick production offers a microcosm of the broader potential for the construction industry. As the sector grapples with its environmental impacts and seeks avenues for sustainable growth, bricks present a tangible starting point. The industry can set a precedent by championing resource equity in brick production, paving the way for comprehensive sustainable development. Bricks might be the key to a harmonious and sustainable future in the intricate dance of demand and supply, innovation and tradition, and ecology and economy.

Keywords: *Resource Equity; Sustainable Development; Bio-based Materials; Environmental Conservation; Construction Industry Transformation*

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The Role Of Experience in Italian Consumers' Intention to Adopt Electric Vehicles (EVs)

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Abstract

Aimed at decarbonizing global production and consumption activities, countries are intensifying efforts to curb annual greenhouse gas emissions. Transportation stands out as a leading contributor, responsible for about 27% of total emissions, with road transport alone accounting for 75% (EEA, 2020; IEA, 2021). This emphasizes the need for a transition to zero-emission or alternatively-fuelled vehicles. While recent research has explored factors influencing electric vehicle (EV) adoption, the literature often overlooks distinctions among EV types — i.e., Battery Electric Vehicles (BEV), Plug-in Hybrid Electric Vehicles (PHEV), and Hybrid Electric Vehicles (HEV) — and the impact of consumer experience on their adoption (Augurio et al., 2022; Brückmann, 2022; Kar et al., 2022; Li et al., 2022; Munshi et al., 2022; Sahoo et al., 2022).

This study analyses the purchase intention of Italian consumers toward EVs through an integrated model based on the *Unified Theory of Acceptance and Use of Technology* (UTAUT) (Venkatesh et al., 2003). This theory considers four antecedents: *Performance Expectation* (i.e., the perceived benefits or utility of the technology), *Effort Expectation* (i.e., the degree of perceived ease of use of the technology by the user), *Social Influence* (which reflects the degree to which other parties believe that the user should adopt the technology), and *Facilitating conditions* (i.e., the perception that users have of the existence of an adequate infrastructure that supports the use of the technology). This research extends UTAUT by integrating the consumer's experience, i.e., the amount of objective or declared knowledge on the part of the consumer's user towards the EVs product (Johnson and Russo, 1984; Rao and Mon Monroe, 1988), investigating the effect of experience on *Performance Expectation* and *Effort Expectation*.

The methodology was developed in two phases. In the first phase, data were collected through a survey of Italian consumers, in which a total of 430 respondents participated. The questionnaire included a 5-point Likert scale (from 1 = "completely disagree" to 5 = "completely agree") organized in multiple blocks repeated for the three EV categories. For each EV category, the questionnaire included a brief product description and investigate whether or not the interviewee had previous EVs experience. The first block examined the construct *Performance Expectation* with four items related to environmental and economic aspects (Gunawan et al., 2022). The second block investigated the construct *Effort Expectation* with four items related to driving ease, charging, interaction, and product learning (Zhou et al., 2021). The third block investigated *Social Influence* by providing four items related to the respondent's important people's thoughts about EVs (Curtale et al., 2021). The fourth block investigated the *Intention to adopt* and included four items asking whether the respondent was considering or planning to adopt an EV shortly (Gunawan et al., 2022; Zhou et al., 2021). The last two blocks were the same for all three products. The fifth block examined the *Facilitating conditions* and included six items concerning the current charging and maintenance infrastructure and government development policies (Gunawan et al., 2022; Zhou et al., 2021). In terms of HEVs typologies, the questionnaire did not include items related to infrastructure. The sixth block concerned the demographic factors of the respondents.

In the second phase, we analyzed the data using AMOS software. First, a confirmatory factor analysis (CFA) was conducted to confirm the validity of the multi-item scales in the study (Jain and Raj, 2015). The CFA was evaluated using the model fit indices (Bagozzi, 2010; Byrne, 2001). Secondly, structural equation models (SEM) were developed. The results show relevant differences among the three categories of EVs. In particular, for BEVs, experience has no significant influence on the purchase intention, while *Performance Expectation*, *Social Influence*, and *Facilitating conditions* positively influence adoption intention. For PHEVs, *Direct Experience* negatively influences *Effort Expectation*, while *Performance Expectation*, *Effort Expectation*, and *Social Influence* positively influence the *Intention to adopt*. Finally, for HEVs, *Direct Experience* negatively influences *Effort Expectation*, while *Performance Expectation* and *Social Influence* positively influence *Intention to adopt*.

In conclusion, it can be said that experience influences the consumer adoption process of EVs and that the effects differ depending on the type of EV. Public and private promotional actions should consider user experiences or media activities aimed at reducing the performance and effort expectations of EVs, taking into account the different types of EVs. This would increase consumer adoption intention.

Keywords: *Intention to adopt, Battery Electric Vehicle (BEV), Plug-in Hybrid Electric Vehicle (PHEV), Hybrid Electric Vehicle (HEV), Unified Theory of Acceptance and Use of Technology (UTAUT)*

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There's Plastic and then there's Bioplastic: Seeking Alternatives to Petroleum-Based Plastic tn Food Packaging through a Circular Economy Lens

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Abstract

The invention of plastics and its now ubiquitous use in food packaging has had mixed impacts and outcomes across the world. On one hand it has revolutionised the production, manufacturing, transportation and sale of food products, and has been essential in preventing food spoiling, food waste and infection, thereby prolonging the shelf life of food products. However, it is also well known that plastic packaging is one of the biggest sources of environmental degradation and pollution connected to the linear plastic production and consumption system with its over reliance on short-lived single-use plastic (SUP) packaging. Among the long list of environmental impacts of plastics in the environment include the contamination of marine and land creatures, including the proliferation of micro-particles of plastics that are known to cause injury or death to marine life. The food industry has been using petroleum-based plastics for food packaging since the post-WWII era and it has shown an annual growth rate of 5% over the last few decades and is now the second most widely used material for food packaging.

Moreover, traditional packaging solutions for food are anticipated to exceed 700 million annually and to reach one billion by the end of 2021. Consequently, the plastic industry is the prime source of plastic pollution and is forecast to increase two-fold by 2050. In 2021 alone, the world traded nearly 369 million tonnes of plastics, equivalent to what would fill 18 million trucks queuing around the globe 13 times! Manufacturing around the world traded about 369 million tonnes of plastics in 2021 – with less than 10% of all plastics produced globally being recycled, most of the products in those trucks will end up littering our streets and flooding our seas. Researchers estimate that the flow of plastic into the ocean is likely to nearly triple by 2040 and without considerable action to address plastic pollution, 50 kg of plastic will enter the ocean for every metre of shoreline. Research has found that between 1950 and 2015, nearly 8300 million tonnes (Mt) of raw, virgin plastics were manufactured around the world, thereby creating almost 6300 Mt of plastic waste, 9% of which has been recycled, 12% incinerated, and 79% accumulated in landfills.

That's a lot of valuable resources that along the whole value chain of plastics manufacturing is being lost to landfills, oceans, roadways and other places in nature. Whilst in those places the plastic is leaching chemicals and slowly breaking down into minute microplastics that is ending up in human and animal food chains, that is having devastating environmental and health impacts. Clearly, we can't continue to allow plastics or pollution of any kind to be mismanaged in these ways, however the path to recovery of plastics in the environment is proving to be a difficult problem with no easy solution. While there are numerous grass roots community and government action occurring that is reversing a lot of the mismanaged plastic pollution in many locations across the globe, the sheer volume of plastics that are continuing to enter the natural environments we rely on for life means a viable solution is a long way off.

This reality leads researchers to wonder whether bioplastics is the 'magic bullet" alternative to petroleum-based plastics. Using a circular economy lens we investigate the options, opportunities and barriers to bioplastics becoming the ultimate solution to the current plastics problem. We examine the scientific, technological, policy and regulative barriers that currently exist to prevent some jurisdictions from enabling the transition away from petroleum-based plastics and suggest alternative options for solving this most wicked of problems for the 21st Century.

Keywords: *Plastic pollution; Cleaner Food Manufacturing; food packaging; Substitutes; Life Cycle; Markets, circular economy*

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Towards a Cleaner Agricultural Production through Sustainable Plastic Mulching Substitutes: The Case for Kenya

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Abstract

When considering single use plastics, plastic mulch used in the agricultural sector might not be an instant association. Nonetheless, agricultural plastic mulch is generally used for a single growing season and when the harvest season comes, it is removed and discarded. Globally, terrestrial farming demands 7.4 million tonnes and this is expected to increase by almost 6% every year by 2026. While plastic films are widely used due to their advantages in agricultural production, including soil water retention, soil temperature regulation, and control weed growth through mulching, they also undermine sustainable farming efforts because of the long-term consequences that threaten both human and planetary health.

In croplands, the use of plastic mulch films is the predominant cause of fragments and microbead plastics in the soil. These small particles continuously leach toxic additives and heavy metals that harm the soil microbiota, a delicate system of soil microbes that plays a leading role in the carbon sequestration capacity of soils by transforming carbon compounds into bioavailable nitrogen for the plants. Not only does the use of plastic mulch in agroecosystems impacts the soil microbiome responsible for carbon-capturing, but also brings about other environmental and economic negatives. The disposal of plastic films used as mulch proves to be challenging and inefficient, often resulting in landfilling, incineration or leaching into natural environments. Currently, there is no end-of-life treatment available for these materials. Furthermore, economic downsides include costly application practices, as the films need specialised machinery, as well as high expenses incurred in retrieval processes.

Selecting substitutes to agricultural plastic mulch is an endeavour that requires careful consideration of several factors to strive for better, cleaner agricultural practices. Firstly, the country context and the significance of crops being grown. The importance of the agricultural sector within a country and its governance practices is pivotal in finding pathways to implement material substitution. This study focuses on Kenya, a country where agriculture plays a decisive role in the economy. Agriculture accounts for a third of the country's Gross Domestic Product (GDP), and for 27% of GDP due to its strong ties with other sectors. Agriculture in Kenya, therefore, is a driving force in the non-agricultural economy. Notably, 60% of the export earnings come from agriculture products. The sector also provides livelihood to over 80% of millions of Kenyans in the form of employment, income, and food security. Consequently, given the unique characteristics of each crop and their importance to Kenya, four main crops will be considered: wheat, tea, coffee, and maize. These are all crops that are of utmost significance in Kenya's economic development and food security needs.

Other aspects to factor in when choosing the best agricultural plastic mulch substitutes are the lifecycle analysis, the availability, and the market scalability of the potential substitute. The ideal substitute to agricultural plastic mulch should ideally be both competitive, that is with strong productive capacities, and efficient in downstream waste management. The former is mainly analysed through economic indicators such as the Revealed Comparative Advantage (RCA), which informs on the competitive edge in producing and exporting identified substitutes. The latter refers to the recovery/recycle rates of potential substitutes. In terms of potential substitutes availability, while there is a focus on tapping into locally accessible resources, options will be provided for building a robust domestic industry using imported raw material inputs.

Lastly, it is important to underscore that while this paper will primarily focus on material substitutes, promising technologies and innovative food production methods may also be considered if they are deemed useful for the crop under study. The outcomes of this study aim to provide alternatives to plastic mulch substitutes in agriculture to reduce plastic pollution, enhancing soil health and fostering growth in both domestic and international markets for these crops.

Keywords: *Plastic pollution; Cleaner Agriculture; Plastic mulch films; Substitutes; Life Cycle; Markets*

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Unveiling Opportunities for Local Circular Bioeconomy Systems Using an Open Innovation Approach

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Abstract

Background, motivation, and scope. There is increasing incentive from governments for companies to transition to a circular bioeconomy (CBE), especially in Europe. A Bioeconomy is rooted in renewable resources. In a CBE, biomass is used to make products of added value, seeking to keep the value at its maximum at all times. Nonetheless, such a transition does not happen overnight, and until we are able to satisfy societal needs with sustainably sourced biomass, we can make the case for a circular bioeconomy proving its value by recovering value from waste streams. This research takes an exploratory stance, proposing a project approach to answer the following question: ***how can we build local circular bioeconomy systems by upcycling biomass waste?*** This study is scoped down to explore municipal biowaste, such as beach wrack (i.e., seaweed and eelgrass), straw, and grass clippings, in the capital region of Denmark and Southern Sweden, as part of the project Power Bio (https://www.gate21.dk/powerbio/). **Methods**. This exploratory study dwells on the possible methods to be used to build local circular bioeconomy systems to make use of biomass waste. The methods to be used are rooted in investigative research (Step 1), innovation sprints (Step 2), and stakeholder dialogue (Step 3), as described hereafter. Step 1: Investigate the biomasses. The biomass wastes should be collected and analysed to get to know their content, such as chemical and physical composition. This allows one to start identifying for what purposes parts of the biomass, or the whole of it, can be used. Step 2. Run innovation sprints (e.g., Hackathons). They can be run with two purposes, (i) finding potential products, for instance by posing an open question such as "what can be made from grass clippings?", or (ii) finding answers to specific challenges, such as "how do we collect and sort beach wrack in order to avoid undesired materials coming along (e.g., plastic waste left on the beach)?". The results of Step 1 should be made available to the participants in the innovation sprints. These can be run in two phases, where in the first phase challenges are made available, participants (companies, university students, citizens) register and submit a summary of a potential solution, the best ranked solutions are invited for a second phase, where they have closer dialogue with the problem owners, have the chance to further develop their solution, produce a prototype, and pitch their idea at a final event, at the end of the innovation sprint. The best solutions win the right to test their solution at a technological institute (technical advice, knowledge, facilities, time, personnel, are provided for the tests). Step 3. Establish a dialogue between the private initiative and the local government and other stakeholders, aiming to identify gaps that need to be bridged to build local circular bioeconomy system. After the testing phase, the best solutions can be pointed out. To put them into practice, a dialogue between the companies that can implement those solutions and the local government should be initiated, in order to reach agreements on how the market, the supply chain, and the regulations and incentives for such solutions to come to life can take place. **Expected Results**. A series of results can be expected at the end of this process, including: (1) a list of potential products that can be made from the biomass wastes. Even if not feasible, they can serve as inspiration for other potential products that might result from the use of the biomasses; (2) a list of the industries that can benefit from the final products. One can identify what industries are more likely to benefit from the products that can be made from the biomass wastes. This can be an input to policy initiatives; (3) insights into the most valuable components. One can hope to identify whether only a few components of the biomass are being valued, or all of it, and why. One can also draw on strategies to valorize the less valuable ones; (4) identify what supply chain links are needed to establish local circular bioeconomy systems. One can hope to identify what is needed to build supply chains in order for the products to be brought to the market. This translates into what incentives need to be created, and refers back to Step 3, stakeholder dialogue. **Further Research**. At the end of this process, one will still be left with the challenges of investigating (a) potential sustainability impacts of the new products (from waste), including financial, social, and environmental sustainability, and (b) potential impacts of substitution (what old products they replace, and which option is sustainably better).

Keywords: *bioeconomy, biomass, circular economy, market innovation, sustainability.*

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Papers

Assessment of sustainability 4.0 practices in service companies

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Abstract

Industry 4.0 has been crucial to the evolution of manufacturing and service companies' production methods. The technologies included in this production model result not only in cost reduction but also mitigate the use of resources, positively impacting the triple bottom line aspects. This panorama leads to Sustainability 4.0, which represents the combination of the definition of Sustainability with Industry 4.0 practices, intensifying procedures, and effects. The current era of services requires analyses that identify the execution of branch activities, to improve their execution and offer higher quality services, which are responsible for greater absorption of labor and income generation throughout the world. world. In this context, the present study evaluated the factors that constitute Sustainability 4.0 in service companies. To this end, the questionnaire was adapted from Monteiro et al. (2022). As the main results, it was observed that digitalization, virtualization, and data analysis were the most evident aspects concerning technologies that enable Industry 4.0., and social and administrative practices were identified as more focused on sustainability. Companies consider that the adoption of Sustainability 4.0 can improve their competitive positioning as well as increase customer satisfaction, among other aspects identified.

Keywords: Sustainability 4.0, Industry 4.0, Services.

1. Introduction

The Fourth Industrial Revolution constitutes a new form of production, where resources and production processes are connected to the internet through intelligent systems, interrelated and capable of operating, supporting decisions, and correcting themselves autonomously (Ed-Dafali et al., 2023; Bag et al., 2020).

Also known as Industry 4.0 (I4.0), it originated in Germany in 2011 and was soon spread throughout the world as it aims to improve the efficiency of production and management processes to raise profitability (Khan et al., 2023; Lichtblau et al., 2015). I4.0 covers and integrates various technologies such as the Internet of Things (IoT), 3D printing, Big Data, robotics, and artificial intelligence (AI), cloud computing, among others (Frank et al. 2019).

The technologies inherent in I4.0 go beyond economic gains as they allow the moderate use of resources, which reduces waste and environmental impacts in the production processes of goods and services, resulting in environmentally sustainable chains (Sharma et al., 2021; Bag et al., 2021).

Sustainability is based on the Triple Bottom Line (TBL), which encompasses the economic, environmental, and social spheres, generating the expansion and encouraging the growth of more environmentally friendly production technologies and friendly products (Pasquale et al., 2023; Fernández-Viñé, 2013). In this way, TBL is included in the sphere of I4.0, as it aims to increase productivity at lower costs and use fewer inputs (Gomes et al., 2022).

Given this scenario, and reflecting on the agile resolution of demands, the concept of Sustainability 4.0 is manifested, as an approach that has been driven by the incorporation of the advanced technology of Industry 4.0 and the balance of economic, social, and environmental dimensions of sustainability (Gomes et al., 2022; Silva, et al. 2022).

It is appropriate to point out that the implementation of the beginnings of Sustainability 4.0 will permeate the veracity of more sagacious and cooperative management compounds, increasing performance in debates, legislation, processes, and results. In this way, it is possible to highlight that I4.0 is committed to sustainable production in various branches of the economy, both in manufacturing and in services. Based on the above, this article aims to evaluate sustainability 4.0 practices in service companies in the state of Pernambuco. To this end, the questionnaire was adapted from Monteiro et al. (2022).

2. Literature review

2.1 Industry 4.0

In the 2011 edition of the Hannover Fair, the fourth industrial revolution was proposed as the crossing of borders between the digital, physical, and biological worlds. These concepts were formally expanded in 2013, in a document developed by the German National Academy of Science and Engineering (GOMES et al., 2023). The conviction of this revolution is based on the integration of innovative technologies and people (Gebhardt et al., 2015; Haddara, Elragal, 2015).

The First Industrial Revolution took place between the years 1760 to 1840 (Schwab, 2016). This revolution was marked by two solemn creations, which led to transformations in the production and transport sector at the time: the discovery of coal as a source of energy, and the development of steam engines, together with the railways. The use of machines in industries provided a dynamic income, as an effect, the industry became a way of working for the population, who started to leave the countryside towards the cities in search of jobs in factories (Vian, 2015).

The second industrial revolution took place at the end of the 19th century, pioneered by Henry Ford, who expanded a mass production line (Mata et al., 2018). This revolution brought as crucial inventions the manufacture of steel, petroleum-derived fuels, the assembly line, the explosion engine of the steam locomotive, the amplification of chemical artifacts, electricity, and incandescent light bulbs (Nóbrega, 2018).

The third industrial revolution originated in the 20th century, portraying the innovative linkage in the information technology sector and its functionalities, in this context of production and consumption. The fabulous actions of this period were: robotics, space climbing, and biotechnology, among others. During this revolution, the use of advanced technologies in the industrial production system became vital (Brito, 2017).

From this perspective, then, the Fourth Industrial Revolution emerges, which, according to Schwab (2018), is based on a set of enabling technologies called AI, robotics, additive manufacturing, neurotechnologies, biotechnologies, virtual and augmented reality, new materials, and energy technologies, these technologies are the basis for the well-known I4.0 that arrived at exponential speed over processes and no longer linear.

2.2 Sustainability 4.0

In I4.0, equipment efficiency plays a key role in reducing the number of rejects, scrap and achieving higher productivity. Behind many green products and processes, which are recognized in the market, sustainable manufacturing contributes to minimizing the risks inherent in any manufacturing operation, thus maximizing the new opportunities that arise, and improving its processes and products (Yazdi et al., 2018). The purpose of green processes underlies the development, and managing the product's life cycle, including environmental practices such as eco-design, clean production, recycling, and reuse, thus allowing the minimization of costs related to production, distribution, use, and disposal of products (Vrcota et al., 2020).

Mendes et al. (2017) used I4.0 in their research on the factory floor of a company in the Brazilian automotive sector, resulting in reduced costs and, consequently, increased competitiveness. The technologies adopted were smart measurement: the vehicles have their measurements provided using laser technology; Intelligent logistics, using the Automatic Guide Vehicle where the car advances through a material conveyor controlled by a programmed computer and the Digital Factory, interconnected institutional programs that virtually simulate the production processes before their implementation (MENDES et al., 2017). Sustainable manufacturing involves three integral constituents, in terms of products/services, processes, and systems, in this regard, such resources demonstrate to improve the specific favoring of environmental, economic, and social competence (JAWAHIR; BRADLEY, 2016).

Jawahir and Bradley (2016) introduced the concept of the 6Rs, (Reduce, Reuse, Recycle, Redesign, Recover, and Remanufacture), going beyond the 3Rs involved in green manufacturing. The 6R perspective extends to what concerns the restricted use of materials, and energy, among other resources, as well as emissions and waste generation. This action concerns the reuse of products until the end of their life cycle, the restoration consists of collecting products at the end of the year stage of their use, being reused in their future life cycles. In summary, redesign strives to allocate materials, components, and resources recovered in the redesign of next-generation products. Remanufacturing is dedicated to restoring products that have been used, then recycling them and making them new again (JAWAHIR; BRADLEY, 2016).

The I4.0 grants that the work is in such a way that it considers the demographic changes and social aspects. I.4.0's intelligent assistance systems freed workers from routine tasks, allowing them to pursue creative and value-added activities (Kagermann et al., 2013). In addition, the author (Gerlitz, 2015) states that design as a tool and process reduces logistical interactions, thus making additional activities surplus, thus becoming a positive focus for the environment, as well as employment, such as the social and environmental positioning of the organization.

Schneider, a company in the electrical industry, enhances digital solutions with an emphasis on sustainability for the energy sector. It has cataloged patents in India, in the areas of Informatics, Processes, and Thermal Devices, both aimed at creating software and smart devices (SCHNEIDER ELECTRIC, 2020). In addition, Schneider also prospered with the EcoStruxure platform that makes up the electrical and cybernetic parts of buildings, homes, and industry data centers (SCHNEIDER ELETRIC, 2020). In this bias, the platform works through the IoT intermediate and the sensoriality of connected devices (electrical and electronic). It allows people included in an integrated environment to monitor and manage equipment efficiently and interactively, thus developing more energy efficiency, in addition to increasing security, and cutting energy costs (SCHNEIDER ELETRIC, 2020).

3. Methods

For Flick (2009) the research process requires the use of methods since scientific knowledge is characteristically rational and produced systematically. Thus, this research is characterized as applied, and descriptive, with a quantitative approach, using the Survey type technique.

The research was conducted in 6 companies providing different services located in the State of Pernambuco, Brazil. For data collection, a questionnaire adapted from Monteiro et al. (2022), Table 1, is structured in four parts. The first part identifies the profile of the respondent, the second part verifies the level of use of technologies that enable I4.0. The third part assesses sustainability 4.0 practices based on six dimensions: administrative practices, natural resources, environment, waste/recycling/effluents and selective collection, suppliers, and social practices, and 29 attributes. The questions were answered according to a 5-point scale, where 1= 0% (There are no applied actions); 2= 20% (The board has action projects); 3= 40% (The actions are at the beginning of the application); 4= 70% (Actions were partially applied) and 5= 100% (Actions were fully applied), for more, N/A= (Not Applicable). The fourth part evaluated the benefits of applying sustainability 4.0 practices in service companies based on a 5-point Likert scale (1= Totally Disagree, 2 = Partially Disagree, 3 = Neither Disagree nor Agree, 4 = Partially Agree, 5 = Strongly Agree).

Table 1: Dimensions and attributes evaluated.

Dimension	Code	Attributes
ADMINISTRATIVE PRACTICES	PA1	Using Scanning
	PA2	Use of cloud storage
	PA3	The equipment has sensors to turn off
	PA4	The internal environments have sensors to reduce energy
NATURAL RESOURCES	RN1	Practice that influences the reduction in energy consumption
	RN2	Use of LED lamps to reduce energy consumption
	RN3	Use of occupancy sensors to save energy
	RN4	Use of solar energy
	RN5	Practices that influence the reduction of water consumption
	RN6	Internal campaigns to raise employee awareness about the consumption of water, energy, and other inputs
	RN7	The standards used in the processes that result in the improvement of the quality of services offered
	RN8	Use of biofuels (biodiesel, biogas, ethanol)
ENVIRONMENT	MA1	Sector responsible exclusively for the environment
	MA2	Practical actions to reduce the impact on the environment
	MA3	Environmental preservation projects
	MA4	Reforestation or revegetation practices
	MA5	Environmental management system
WASTE / RECYCLING / EFFLUENTS AND SELECTIVE COLLECTION	RR1	Disposal of solid waste is conducted following the National Solid Waste Policy Law
	RR2	Waste treatment
	RR3	Practices that influence the reduction of waste emissions
	RR4	Recycling or reuse of waste generated
	RR5	5S program
	RR6	Selective collection points
SUPPLIERS	FO1	Suppliers use sustainable practices
	FO2	Training program to train your suppliers in sustainable practices
	FO3	Prioritization of acquisitions from closer suppliers to reduce organization costs
SOCIAL PRACTICES	PS1	Actions that are concerned with the well-being of employees, society, and the environment
	PS2	Internal reporting channel (harassment and/or embarrassment)
	PS3	Conducting social work with the surrounding community

Source: Adapted from Monteiro et al. (2022).

Data were collected at the companies for the convenience of the researcher. The companies answered the questionnaire via e-mail. The results of this research are characteristic of the studied sample.

4. Results

The first part of the questionnaire deals with the profile of the companies studied. Six service providers answered the questionnaire, the respondents' areas of activity were: Teaching/Education (2 companies), Civil Construction (1 company), Energy Production and Commercialization (1 company), Technology (1), and Legal Services (1 company). Regarding the size of the organization, the sample consisted of small (2), medium (1), and large (3) companies. As for the number of employees, one company had up to 19 employees, one company had between 100 and 499 employees and 4 companies had more than 500 employees.

The second part of the questionnaire diagnosed the use of I4.0 enabling technologies, Figure 1.

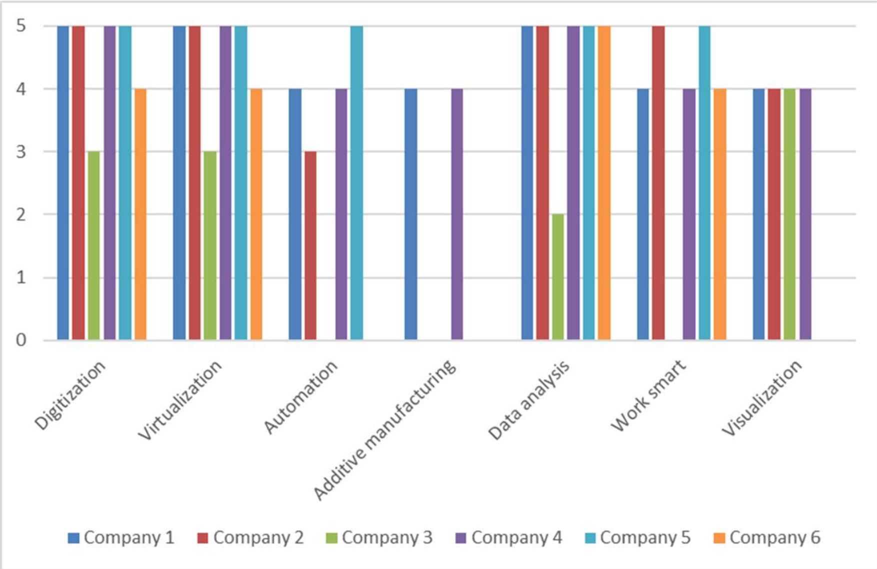

Fig. 1. Diagnosis of the I4.0 enabling technologies of the companies studied.

Based on the results shown in Figure 1, the maturity radar graph of the enabling technologies of I4.O, Figure 2, was developed. It is seen that the aspects that had the most evidence were digitization, virtualization, and data analysis.

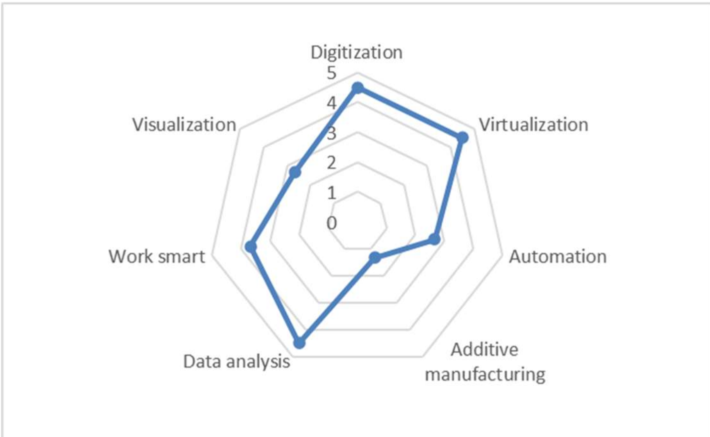

Fig. 2. Radar chart of I4.0 enabling technologies.

The third part of the questionnaire evaluated sustainability practices based on the six dimensions: administrative practices, natural resources, environment, waste/recycling/effluents and selective collection, suppliers, and social practices, which were divided into 29 attributes. Figure 3 proves that social and administrative practices are the ones with the most evidence, while the other practices have low evidence.

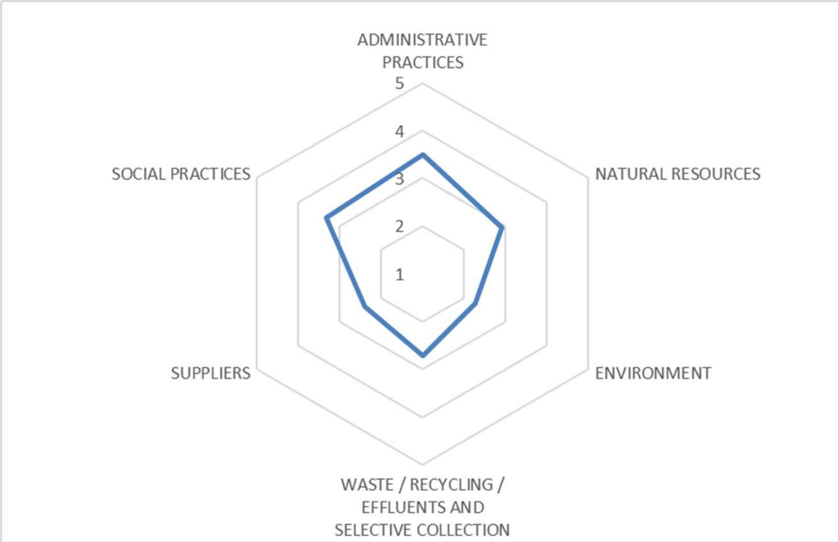

Fig. 3. Radar chart of the dimensions of sustainable practices.

The fourth part evaluated the benefits of applying sustainability 4.0 practices in service companies based on a 5-point Likert scale (1= Totally Disagree - TD, 2 = Partially Disagree - PD, 3 = Indifferent - I, 4 = Partially Agree - PA, 5 = Strongly Agree - SA). The perspectives addressed in the fourth part and their results are shown in Table 2.

Table 2: Benefits of applying sustainability 4.0 practices in service companies.

	TD	PD	I	PA	SA
Application of sustainable practices increase competitiveness				1	5
Customer satisfaction survey				4	2
Consider customer requirements to offer more sustainable processes		3			3
Sustainable practices used to reduce process costs			3		3
Increase in service delivery capacity			3		3
Customer loyalty			4		2
Increase in the number of customers	4				2

As for the application of sustainable practices to become more competitive, it is observed that 5 companies totally or partially agreed. When asked if they conduct satisfaction surveys with their customers, 4 claim that they do them partially or completely. About the company considering customer requirements in its processes sustainably, 3 companies totally or partially agreed. Related to the use of sustainable practices used to reduce process costs, it was verified that 3 companies agreed. According to the criterion, of increasing the capacity to supply services, 3 companies said that they totally agree, and another 3 companies said that they partially disagree or that they do not agree/disagree. Related to customer loyalty, it was found that 2 companies totally agree, and another 4 companies totally disagree or do not agree/disagree. Regarding the increase in the number of customers, it was verified that 2 companies said that they totally agree, and another 4 companies said that they totally disagree or that they neither agree/disagree.

A study of maturity models (MMS) developed by Hizom-Hanafiah, Soomro, and Abdullah (2020) analyzed the proportions of Industry 4.0 and identified that 6 groups were relevant for the evaluation of the MMS, thus, the respective results were obtained: innovation and processes, technology, people, leadership, and strategy. In this research, only innovation and processes were adopted in the studied companies.

Dikhanbayevaet et al. (2020) identified that the design principles of I4.0 are, respectively: virtualization, real-time information processing, and decentralization, these services demonstrated the orientation towards MMS as evaluation parameters. Given this, in this article, all companies used only virtualization for their diagnosis.

According to Vrcota et al. (2020), environmental practices are fundamental for the development of organizations and eco-designer practices, clean production, recycling, and reuse reduce the costs of production processes. This research found that 3 companies partially implemented the practice of recycling and reuse in their services.

In this study, the respondents' lack of knowledge regarding the sustainable practices of I4.0 was observed. and Sustainability 4.0. For Kane et al. (2015), the ability to rethink the business is determined by an objective digital strategy, supported by leaders who promote a culture that allows for change and innovation. Furthermore, digital transformation promotes the effective management of the entire supply chain, increasing the productivity and quality of its services and products delivered (GOMES et al., 2023). Therefore, it is emphasized that, in summary, it is relevant to expand the corporate mentality, as well as its vision.

5. Conclusion

This article aimed to present the relationship between Sustainability 4.0 and service companies, given the importance of this field of activity. Based on the results obtained, it was possible to identify the profiles of the companies, list the most used I4.0 enabling technologies, and identify sustainable practices for the different dimensions, in addition to the benefits arising from the application of Sustainability 4.0 practices.

According to respondents, some sustainability 4.0 applications have not yet become practical for companies. The answers pointed out that there is a science of what these practices are, and that their adoption makes companies more competitive and generates improvements in processes.

Although companies do not use all Sustainability 4.0 practices, they are interested and the initial results are positive, demonstrating the respondents' interest in investing in stocks in the long term.

It is important to emphasize the importance of the respondents' perceptions, given that the service sector is responsible for around 70% of the Gross Domestic Product (GDP) of most countries, whether developed or not. That is, it is the sector responsible for most of the jobs and income of the world's population, and it is necessary to frequently improve the mechanisms of these undertakings.

In addition to the listed factors, this research is aligned with the sustainable development objectives (SDGs) proposed by the United Nations Organizations (UNO), linked to Objective 12 – Responsible Consumption and Production, contributing to actions to reduce environmental impacts and improve the quality of life in communities.

The number of respondents was restricted due to the lack of feedback from companies. It is noteworthy that the data reflect the characteristics of this sample, as well as the difficulty in obtaining more responding companies. For future work, we suggest applying this study to a larger number of companies and diverse types of services.

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Analysis of sustainability reports based on the Sustainable Development Goals (SDGs): study in the industrial center of Manaus

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Abstract

The growing concern with social, environmental, and economic issues is a global trend. In this context, companies have the opportunity to publish sustainability reports as a way of demonstrating their actions in the socio-environmental sphere. These reports allow companies to communicate their initiatives, goals, and results related to sustainability, demonstrating transparency and responsibility towards society. In this way, this article aims to analyze the sustainability reports based on the Sustainable Development Goals of the United Nations, surveying companies from different segments of the Industrial Pole of Manaus. The sample used in this article consisted of 40 companies, with information collected through content analysis of sustainability reports. Regarding methodological procedures, the study is qualitative, descriptive, and documentary research. The Industrial Pole of Manaus is characterized by the large volume of industrial companies in activity, in this way, the results were obtained from the sustainability reports published by the companies in the years 2021 and 2022. The results demonstrate that the studied companies almost apply actions focused on the SDGs. It is also concluded that companies approach SDGs directed to the internal scope, intending to influence the external area, creating distance to the social environment and embezzlement with the environment. So that companies can effectively contribute to these goals, they must expand their initiatives and partnerships to face the socio-economic challenges present in the community and society in general.

Keywords: Sustainability, SDG, UN, Industrial Pole of Manaus.

1. Introduction

Faced with the changes that have occurred in the world, characterized by tensions in society, disruptive policies, and the depletion of natural resources, the need to create a new development model becomes evident - a viable combination of economic growth, environmental preservation, and social inclusion. According to Molina (2019), this urgency reflects the importance of seeking alternatives that promote sustainable balance, along with economic, social, and environmental aspects contributing in an integrated and harmonious way.

In this way, the challenge of the 21st century arises: to enable sustainable development in society. The definition of sustainable development presented by the World Commission on Environment and Development - WCED, in 1987, in the Brundtland Report, highlights the importance of adopting approaches that consider longevity, the preservation of natural resources, and the balance between social, economic, and environmental dimensions, aiming to guarantee a viable and prosperous future for all.

In 2015, when exploring the topic in question, the United Nations (UN) defined a set of 17 Sustainable Development Goals (SDGs), subdivided into 169 goals, aimed to be achieved by 2030. These goals represent a comprehensive global agenda that addresses urgent challenges and promote a sustainable future for the planet, covering social, economic, and environmental aspects (ONUBR, 2015). This set of objectives aims to integrate society, government, and companies seeking preservation.

In this context, corporate or corporate sustainability reports are developed and published by companies for stakeholder consultation, the reports present results and plans of the company concerning sustainability standards. These reports intend to publicly disclose the company's responsibility and concern for people and the environment, establishing links with society. In this way, sustainability reports are the principal communication tool used by corporate organizations to present their social, economic, and environmental performance (Feil et al., 2013).

According to the study carried out by Campos et al. (2011), participation in these publications is optional and seeks to achieve the following purposes: to support and simplify the management of issues related to the sustainability of organizations in a methodical manner; disclose potential risks and opportunities; and establish a clear and more reliable corporate image.

Based on the above, this article aims to analyze the sustainability reports of the actions adopted to contribute to the 17 Sustainable Development Goals (SDGs) of the United Nations (UN), statements published voluntarily by 40 companies from different segments of the Manaus Industrial Pole (PIM), during the period 2021 and 2022.

The research justifies the relevant role of companies in the city of Manaus, Brazil, where the preponderance of the economy comes from the Industrial Pole. Sustainability reports emerge as a way of highlighting the contributions and actions of companies aimed at society. The analysis of these reports allows for assessing whether they align with the SDGs, in addition to understanding the main measures adopted by the companies studied.

2. Theoretical foundation

2.1 Corporate Social Responsibility

The UN actively defends that the participation of Corporate Social Responsibility - CSR collaborates and encourages sustainable development. The improvement of corporate responsibility in society is of paramount importance to all structural layers of economic, social, and environmental development (Ranangen and Lindman, 2017). For a company to be socially responsible, it must act responsibly and ethically in all areas, going beyond the objective of taking action toward society and the environment solely to obtain recognition and profit. On the opposite, it seeks to achieve a balance between the development of society and the environment through actions of a social and environmental nature (Júnior and Galvão, 2020)

The theme of Corporate and Business Social Responsibility has gained prominence in debates, especially concerning the environment. Companies are increasingly aware of the risks associated with activities. Many of these companies seek to reach a stage where they can be recognized as "socially responsible companies"; contributing to the construction of a sustainable society (Freire et al., 2008). For Kreitlon (2004), the debate and dissemination on corporate social responsibility, which was rare in society as well as in other areas, has become omnipresent today, being discussed in corporate places as well as in international organizations. Furthermore, this theme is present not only in civil society movements but also in academic institutions.

A relevant contribution to the definition of CSR was made by the Committee for Economic Development in 1971 by recognizing that companies operate with society and have the purpose of meeting the needs of citizens. Therefore, the committee defined social responsibility based on three circles: internal, intermediate, and external (Videira, 2022). In Brazil, social responsibility has been the subject of discussions in the academy and businesses. According to some authors, it can be considered an instrument that not only provides the company with good operating results, financial solidity, quality products, and services, competitive prices, a high standard of service, advanced technology, and highly qualified teams but also contributes to improving the quality of life of the current and future generations in the country (Guita et al., 2022). When exploring the topic in question, Garcia et al. (2006) conceptualize that social responsibility in Brazilian organizations is an important issue that is being addressed in various ways and perspectives. It represents an emerging culture in companies and the most significant and relevant change recorded in the corporate environment in recent years.

2.2 Sustainability Reports

Throughout history, sustainability reports have been preceded by three distinct types of statements: Social, Environmental, and Annual Reports. (Morais et al, 2020). According to Reis et al. (2020), organizations aim to disclose accounting and financial information to those interested in the assets and activities of the company. This information is intended for shareholders, investors, market analysts, administrators, and anyone interested in examining this data (Reis et al., 2020).

The production of sustainability reports is an increasingly common practice in large organizations worldwide, gaining prominence from the end of the 1990s. These reports are prepared voluntarily and have evolved according to market trends (Fields, 2013). Organizational sustainability values fair operating practices and proper conduct in relationships with other organizations. Companies must base themselves on ethical principles, promote anti-corruption initiatives, encourage positive environmental practices, foster leadership, manage risks and opportunities, ensure employee satisfaction, implement occupational health and safety measures, establish an efficient system of self-regulation, prioritize customer satisfaction, and assume social responsibility (GRI, 2019, Bellatuono, 2016, Renangen and Lindman, 2017, Batista and Francis, 2018).

Sustainability reports play a fundamental role in helping and simplifying the management of companies' sustainability-related companies systematically, enabling the disclosure of risks and opportunities and contributing to the construction of a transparent corporate reputation (Morais et al., 2020). Organizations have the option of developing their sustainability reporting template or adopting an existing template, such as those offered by specialist companies such as Global Reporting Initiative (GRI), Ethos, Ibase, and Akatu. These institutions provide guidelines and structures for preparing reports that comprehensively address sustainability issues, helping companies to communicate transparently and consistently on their social, environmental, and economic performance (Santos, 2020, Campos, 2013).

Currently, the most widely used model worldwide for sustainability reporting is GRI. The GRI standards are recognized as the first global standards for sustainability reporting. These standards have a modular and interrelated structure, encompassing best practices for reporting a wide range of economic, environmental, and social impacts. The GRI standards are aligned with the 17 SDGs established by the United Nations General Assembly in 2015, as part of the so-called 2030 Agenda. These goals cover several relevant areas, such as poverty eradication, gender equality, climate action, health, and well-being, among others (GRI, 2019).

3. Methods

The research developed in this article comprises the study and survey of sustainability reports, analyzing information that points to similarities between the data presented by PIM companies and the SDGs published by and managed by the UN, a qualitative, descriptive, and documentary (data collection).

Documental research and bibliographical research have similarities in their data collection procedure. Both are based on the search and analysis of information sources. The main difference between them lies in the type of source used. While documentary research is based on primary sources, how original documents are explored, such as reports, letters, diaries, and historical records. Bibliographical research relies on secondary sources, where works already published are used, such as books, scientific articles, theses, and dissertations (Voss et al, 2002, Leonel, 2007).

The present study focuses on the analysis of compliance with the SDGs, a global agenda established by the United Nations in September 2015 to promote Sustainable Development. This agenda comprises 17 objectives and 169 goals to be achieved by 2030. To verify adherence to UN sustainability goals, the reports published by companies located in the PIM for 2021 and 2022 will be analyzed. Data were collected through content analysis of sustainability reports, published by companies on their websites. The 17 verification items and their descriptions are presented in Table 1.

4. Results

The sample examined includes entities established in the PIM, which are awarded tax privileges granted by the Superintendence of the Manaus Free Zone - SUFRAMA upon approval of an economic-financial technical project (SUFRAMA, 2017). According to SUFRAMA (2017), the indexes corresponding to established companies are as follows: Electronics (18%), Two wheels (13%), Services (13%), Plastics and Adhesive Tapes (10%), Mechanics (10 %), Components (8%), Metallurgy (7%), Chemical and Pharmaceutical (6%), Beverages/Food (3%), Watchmaking (3%), Editorial and Graphics (2%), Lighters and Shaver's (2 %), Photographic (1%), Marine (1%), Optical (1%), Textiles and Apparel (1%), and Other (1%).

Table 1: Sustainable Development Goals (SDGs)

ODS	Description
1. Poverty Eradication	End poverty in all its forms, everywhere
2. Zero hunger and sustainable agriculture	End hunger, achieve food security and improved nutrition, and promote sustainable agriculture.
3. Health and well-being	Ensuring healthy lives and promoting well-being for everyone at all ages
4. Quality Education	Ensure inclusive, equitable, and quality education and promote lifelong learning opportunities for all.
5. Gender equality	Achieve gender equality and empower all women and girls.
6. Clean water and sanitation	Ensure availability and sustainable management of water and sanitation for all.
7. Clean and affordable energy	Ensure access to cheap, reliable, sustainable, and renewable energy for all.
8. Decent work and economic growth	Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all.
9. Infrastructure innovation	Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.
10. Reduction of inequalities	Reduce inequalities within and between countries.
11. Cities and communities sustainable	Make cities and human settlements inclusive, safe, resilient, and sustainable.
12. Consumption and production responsible	Ensure sustainable production and consumption patterns.
13. Action against global change of the climate	Take urgent action to combat climate change and its impacts.
14. Life in the water	Conservation and sustainable use of oceans, seas, and marine resources for sustainable development.
15. Earth life	Protect, restore, and promote the sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation, and halt biodiversity loss.
16. Peace, justice, and effective institutions	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all, and build effective, accountable, and inclusive institutions at all levels.
17. Partnerships and means of implementation	Strengthen the means of implementation and revitalize the global partnership for sustainable development.

In this way, the sample used corresponds to the percentage of relevance and number of companies installed in the same segment in the PIM, where, in short, the majority are companies considered medium and large. Data collection was carried out at the electronic address of each company. The companies studied were mostly multinationals, in this way, a large part of the reports were published in English or the native language of each company.

Considering a total of 40 companies from 7 segments and different nationalities, the analysis was conducted using different amounts of reports per segment, since these are composed of variable numbers of companies. Thus, the collected sample was composed of the segments that have the greatest percentage impact of companies installed in the PIM. In addition, it was considered relevant to collect data from companies that have significant production, regardless of having a smaller amount in percentage, since they are yet considered large corporations. In this article, the results obtained from three of the main sectors of the Industrial Pole of Manaus (PIM) will be presented: Two wheels, Electronics and Plastics, and Adhesive tapes.

4.1 Two Wheels

According to Abraciclo (2018), the production of motorcycles in Brazil is predominantly centralized in the PIM and is among the eight main industrial centers of the sector globally, being in a lower position only concerning Asian countries, such as India, China, Indonesia, Vietnam, Thailand, Taiwan, and the Philippines. From the statement of the SDGs mentioned in the sustainability reports of 6 companies in the Duas Rodas segment, it is observed that, out of the 6 companies under analysis, 4 of them are of Japanese origin, 3 of which are large and 1 medium-sized. Among the four companies, 3 chose to publish their sustainability reports in Portuguese, which facilitates the understanding of the data and information presented. Furthermore, all 4 Japanese companies analyzed highlighted the goals of the SDGs that are met at their PIM headquarters, evidencing the commitment towards the Amazon region. The two remaining companies have different origins. Company 1 is of German origin, while Company 2 is of American origin, both large. Company 1 opted to publish its report in English and presented the SDG targets achieved at its headquarters in the PIM. In turn, Company 2 published the statement in Portuguese and evidenced the fulfillment of the SDG targets at its headquarters in the PIM.

Regarding the addressed SDGs, it is possible to observe significant disparities in the Two Wheels segment when comparing Company 1 with Company 6. Company 1 mentioned only 3 SDGs in its sustainability report, while Company 6 addressed 14 of the 17 SDGs. On the other hand, companies 2 (9 SDGs), 3 (7 SDGs), 4 (8 SDGs), and 5 (6 SDGs) fell short of expectations, failing to address a minimum of 10 SDGs in their respective reports. When carrying out a comprehensive overview of the SDGs mentioned by the 6 companies, it is evident that SDG "1 - Eradication of Poverty" was not mentioned by any of them. SDGs 2, 6, and 16 were mentioned once each. In turn, SDGs 4, 14, 15, and 17 were mentioned twice each. Objectives 3, 7, 8, 9, and 10 were mentioned three times each. However, SDG "13 - Actions against global climate change", was mentioned by 5 of the 6 companies, thus becoming the objective most addressed by the Two Wheels sector. Meanwhile, SDG 1 has not been approached by any company within that specific branch.

4.2 Electronics

The Electronics sector is recognized as the leading producer within the PIM today. According to Olave et al. (2010), the contribution of this sector to industrial revenue is significant, representing approximately 34.58% of the total. In the data collection carried out for the sample of the electronics sector, information was collected from 10 companies in this field, which resulted in a diversity of countries of origin for analysis. Japan was the country with the highest number of representatives, 3 large and 1 medium. Of the four Japanese companies, two chose to publish their sustainability reports in Brazilian Portuguese, while the remaining used the English language. Of the 4 Japanese companies analyzed, companies 6, 7, and 10 presented the SDG targets met at their headquarters in the PIM, focused on the Amazon region. On the other hand, Company 1 addressed the SDGs related to Brazil as a whole, not just the PIM.

Therefore, the remaining 6 companies belong to 3 different countries: 2 from Taiwan, 2 from Brazil, and 2 from South Korea. The Taiwanese companies (Company 2 and Company 3) are large and have published their sustainability reports in English, both highlighting the SDG targets addressed at their headquarters located in the PIM. Company 4, of Brazilian nationality and classified as medium-sized, published its sustainability report in Portuguese, highlighting the applications related to the PIM. On the other hand, Company 8, also of Brazilian nationality and large, published its report in Brazilian Portuguese, indicating the SDGs applied to the PIM headquarters. Companies 5 and 9, both large and South Korean, published their reports in Portuguese, addressing the SDGs related to their headquarters in the PIM.

When analyzing the ODS mentioned and discussed in the Electronics segment, it is evident that the companies present significant differences, with an unequal average between them. It is possible to make a comparison between companies of the same nationality, starting with the Japanese ones: Company 1, Company 6, Company 7, and Company 10. Only Company 7 mentioned 10 SDGs in its report, while Company 1 addressed 7 SDGs, and Company 6 mentioned only 4 SDGs. It is noted that, even though it is from the same pole and the same nationality, Company 10 addressed only 1 SDG in its report, falling far short of the expected average for large companies installed in the PIM.

In the case of Taiwanese companies, Company 2 and Company 3, both remained below the 10 SDGs mentioned and addressed in their sustainability reports. Company 2 addressed 5 SDGs, while Company 3 addressed 9 SDGs. Concerning national companies, Company 4 and Company 8 also remained below 10 SDGs per report. Company 4 addressed only 4 SDGs, and Company 8 addressed 9 SDGs. Finally, in South Korean companies, Company 5 scored under 10 SDGs per report, while Company 9 addressed more than 10 SDGs. Company 5 mentioned only 3 SDGs in its report, showing a significant difference from Company 9, which addressed 12 SDGs in its sustainability report.

When making an overview of the SDGs mentioned by the 10 companies in the electronics sector, it is possible to observe that the SDGs "2 - Zero Hunger and Sustainable Agriculture" and "14 - Life in the Water" were not mentioned by any companies. On the other hand, SDG 1, 6, 7, 8, and 10 were mentioned 3 times each. In addition, objectives 3, 7, 8, 9, and 10 were also cited 3 times each. It is noteworthy that the objectives "12 - Responsible Consumption and Production" and "13 - Actions against global climate change" were mentioned by 8 of the 10 companies, thus becoming the Objectives most addressed by the Electronics sector. Then, SDG 17 received 5 mentions and SDG 4 was mentioned 6 times. SDGs 3 and 15 were cited 4 times each.

4.3 Plastics and Adhesive Tapes

The Plastics and Adhesive Tapes segment plays a significant role in the PIM, representing 10% of the companies established in this region. These industries are responsible for the production and supply of a wide variety of products, including plastic packaging, adhesive films, and tapes of different types. The sample collected in the Plastics and Adhesive Tapes segment comprised seven companies in the field, of which four are of Brazilian origin and two have different nationalities.

Company 1, of Swiss origin, stands out as a large company, whose sustainability report was published in English, which can make it difficult for the general public to understand. However, the report points out that the SDGs were applied to the PIM headquarters. Company 4, of French nationality, also classified as large, opted for the English language in its publication and indicated the SDGs applied at its headquarters in the PIM. As for companies 2, 3, 5, and 6, all of Brazilian origin, they published their reports in Portuguese. All companies except Company 2, which is medium-sized, are considered large. All of them signaled the application of the SDGs in the PIM. For the Plastics and Adhesive Tapes segment, it is evident that companies had an average of fewer than 10 SDGs mentioned in their sustainability reports.

Companies 1, 4, and 6 addressed 6 SDGs each. In turn, Company 2 was the one that mentioned the lowest number of SDGs, totaling 4 objectives. Company 5 stood out by mentioning 7 SDGs in its report. However, it was Company 3 that addressed the highest number of SDGs, totaling 8 objectives in its sustainability report. When analyzing the number of SDGs mentioned by companies in the Plastics and Adhesive Tapes segment, it can be seen that no SDG was mentioned by all of the companies. However, SDG "9 - Innovation in Infrastructure" obtained the highest number of mentions among the sample, demonstrating the importance given to this objective by the analyzed companies. On the other hand, SDGs "1 - Eradication of Poverty" and "17 - Partnerships and means of implementation" were not mentioned in any of the sustainability reports. Among the other SDGs, it is noteworthy that SDGs 2, 3, 4, 5, 7, 8, 12, and 13 were mentioned three times each. SDG 10 and 11 received two mentions each, while SDG 6, 14, 15, and 16 were cited only once each.

5. Conclusion

Disclosure of the SDGs varied between companies, as they are presented in different ways throughout the text, with some highlighting these goals throughout the text, others mentioning them in the Global Reporting Summary Initiative (GRI), and some only indicating that they considered these aspects. The companies present at the PIM are of different nationalities, as they seek to take advantage of tax incentives, such as the ICMS (Tax on Circulation of Goods and Services), offered by the state of Amazonas. These incentives reduce production costs, including taxes, boosting Manaus - Amazonas as an important industrial hub. As a result, most of the companies located in this region are giants of the industry, supplying goods to several countries.

In this context, it was investigated whether these companies disclose their sustainability reports in Portuguese, to facilitate public access and ensure understanding of the information provided. Most companies published their sustainability reports in Portuguese and English, making these the languages most used to transmit information transparently. In addition, during the analysis, an attempt was made to determine whether the companies present in their reports and whether the targets addressed are specifically applicable to the factory located in the PIM. This analysis is crucial because many of these companies have manufacturing units in different countries, which can result in the mention of the SDGs in the reports, but without an effective implementation at the PIM headquarters. It was identified that only one company did not explicitly mention whether the addressed objectives were directed to the PIM, indicating that the SDGs applied to Brazil as a whole, and not to a specific factory.

Given these considerations, the research concluded that companies effectively adopt sustainable practices in their internal activities to contribute to the community and the environment. However, it was observed that many of these measures are predominantly directed to the internal sphere, to influence the external environment as a consequence. Several initiatives, such as sustainable consumption and production, health and well-being, and proper waste management, are mainly focused on companies' internal actions. However, there was a limited number of measures specifically aimed at the external environment, which are related to environmental preservation, such as the protection of marine life (Life Below Water) or reforestation (Terrestrial Life).

The survey highlights the need to prioritize certain SDGs, such as Poverty Eradication, Gender Equality, and Zero Hunger. Specifically with Fome Zero, it was observed that few companies have programs that cover this social aspect, demonstrating a difficulty for corporations to get in touch with programs for the disadvantaged community. It is essential to add, in the dimensions discussed above, the need for effective participation by society, both in monitoring and demanding the progress of companies in socio-environmental aspects.

Limitations were observed during the study, such as the restriction on the number of companies considered in the survey. As this is a voluntary disclosure, it is common for companies to focus their annual reports on positive aspects, which makes it difficult to identify failures and areas that require greater attention about the achievement of the SDGs, which may have a direct impact on this study. As a suggestion for future research, it would be interesting to analyze the level of knowledge of the employees of the companies studied about the SDGs addressed by the companies where they work, since the study showed that most of the objectives placed in the reports are internal actions. In this way, an index could be created based on these results to understand whether companies are effectively putting the SDGs into practice or if they are only mentioned in formal documents. This provides a broader view of employee engagement and awareness of sustainable development goals.

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Bulk recycling of c-Si solar panels to aid in sustainable waste management strategies

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Abstract

South Africa has seen a tremendous increase in the installations of solar panels over recent years, mainly due to the pro-longed loadshedding practice. This rate will be further amplified with the transition to renewable energy generation while decarbonizing electricity power generation with energy storage. The volume of solar panel waste is expected to increase exponentially once solar panels, currently in service, become obsolete. Such trends are seen in many European countries with a push for waste treatment facilities for this electronic waste fraction. As of 2021, South African Legislature declared that decommissioned solar panels, and any electronic waste could no longer be disposed of in landfills. The overall aim of this study was to propose a sustainable recycling process for crystalline silicon photovoltaic (c-Si PV) panels that is suitable within a South African context. Experimental tests were conducted on the frame disassembly and delamination phases of the proposed recycling process to determine what percentage of the total initial silicon photovoltaic panel weight could be recovered as the aluminium frame, junction box, and glass. Furthermore, a life cycle analysis was conducted on the environmental impact of the proposed recycling process to that of the production process using the virgin raw materials of the recoverable materials. In the frame disassembly, the aluminium frame and junction box were manually recovered. The frameless panel was fed into a crusher and separated into three size fractions, i.e., fines, intermediate and coarse. A thermal delamination method was proposed with the coarse fraction undergoing further thermal treatment to disintegrate the ethylene vinyl acetate resin. Thermogravimetric analysis showed that the resin was completely disintegrated during thermal treatment. The overall percentage of 85% of the total initial c-Si PV panel weight was recovered. The remaining 15% of the panel weight was lost due to handing during processing. X-Ray diffraction analyses showed that the intermediate fraction contained metallic impurities hence this fraction cannot be classified as directly recoverable clean glass. Furthermore, the analysis showed that the fines fraction contained a significant amount of metals which can be valorised through a metal recovery process. The results from the life cycle analysis, performed only over this proposed process, showed that the environmental footprint was predominately due to thermal treatment since it comprised 80.5% of the total environmental impact. While the proposed recycling process is sustainable a comprehensive environmental impact assessment is necessary.

Keywords: solar panel recycling, electronic waste

1. Introduction

Of the total primary energy supply in South African, 65% was dominated by coal and 11% by renewables with a total of 10 809 GWh renewable energy produced in 2018 (Department of Minerals Resources and Energy, 2022). From the renewable energy supply, 30% was photovoltaic power. Considering South Africa’s ongoing energy crisis, the country aims to rollout renewable energy technologies with utility-scale renewable energy and battery storage public procurement of 22.9 GW planned from 2022 to 2030 as per the 2019 Integrated Resource Plan. Private sector investment in large scale renewable energy projects is also set to boom with 8.3 GW of solar photovoltaic private sector-led projects in advanced development (Department of Minerals Resources and Energy, 2023). This shift is observed globally with the need to move to renewable energy supplies to achieve energy security and decarbonize electricity generation and supply. While solar power is certainly a cleaner energy source, the emerging concern is about the end-of-life of these electronic products. Therefore, with the transition to renewable sources (solar, wind, hydro) for power, there is an alarming increase in demand for solar panels and metals used in these electronic devices for the generation of clean energy.

Photovoltaic (PV) panels have a life span of 25-30 years (Weckend, et al. 2016), though this can be reduced with panels being disposed of earlier or decommissioned due to weather damage (hail, water, rust, and wind), technical failures (wiring, inverter and delamination), regulations (replacement of old parts) and preference for commodity items (cheaper, more efficient systems) (Mathur et al., 2020). South Africa's first solar plant, the Leeupan project, built in 2012, with a generation capacity of 200 kW from 860 PV panels also included an expansion plan to 600 kW. This is yet to reach its end of life (Green Cape, 2020). The International Renewable Energy Agency (IRENA) projects that South Africa will generate 750 000 tons of EOL panels by 2050 based on the PV lifespan of 30 years (Weckend et al. 2016).

Solar panels are classified as hazardous waste electrical and electronic equipment (WEEE). The devices are prohibited from being disposed of in landfills (Department of Environmental Affairs, 2013). The European Union guidelines (2012/19/EU) (Waste electrical and electronic equipment WEEE Directive, 2012) set recovery targets of 70-85%, and reuse and recycling targets of 50-80% differentiated for the respective categories of EEE. Therefore, a sustainable waste management plan, with policies and regulations on solar panel recycling, must be developed to ensure manufacturers are responsible for recycling and safe disposal of waste. This responsibility should also extend to producers throughout the energy industry for safe and sustainable practices to match the accelerated growth in the solar renewable energy sector (Heath et al. 2022; Xu et al.2018).

This investigation adopted a bulk recycling approach as opposed to a high-value recycling approach, to recycle crystalline silicon (c-Si) panels. The c-Si photovoltaic panel consists of an aluminum frame, glass, a silicon wafer, ethylene vinyl acetate (EVA) resin, a back sheet and junction box, with the glass and aluminum frame constituting approximately 85-90% of the panel weight (Sinha et al., 2018; Lewis, 2022). The recovered glass can be used in the float and glass industries depending on its grade (Bio Intelligence Service, 2011), or as a raw material in cement production. Aluminum is a formidable recycling material with high scrap value as its integrity is not compromised during the recycling process (Xu et al., 2018), enabling its use in cans and packaging.

The valuable metals such as copper, silver, and silicon make up the semiconducting wafer which can be recovered intact, or recovery of components individually. The preferred route is to recover this intact for reuse, since it constitutes 50—65% of the total production cost of the c-Si panel (Lee et al., 2017; Pagnanelli et al., 2019). Therefore, recycling the semiconducting wafer significantly lowers the cost of the panels compared to the use of virgin materials. The high-value recycling approach to recover these metals from the smaller proportions of the panels is also of significant benefit since silver, followed by aluminum, copper, glass and silicon are components with the highest virgin material cost and global warming potential per m^2 (Maani et al., 2020; Tokoro et al., 2020). Silicon is used in a wide range of applications from ceramic, brick, catalyst, electronic industries, and a growing demand in lithium-ion battery anode (Xu et al., 2018; Zhang et al 2021).

The recovery of the metals can be performed via chemical or electro-thermal techniques. SolarWorld and FirstWorld reports a recovery efficiency of 95% of the semiconducting materials (Tao & Yu, 2015). Chemical etching solutions comprising of water, hydrofluoric acid, nitric acid, acetic acid and sulphuric acid in which simultaneous oxidation and reduction of the metals occurs such that these dissolves into the etching solution in the form of ions (Kang et al., 2012; Klugmann-Radziemska & Ostrowski, 2010). Lead is a hazardous component existing in the panel, having adverse effects on humans and the environment depending on its extent of exposure. Mathur et al. (2020) reported that high levels of lead were detected in the leachates of c-Si panels that were manufactured before 1997, and these dropped in PV panel manufactured thereafter.

This study investigated a proposal for the c-Si panel recycling process best suited within a South Africa context, of frame disassembly and glass recovery only. After crushing of the frameless c-Si panels, and sieving of the particles, thermal delamination was applied to the coarser fraction. X-Ray diffraction analyses showed the recovery of materials as clean glass, and metals. A life cycle analyses (LCA) was also conducted to compare the environmental impacts of the proposed recycling process to the use of virgin materials for the recovered materials. Delamination refers to the disintegration of the resin layer residing between the silicon wafer and the glass/polymer backing. Thermal delamination was chosen over chemical delamination to avoid the drawbacks in the use of substantial quantities of toxic and expensive chemicals for the separation of the EVA from the panel. Pagnanelli et al. (2019) reports that high grade glass can be recovered via chemical treatment, to be reused in the manufacturing of new panels as opposed to the lower grade glass recovered via thermal treatment. Though with the lack of information on the economic viability of chemical treatment, its waste handling and disposal of materials, as well as limited data on process kinetics, the thermal delamination was applied.

A LCA was performed to determine which steps in the recycling process contributed significantly to the environmental impact of the process. The process proposed in this study was compared to the use of extraction processes of virgin raw materials (EPVRM) of the recovered materials (aluminum and glass) with the primary aim being to improve the environmental sustainability of the c-Si PV panel life cycle.

2. Method

The project was performed in two parts, the first being experimental and the second an LCA study based on the experimental results and supporting information in literature. For the experiments the frame was disassembled manually, then the panels were crushed, followed by thermal treatment. Five c-Si PV panels which were donated were used for the experiments. The details, power ratings, masses of these frames were recorded. Two panels had a glass backing while the remaining three had polymer backings. The frame disassembly involved physical separation of the cables and aluminum frame, after which the panels were cut into strips to be fed into a knife mill. The crushed panels were sieved, and the particle sizes categorized into fine (d < 0.075 mm), intermediate (0.075 < d < 1.180 mm) and coarse (d>1.180 mm). The coarse fraction was heated in a furnace from room temperature to 600 °C and held at this temperature for 30 minutes. A heating rate of 12.8 °C/min was used corresponding to a heating duration of 45 minutes. The furnace door was then opened to allow for ventilation of the product gases through the vents. Once the samples were cooled, these were further sieved to separate the material into the three size fractions mentioned. The coarse material was sent for thermal gravimetric analyses (TGA) to determine whether the EVA had completely degraded.

Safety precautions were followed during each process, with a task risk assessment prepared and approved by the safety officers. Correct personal protection equipment (full-face shield, dust mark, ear plugs, laboratory coats, full protective wear, and leather gloves) were worn during the cutting of the panels, crushing steps and thermal treatment steps, respectively. A cover was constructed for the knife mill to prevent debris from being propelled outward and cutting and grinding were performed in fully ventilated areas with extraction fans to ensure there was no buildup of hazardous dust.

A LCA of the proposed bulk recycling process was conducted to determine which of the stages in the process contributed significantly to the environmental impact in relation to the EPVRM. The system boundaries included only the delivery of the waste PV panels up to the thermal treatment of the coarse particle fractions. The environmental impact associated with the transportation of the materials to and within the plant was not included. For the analysis, the process was categorized into the following steps: frame disassembly (with cable and frame recovery), crushing, sieving (recovery of intermediate and fine materials), thermal treatment (gas emissions) and lastly sieving (recovery of coarse and intermediate materials). Electricity use was accounted for in each of these steps. To compare the results of the LCA with the findings in literature, the functional unit of 1000 kg PV waste was applied, as used by Latunussa et al. (2016) and Pagnanelli et al. (2019). Based on the mass distribution of the entire panels, 14 kg was added to account for the junctional box. The process inputs and outputs were calculated to be applied in the LCA modeling. To compare this proposed recycling process to the use of virgin raw material, the production of aluminum frame and glass were determined relative to the basis specified since these were the only two materials recovered in this process. The furnace gas emissions were predominantly carbon dioxide, carbon monoxide, ethene, propene and other gases as reported by Pagnanelli et al (2019) and Fiandra et al. (2019) and were accepted for this work and further calculations, since it was not possible to analyze the exiting furnace gas in this study.

In the life cycle impact analysis, the Product Environmental Footprint (PEF) impact assessment methods were used for midpoint characterization. The PEF impact assessment methods were developed by the European Commission as part of the Single Market for Green Products Initiative. This impact assessment considers 19 impact categories which can be accessed in the method program. The life cycle inventory data were compiled using the openLCA (version 11.0.1) software (openLCA, 2022) and environmental footprint database (version 2.0) since these were compatible with the PEF impact assessment methods. Normalization was carried out according to the PEF method so that the results were comparable to the LCAs performed in the literature. The weightings were not modified; hence all impact categories were assumed to be of equal importance.

Since the study is based in South Africa, electricity from hard coal (a primary energy supply) was applied in the life cycle inventory dataset in the PEF database used to model the impacts of electricity usage. The waste production due to the recovery of the junction box was modeled as plastic waste. Since the proposed c-Si PV panel recycling process only recovers the aluminum frame and low-grade glass, only the virgin impacts of these components were modelled. The *CFF* aluminum alloy (AlMg3) life cycle inventory dataset in the *EF* database was used to model the impacts of the virgin frame production process. This contained the relevant life cycle inventory data for the production process of the aluminum frame used specifically in the c-Si PV panel. The glass cullet (*RER*) life cycle inventory dataset in the *EF* database was used to model the impacts of virgin low-grade glass production process. This was selected because it contained the relevant life cycle inventory for the low-grade glass production process. Further details of the LCA approach are reported in Lewis (2022).

3. Results and discussion

3.1 Bulk recycling experiments

The weight distribution of the recovered material from the frame disassembly and crushing is presented in Fig. 1. The aluminum frame and cables are easily recoverable though manually disassembly thereof is time consuming requiring at least two persons and an approximate one hour per frame. Economic studies show that the minimum feasible annual capacity for an industrial scale recycling plant is 20 000 kt (Mahmoudi et al. 2021), with an estimated 18000 panels per day. Hence, manual dismantling may not be feasible on a large scale. With the change in the design of the PV panel, the frame could be easily removed for reuse. Of the total initial c-Si PV panel weight, on average 13.1 + 1.7% was recovered as the frame, in agreement with literature findings in which the aluminum frame constitutes 13.7 + 3.61% of the total panel. As the weight of the panel increases, the percentage recovery decreases due to losses in the handling and crushing along the process.

For panels 1 and 2, the average particle size distribution (PSD) of the recovered crushed material was the intermediate fraction of (0.075 < d < 1.180 mm). For panels 3, 4 and 5 with polymer backings, most of the crushed material recovered was the coarse fraction. This difference in distribution occurs due to the difference in strength of the backing material. Glass is more brittle than polymers, hence it is crushed to a finer particle size.

The PSD of the crushed material was compared to literature studies as shown in Table 1, reproduced from Lewis (2022), in which for this study variability is observed mostly due to the different comminution equipment used. A knife mill was used in this work, while Pagnanelli et al. (2019) used a single shaft shredder and Granata et al. (2014) used a two-blade rotor crusher followed by a hammer crusher.

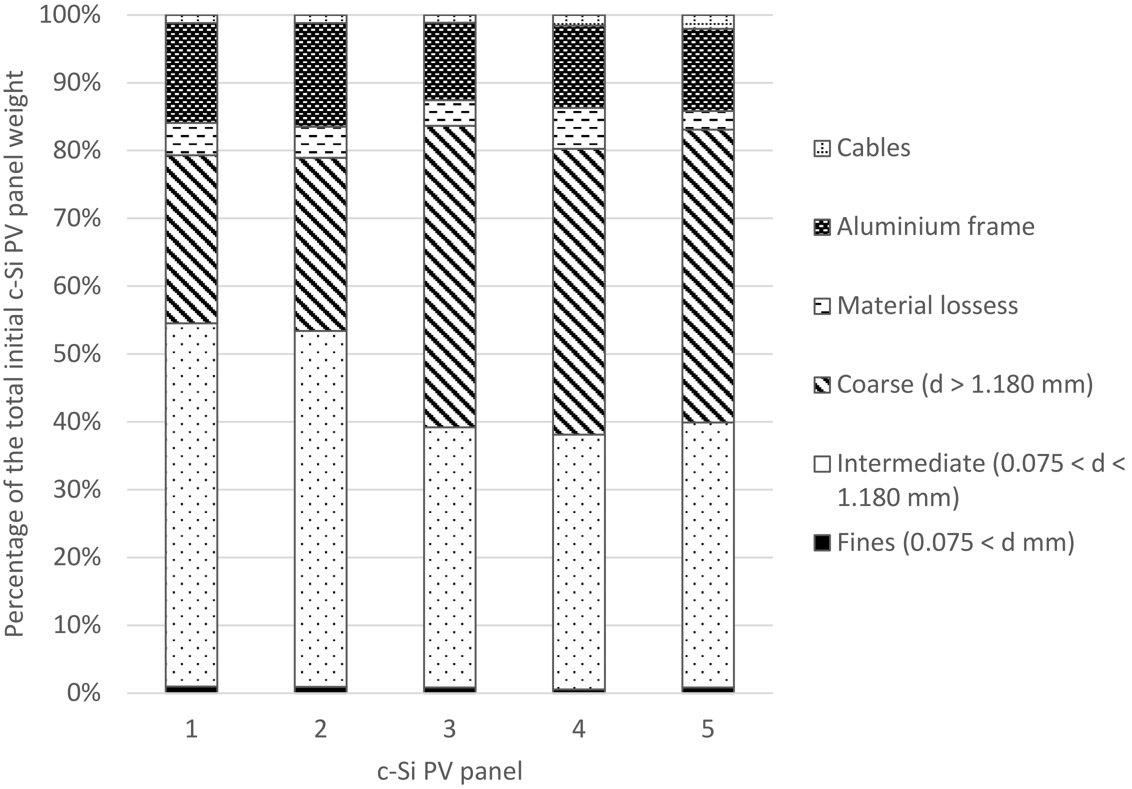

Fig. 1. Weight distribution of recovered materials from bulk recycling of five different solar panels. Panels 1, 2, 4 and 5 were of the same model from the same manufacturer (similar dimensions and power ratings), while panel 3 was approximately double the dimensions and power rating of the others. Furthermore, c-Si PV panels 1 and 2 had glass backings while c-Si PV panels 3, 4 and 5 had polymer backings. Extracted from Lewis (2022).

XRD analysis was conducted on two PSD fractions, the intermediate and fines. XRD analyses identifies compounds in a material based on the structures with amorphous (non-crystalline) structures producing scattering patterns with broad poorly defined peaks and crystalline compounds identified via sharp well-defined peaks. Glass is amorphous and metal oxides have crystalline structures. The XRD analyses for the intermediate PSD all contained sharp distinct peaks indicating the presence of metal oxides. Hence this fraction could not be recovered as clean glass. Granata et al. (2014) and Wahman & Surowiak (2022) performed similar experiments and reported that the intermediates also could not be directly recovered as clean glass. However, this fraction can be used as raw material for cement production. Letelier et al. (2019) and Shao et al. (2000) reported that for a 30 vol% addition of recycled glass to the cement aggregate, the maximum allowable particle size was 38 um. Larger particle sizes decreased the compression strength. Additional crushing stages are possible to ensure that the size fraction meets the <38 um. The presence of metal oxides in the fines particle size fraction was considerably higher, similar to findings in literature. The coarse fraction was not analyzed as this fraction underwent thermal treatment.

Table 1. Comparison of particle size distribution of crushed c-Si PV panel to literature.

Particle size fractions	**Average PSD (%)**	
	This work	
	***Glass backing**	****Polymer backing**
Fines (d < 0.075 mm)	1.2 ± 0.02	0.9 ± 0.19
Intermediate (0.075 < d < 1.180 mm)	65.4 ± 0.66	45.3 ± 1.1
Coarse (1.180 < d mm)	31.1 ± 0.81	51.1 ± 0.88
Material losses	2.3 ± 0.13	2.7 ± 1.83
	Pagnanelli, et al. (2019)	*****Granata, et al. (2014)**
	Polymer backing	**Polymer backing**
Fines (d < 0.08 mm)	2.1 ± 0.1	2
Intermediate (0.08 < d < 1.0 mm)	34 ± 2	12
Coarse (1.0 < d mm)	63 ± 3	86
Material losses	N/A	N/A

* c-Si PV panels 1 and 2 had glass backings.
** c-Si PV panels 3, 4, and 5 had polymer backings.
***Granata, et al. (2014) reported these results in a figure hence approximations of these values were obtained.

3.2 Thermal treatment

Samples from the coarse fraction obtained from panels 4 and 5 underwent thermal treatment for EVA degradation and removal. These samples were first analyzed using thermal gravimetric analysis (TGA) to determine the conditions for complete EVA removal. Then the samples were heated in the furnace, followed by further TGA analyses to confirm EVA degradation. It was difficult to obtain a representative sample for analyses before thermal delamination because the silicon wafer fragments could not be crushed into powder and smaller sample sizes for TGA analyses. Therefore, specific glass fragments were used for the TGA experiments.

After thermal treatment it was visually evident that all samples no longer contained silicon wafer fragments and that complete EVA degradation had occurred. There was a <2% decrease in the sample weight for all TGA analysis of the samples after thermal treatment indicating small weight losses probably attributed to metal and glass being lost. The thermal conditions applied were effective in removing the resin layer. Tammaro et al. (2015) reported similar findings of complete EVA degradation on tests using three c-Si panels at the same operating conditions.

3.3 Life cycle analysis

The normalized results for the LCA are presented in Fig. 2 where the environmental impacts (Eis) for each stage of the recycling process are shown per impact category. Overall, the EIs were predominantly due to the thermal treatment which constituted 80% of the overall environmental impact (climate change and photochemical ozone formation impact categories) due to the impact of volatile organic compounds in the gaseous products leaving the furnace. Fiandra et al. (2019) reports that this can be reduced significantly by the removal of the polymeric backing sheet prior to thermal treatment. For the current process, this is not possible as the material is crushed before thermal treatment is applied. The use of a glass backing sheet instead of a polymer backing is a possible solution to avoid the concerns in emissions.

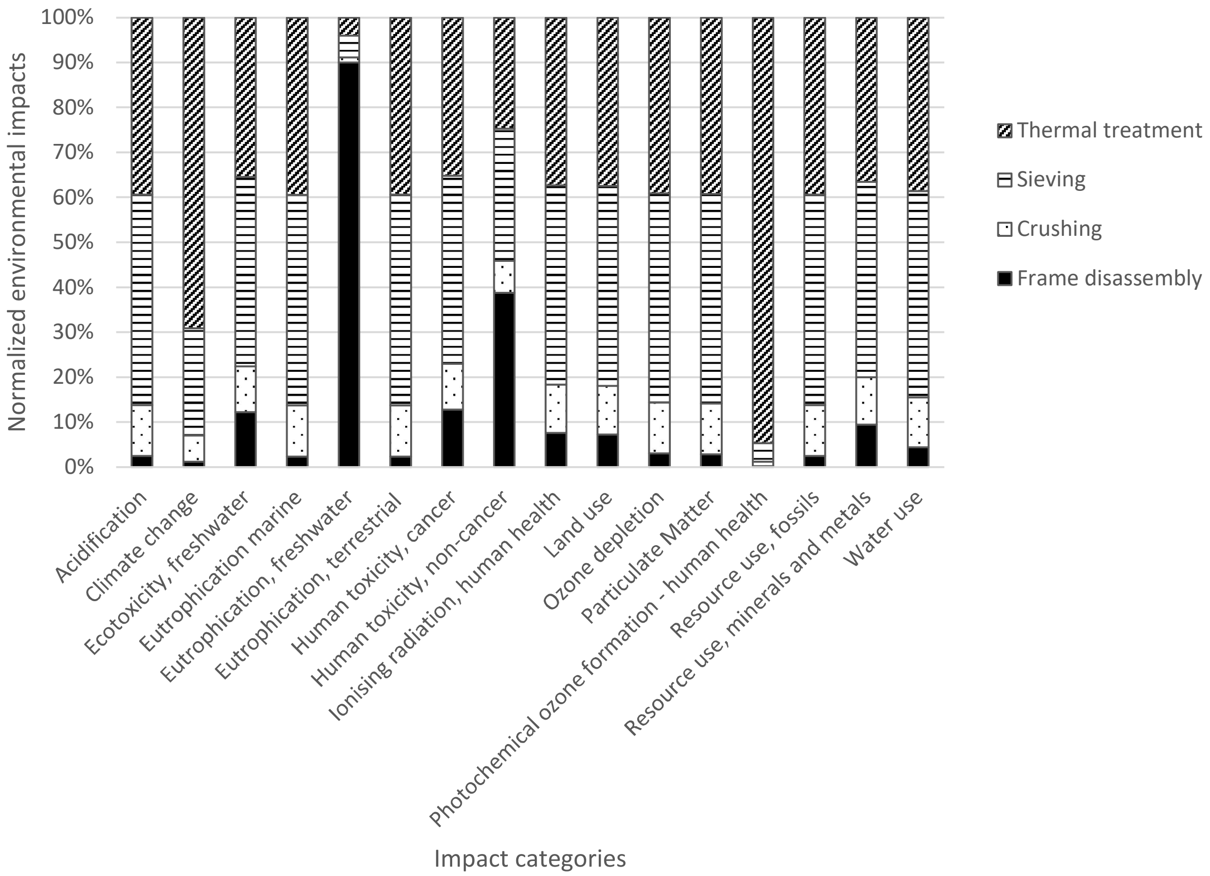

Fig. 2. Normalized and disaggregated environmental impacts of the proposed recycling process for a functional unit of 1014 kg of c-Si panel waste.

The impact of the frame disassembly, crushing and sieving steps constituted a relatively small proportion towards the total environmental impact analyses, which agrees well with the findings from Latunussa et al. (2016), Maani et al. (2020) and Pagnanelli et al. (2019). Although the frame disassembly does contribute to freshwater eutrophication and human toxicity (non-cancer) impact categories as shown in Fig. 2, since this is due to the impact of the plastic waste generated by the recovery of the junction box.

When comparing the normalized environmental impact results to that of EPVRM (aluminum and glass recover), the impact of the recycling process is significantly lower than the use of virgin raw materials in all categories indicating that this process is environmentally sustainable. However, the constraints applied in this work did not include transportation of the PV panels to and from the recycling plant which must be considered in a comprehensive study. Inclusion of transportation can contribute significantly to the environmental footprint as demonstrated by Latunussa et al. (2016). Furthermore, a direct comparison of the results from this study to other literature reports was not possible since aggregated data was presented, including different impact categories, and modifications to the recycling process.

3.4 Limitations and constraints in this study

With limited samples used in the experiments, the results obtained will change with increases in volumes of panels processed, and types or models of panels used in the recycling process. A larger sample set is needed to expand this experimental work, hence the findings. Furthermore, the weight of samples used in the thermal treatment experiments were considerably small relative to the weight of the coarse material obtained after crushing. A larger sample variance is needed, and future studies will incorporate a wider sample selection in the thermal treatment step. The metal recovery in the waste powders can be investigated further via chemical/hydrometallurgical recovery methods.

There were several constraints applied in the LCA study, one being the transportation which is necessary. Knowing possible location points for collections and recycling plants to be established will aid in improving the analysis. The results from the LCA can be modelled using alternate software and methods to allow for direct comparison among categories, improving certainty and robustness of the results.

5. Conclusions

A sustainable c-Si PV panel bulk recycling process is proposed which can be implemented on a large scale within the South African context. This targets the recovery of aluminum and glass, with these steps in the process allowing for job creating and enabling economic beneficiation in the waste recycling process.

For the delamination phase, i.e., removal of the resin, a thermal treatment method is proposed since this has a significantly lower processing time and environmental footprint compared to chemical treatment techniques.

Experiments were conducted on five photovoltaic panels, and 65.4 + 0.66% of the panel weight was recovered as intermediate particle sizes after crushing of panels with glass backings, and 51.1 + 0.88% as coarse particles for c-Si PV panels with polymer backings. X-Ray diffraction analyses showed that these particles contained metal impurities hence these could not be recovered as clean glass, rather used as additives in cement production. For the coarse articles complete degradation of the resin was successfully achieved via heating, and the recovered material was deemed suitable as clean glass.

The results from the LCA of the proposed process show an environmentally sustainable method for bulk waste handling, with thermal treatment constituting 80.5% of the overall environmental impact. Solutions must be sought for the product gas release from the heat treatment for thermal delamination and plastic reuse of the panel materials.

Limitations in this study identified that transportation of the waste panels to the facilities and within the process must be accounted for in the environmental impact assessment, hence a comprehensive analysis is necessary.

Overall, with the 85% panel weight recovered in the experimental work via bulk recycling, this is acceptable according to the EU guidelines for PV panel recycling processes. Therefore, opportunities exist for the uptake of this recycling process and integration into other waste processing facilities for further waste beneficiation.

Policies and regulations on solar panel recycling must be developed and a recycling industry standard established for safe and responsible management of this electronic waste.

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Can smaller be more sustainable? Comparative outcomes of Brazilian medicines reverse logistic systems based on a local benchmarking

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Abstract

In June 2020 the Federal government enacted Decree 10,388, creating the National Medicines Reverse Logistics (NMRL) program, with goals for the collection and final disposal of unused medicines from large municipalities (over 500,000 residents). The NMRL system collected a total of 52.7 tons, in 2021, in 20 state capitals, in the Federal District and in another 38 Sao Paulo state municipalities, comprising a total of 3,634 collection points. At the same time there are at least 46 medicines reverse logistic programs running in small municipalities of Brazil (defined as below 100,000 residents). However, only one - Farroupilha, in Rio Grande do Sul State, which is taken as the reference municipality (RM) - provided full access to data available from 2017 to 2022 regarding the quantities sent to landfill. This research examined the outcomes of this existing program compared with the respective results of the NMRL in 20 Brazilian state capitals and in the Federal District. It was found that the RM, with an average of 72,523 residents, correctly disposed 1.1 kg per capita/year of medicines wastes between 2017 and 2022. With respect to the state capitals, Sao Paulo presented the best performance with 21.36 kg per collection point. However, the per capita collected values are very low in all state capitals with Sao Paulo being the best performer with only 134.57 x 10^{-5} kg per capita collected. It is apparent that the number of collection points does not necessarily influence the results. For instance, Belem (Para State) ranks fifth of the state capitals in terms of the number of collection points, but ranks 18th in per capita collected quantity. An estimate was made of the extra amount per capita each state capital would need to collect to get the proportional performance of the RM. Following this reasoning, Sao Paulo would need to collect an extra 250 g per capita/year. It can be concluded that the NMRL needs more diffusion to better harness the already installed collection points, as it intends to reach municipalities as equal as 100,000 residents. The local systems suffer from lack of data, but the RM presents high intensity collection per capita.

Keywords: *Brazilian medicines reverse logistics. Local medicines reverse logistics. Medicines reverse flows.*

1. Introduction

After facing constraints during the Covid pandemic, the pharmaceutical supply chain in Brazil is expected to recover and reach USD $31.7 million in sales in 2026, surpassing the performance of USD $22.5 million in 2020 (Industry Report, 2022). The large amount of medicines circulating indicate the need for more care with respect to pharmaceutical goods wastes. According to Quadra et al. (2017), Brazilian surface wastewater presents significant concentrations of discharge products derived from medicines, such as, anti-inflammatories, lipid regulators, hormones and antiepileptics compared to other countries' wastewater. The concerns related to the destination of these products require attention because Brazilian regulations on water treatment do not include the removal of pharmaceutical substances, and 47% of the Brazilian population lack proper sewage treatment according to recent demographic research (Danelon et al., 2021). Furthermore, according to studies carried out in other countries, willingness to pay for medicines wastes avoidance lies more in the awareness than in the practices of the majority of the population (Kotchen et al., 2009; Kusturica et al., 2020).

Reverse logistics of medicines is significantly studied at local and national levels in Brazil (Viegas et al., 2022), in cities below 100, 000 residents, where the reuse of collected medicines from the population or other sources as physicians, laboratories, and industry, is enabled as long as they have the technical approval of pharmacists' inspection. A recent study highlighted that mediation, supervision, infrastructure, information technology, and policy orientation are critical factors to manage the returns of medicines (Campos et al., 2023). The National Medicines Reverse Logistics (NMRL) program in Brazil is a system in development since 2013. This is when the Health Ministry started to promote calls in order to arrange a commitment term and a sectorial agreement for the NMRL following the principles of the National Policy of Solid Wastes according to Law 12,305 (Brazil, 2010). At that time, medicines were not considered goods subject to RL. Nonetheless, new normatives (Brazilian legal instruments) were enacted at the end of 2010 that created the Guiding Committees of RL systems, with the perspective to amplify the number of sectors participating in RL. Between 2013 and 2014, the Environment Ministry published calls in the Official Diary of the Union trying to gather the stakeholders of the pharmaceutical industry so they could organize themselves (Aurelio, 2015). The inclusion of medicines as products subject to the NMRL in Brazil was facilitated by Decree 10,388 adopted in June 2020 (Brazil, 2020). This normative has established that unused medicines should be delivered back by consumers to retailers, and from these agents to distributors, and then to industry, for final ecologically correct disposal.

According to Decree 10,388 (Brazil, 2020), the first step to the NMRL should be the creation of a Performance and Follow-up Group with representatives of diverse sectors of the pharmaceutical supply chain to distribute the tasks and obligations of each part. This group was organized between December 2020 and July 2021, in the first phase of the NMRL. The retailers are expected to acquire their own collection boxes and make them available to the consumers in their pharmacies. The distributors should provide proper packages and collect the leftover medicines stored in the collection boxes, and transport these goods to industry (the producers), which should pay for adequate final disposal. Thus, each business part of the supply chain has its own economic burden to participate in the NMRL. In the second phase of the NMRL, between September 2021 and September 2023, the participants should choose the firms of the third party sector and give them specific training, elaborate the communication plan to get the participation of the consumers, and deliver fixed collection points in each state capital and in the Federal District, plus all municipalities with 500,000 or more residents. In the next phase, from September 2023 to September 2026, the system would be extended to municipalities of at least 100,000 residents, and by December 2025 a review of the system performance is scheduled (Sao Paulo Regional Council of Pharmacy, 2023).

Regional initiatives helped the national environmental authorities to organize the national system. In April 2018, the Environmental Authority of São Paulo State (CETESB) enacted the incorporation of the RL system to the environmental licensing procedures, including medicines in the RL targets through Decision Board 76 (CETESB, 2018). A target of 3,03 kg was set to be collected from each collection point between 2018 and 2021, including 80% of the São Paulo State municipalities above 100,000 residents. Furthermore, it was required that 100% of the municipalities with more than 200,000 residents should have at least one delivery point for every 10,000 residents from 2023 to 2025 (CETESB, 2021).

Regardless of the well stated goals of the NMRL, Decree 10,388 has omitted the concept of unused medicines, and this gap was filled by the Brazilian Technical Norm NBR 16,457 (ABNT, 2022). NBR 16,457 declares as unused the medicines discharged by the consumers - those from domestic human consumption, expired or unused, with respective packages; and those that did not expire, coming from the same source, but whose use was discontinued by the consumer, or that present quality failures that make them improper for consumption. From the point of view of the local medicines reverse logistic systems, such as those implemented in diverse Brazilian municipalities including Farroupilha, Rio Grande do Sul State (Municipal Laws, 2019), or in another 45 municipalities of the same State (Rio Grande do Sul Health State Secretary, 2022), some unused medicines can be considered viable for a new cycle of consumption as long as the responsible pharmacists approve them after a technical inspection. These local medicines RL systems, like the NMRL, divert expired and damaged medicines to the proper disposal. In both cases, the role

of the pharmacist is considered pivotal to the success of the leftover medicines, and it is necessary that consumers have easy access to disposal boxes and receive proper information to be incentivized to give back the medicines (Ehrhart et al., 2020).
Aurelio (2015) observed that the lack of knowledge of the consumers about the legal (and appropriate) procedures for discarding medicines, difficulties to coordinate the supply chain agents of the RL, and high costs involved in the returns systems still jeopardize the efficiency of the initiatives in this sector. With respect to consumers, as also highlighted by Kotchen et al. (2009), Ehrhart et al. (2020), and Kusturica et al. (2020), the awareness of the environmental implications of the damage caused by the incorrect disposal of medicines is not sufficient to determine the correct action.
This article has the purpose of showing the preliminary results of the first year of the NMRL with respect to the physical amounts collected in 20 Brazilian state capitals and in the Brazilian Federal District; the number of collection points installed; and of proportionally comparing these results with the outcomes of Farroupilha, taken as the RM. Independently of the NMRL, Farroupilha started its own program of returns in 2015. It has an average of 72,532 residents (2017-2022), collected and correctly disposed 1.1 kg per capita of unused medicines. Regardless of the lack of data availability of other small-scale municipalities that are running medicines RL programs, and based only on the reference municipality as a benchmark, the following research question will be addressed: can smaller municipalities be more sustainable in medicines RL than larger ones? To answer this question, secondary data for the NMRL system was collected and analyzed, aggregated for each state capital, and compared with the RM (obtained through direct contact with the pharmacists of this establishment). The results are presented in section 3 with some discussion, after the methodological section (2); section 4 presents the final conclusions and provides some suggestions for future related research.

2. Methods and procedures

This research employs mixed qualitative and quantitative methods (Onwuegbuzie and Johnson, 2006), and it is strongly based on secondary data (Martins et al., 2018). In order to obtain data from the small-scale municipalities that started their medicines RL programs, questionnaires were sent to 22 selected municipalities in Rio Grande do Sul State, Brazil, that started their programs between 2015 and 2020. These questionnaires were sent between July 2021 and December 2022, and eight responses were recorded, but only one municipality (Farroupilha) returned information about the quantities of medicines it collected and sent to the landfill. Meanwhile, another 24 municipalities started their own local programs, and were not included in the research, as they would not have time to generate data.

The data of the NMRL performance are available on the website of the National System on the Solid Wastes Management (SINIR, 2022), and shows the quantities of unused medicines collected (in kg) in each state capital and in the Brazilian Federal District, and the number of collection points installed in these cities, included among the most populous municipalities of the country. Having the demographic data of these state capitals as well, it was possible to calculate the amounts of medicines wastes collected per capita, and the number of collection points installed per capita. There the results of collection per capita were compared with the results of number of collection points per capita in order to get conclusions on whether the availability of collection points positively influences the amount of medicines wastes collected.

From the RM, two pharmacists provided data on the physical amounts of medicines collected and correctly disposed between 2017 and 2022. It was possible to calculate the average quantity per capita sent to landfill in this municipality in this period. This quantity was compared with the quantities for each state capital. To properly perform this comparison, the number of residents of each state capital was divided by the number of residents of the reference municipality. The result of each division was considered the "size effect", meaning the number of times each state capital surpasses the reference municipality in amount of residents. Each of these results ("size effect") was multiplied by the performance of the reference municipality to get the respective quantity per capita each state capital must deliver as a "plus per capita" to reach the proportional performance of the reference municipality. Figure 1 summarizes the procedures of the research.

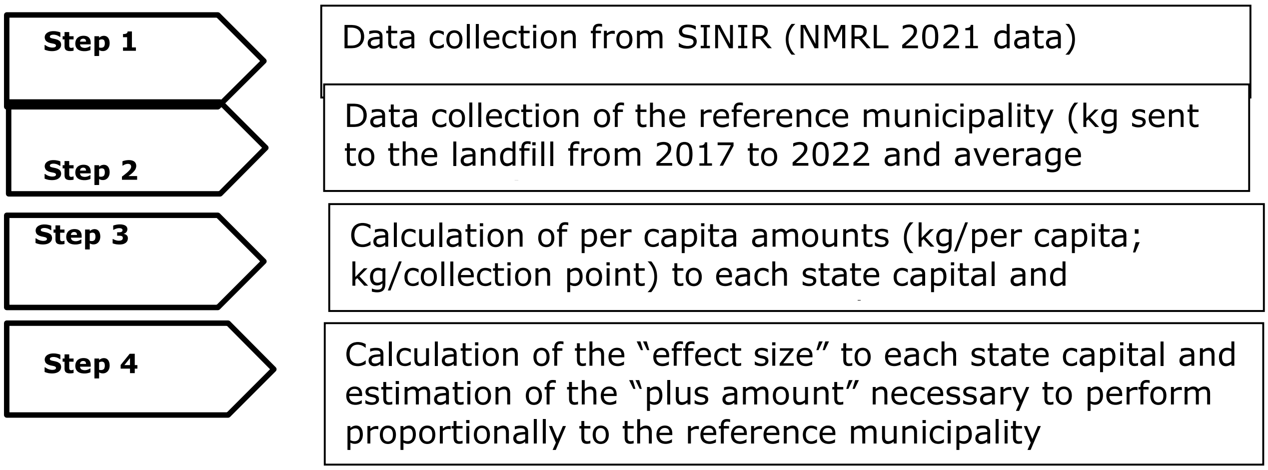

Fig. 1. Research procedures

3 Results and Brief Discussion

The results of the research are displayed in Tables 1 to 4. Table 1 presents the list of the state capitals (alongside the two-letter State code, see https://brazil-help.com/brazilian_states.htm) with the respective number of residents, physical amounts collected through the NMRL system, number of collection points in each state capital, and the respective per capita amounts. Table 2 displays the comparison among the state capitals with respect to the quantities collected per capita and number of available collection points per capita, displaying the list of the state capitals in descending order with respect to the collection point performance, in the left-hand column, and the list of state capitals in descending order of collection point numbers per capita, in the right-hand column. Table 3 shows the results of the RM – quantities of collected medicines from 2017 to 2022, population, and respective averages. Table 4 compares the collection performance of the RM and the performance of each state capital, and shows the results of the calculation of the "size effect" regarding the RM as well as the necessary extra amount per capita each state capital should collect to have a proportional performance with respect to the reference municipality.

Capital (State)	Number of residents in 2021	Medicines collected (kg)	Number of of collection points	Medicines collected (kg per capita) ($x10^{-5}$)	Number of collection points per capita ($x10^{-5}$)	Kg collected per collection point
São Paulo (SP)	12,396,372	16,681.52	781	134.57	6.3	21.36
Rio de Janeiro (RJ)	6,775,561	244.02	303	3.6	4.47	0.81
Brasília (DF)	3,094,325	327.73	116	10.59	3.75	2.82
Salvador (BA)	2,900,319	99.62	151	3.43	5.2	0.66
Fortaleza (CE)	2,703,391	66.79	67	2.58	2.48	0.99
Curitiba (PR)	1,963,726	302.1	105	15.38	5.35	2.88
Recife (PE)	1,661,017	83.31	65	5.01	3.91	1.28
Goiânia (GO)	1,555,626	141.94	72	9.12	4.63	1.97
Belém (PA)	1,506,420	38.17	114	2.53	7.56	0.33
Porto Alegre (RS)	1,492,530	75.05	81	5.03	5.4	0.93
São Luís (MA)	1,115,932	4.5	14	0.4	1.25	0.32
Maceió (AL)	1,031,597	29.57	55	2.87	5.33	0.54

Campo Grande (MS)	916,001	75.63	27	8.26	2.95	2.8
Natal (RN)	896,708	28.65	81	3.2	2.2	1.43
Teresina (PI)	871,126	3.46	20	0.4	2.29	0.17
João Pessoa (PB)	825,796	51.77	42	6.27	5.08	1.23
Aracaju (SE)	672,614	106.97	21	15.9	3.12	5.09
Cuiabá (MT)	623,614	4.25	22	0.68	3.53	0.19
Florianópolis (SC)	516,524	47.68	21	9.23	4.06	2.26
Vitória (ES)	369,534	42.74	34	11.56	9.2	1.26
Palmas (TO)	313,349	13.75	10	4.39	3.2	1.37

Table 1. Data collected from the NMRL system in 2021. Source: SINIR (2022)

It is clear that Aracaju performed well regarding the per capita collected amounts with only 21 collection points, followed by Curitiba, that had 105 collection points. The same observation can be applied to Vitória, with the fourth highest per capita collected amount. Aracaju also presents the second place in concentration of collected medicines wastes per collection point. São Luís and Teresina show the worst results per capita in collection.

State capitals in rank order with respect to the RL	
kg per capita collected ($x10^{-5}$)	Number of collection points per capita ($x10^{-5}$)
São Paulo (134.5)	Vitória (9.2)
Aracaju (15.9)	Belém (7.6)
Curitiba (15.4)	São Paulo (6.3)
Vitória (11.6)	Porto Alegre (5.4)
Brasília (10.6)	Curitiba (5.35)
Florianópolis (9.2)	Maceió (5.33)
Goiânia (9.1)	Salvador (5.2)
Campo Grande (8.3)	João Pessoa (5.1)
João Pessoa (6.3)	Goiânia (4.6)
Porto Alegre (5.03)	Rio de Janeiro (4.5)
Recife (5.01)	Florianópolis (4.1)
Palmas (4.4)	Recife (3.9)
Rio de Janeiro (3.6)	Brasília (3.7)
Salvador (3.4)	Cuiabá (3.5)
Natal (3.2)	Palmas (3.2)
Maceió (2.9)	Aracaju (3.1)
Fortaleza (2.6)	Campo Grande (2.9)
Belém (2.5)	Fortaleza (2.5)
Cuiabá (0.7)	Teresina (2.3)
São Luís (0.4)	Natal (2.2)
Teresina (0.4)	São Luís (1.2)

Table 2. List of state capitals in rank order from greatest to least in amounts collected per capita and in number of collection points per capita

From Table 2, it is possible to conclude that São Paulo state capital presented a good productivity with respect to both the per capita collected amounts and the number of per capita collection points available. This is also the case for Curitiba. However, there are several state capitals with low numbers of per capita collection points that otherwise presented a good productivity on amount collected per capita, such as, Aracaju, Brasília, and Florianópolis. It shows that the points were probably well placed – which is a facilitator of the collection (Aurélio, 2015), or shows that the population is more aware of the medicines RL problem, or that the pharmacists were more engaged in the return campaigns (Ehrhart et al., 2020). The opposite is observed as well. State capitals, such as, Belém, Maceió, Porto Alegre, and Salvador present low rates of amounts collected per capita although with high numbers of available points of collection per capita. Table 3 provides data on the RM.

Year	Collected amounts (kg)	N of residents	Collected amounts per capita (kg)
2017	121,909	69,542	1.75
2018	83,998	71,570	1.17
2019	43,099	72,331	0.59
2020	53,214	73,061	0.73
2021	39,557	73,758	0.54
2022	138,044	74,879	1.84
Average	79,970	72,523	1.10

Table 3. Data provided by the reference municipality (Farroupilha, RS State) in the columns 1 and 2; provided by the Brazilian Institute of Geography and Statistics in column 3; and calculations based on previous columns in column 4.

Having just one collection point – in the Basic Unity of Health of the municipality, Farroupilha gathered an average of almost 80 kg/year of medicines wastes. The average per capita amount during this period (2017-2022), 1.1 kg, was used as the benchmark for calculating the proportional performance of each state capital of Brazil and the Federal District. The results are shown in Table 4.

Capital (State)	Number of residents in 2021 (A)	Population of each state capital / average population of the reference municipality = 72,532 (=~size effect) (B)	Size effect of each state capital x Performance per capita of the reference municipality = 1.1 kg per capita (C)	Medicines collected (kg per capita) ($x10^{-5}$) in each state capital (D)	Expected proportional performance compared to the reference municipality (**plus g/per capita to be collected in each state capital**) (CxD)
São Paulo (SP)	12,396,372	171	188.0	134.57	252
Rio de Janeiro (RJ)	6,775,561	93	102.3	3.6	3.7
Brasília (DF)	3,094,325	43	47.3	10.59	5
Salvador (BA)	2,900,319	40	44	3.43	1.5
Fortaleza (CE)	2,703,391	37	40.7	2.58	1
Curitiba (PR)	1,963,726	27	29.7	15.38	4.6
Recife (PE)	1,661,017	23	25.3	5.01	1.3
Goiânia (GO)	1,555,626	21	23.1	9.12	2.1
Belém (PA)	1,506,420	21	23.1	2.53	0.6
Porto Alegre (RS)	1,492,530	20	22	5.03	1.1
São Luís (MA)	1,115,932	15	16.5	0.4	0.06
Maceió (AL)	1,031,597	14	15.4	2.87	0.4
Campo Grande (MS)	916,001	13	14.3	8.26	1.2
Natal (RN)	896,708	12	13.2	3.2	0.4

Teresina (PI)	871,126	12	13.2	0.4	0.05
João Pessoa (PB)	825,796	11	12.1	6.27	0.7
Aracaju (SE)	672,614	9	9.9	15.9	1.6
Cuiabá (MT)	623,614	8	8.8	0.68	0.06
Florianópolis (SC)	516,524	7	7.7	9.23	0.7
Vitória (ES)	369,534	5	5.5	11.56	0.8
Palmas (TO)	313,349	4	4.4	4.39	0.9

Table 4. Expected improved performance of collection per capita for each state capital based on the reference municipality

The estimation of the extra amount each state capital should collect to proportionally perform as well as the RM considers both, the population size of the state capital and the current performance. São Paulo, Brasília, Curitiba, Rio de Janeiro, Goiânia, Aracaju, Salvador, Recife, Campo Grande, Porto Alegre, and Fortaleza should receive special attention with respect to public awareness campaigns and orientation to consumers. Perhaps this information could help the managers of the NMRL system regarding where to concentrate their efforts in the advancement of the program.

4 Final remarks and suggestions for further studies

The NRML system in Brazil is its infancy, although it has already developed data based on operation in 2021. The municipal medicines reverse logistics schemes in small municipalities, such as, Farroupilha, in Rio Grande do Sul State, could help and inspire the NRLM system because they have been running at least since 2015 with strong community engagement and high visibility facilitated by the proximity of locally empowered stakeholders and the leadership/commitment of these public agents. At the same time, the difficulties experienced by the local systems, such as, lack of data normalization and transparency (Viegas et al., 2022) could be solved as long as these small schemes start adopting professional practices already structured by the national system. Infrastructure, information technology to provide traceability, and supervision (Campos et al., 2023) in all reverse stages are necessary in both local and national medicines RL schemes. It is necessary to highlight that the local systems, in cities with less than 100,000 residents, is based also on a presumption that some medicines will be re-used if possible, rather than automatically disposed of. It changes the perspective of the consumers and probably influences the willingness to participate. Although such assumption was not investigated in this research, the expectancy that the returned medicines can help anyone that cannot afford these types of goods will likely influence the amount of medicines returned because these acts of delivery can be seen as more ethically accepted than the delivery for destruction or landfill destination.

This paper started asking whether small/local systems are more sustainable than larger ones, and the direct and indirect data analysed provided some clues in favour of the small ones. Although other variables were not included in this study, such as, an examination of the whole processes of the smaller and the larger systems – mainly because of the lack of data availability from the small municipalities that adopt their own medicines RL schemes - it was possible to conclude that the availability of collection points installed through the NMRL system does not necessarily ensure effectiveness of collection in terms of physical amounts. Thus, the local system, regardless of their organizational limits, appear closer to the consumers than the national ones, and it is probably that the pharmacists' roles (Ehrhart et al., 2020) in motivating the residents to deliver back the unused or expired medicines is pivotal in this "proportional higher sustainability".

Consumers' awareness does not necessarily indicate consumers' engagement (Kotchen et al., 2009; Kusturica et al., 2020) in terms of participation in medicines returns programs, which has been confirmed through the data analysed and compared in this study - mainly with respect to the relationship between the physical amounts collected per capita and the number of per capita collection points available. The findings of this research raise concerns about the future of water quality in Brazil considering that this resource is largely affected by the pharmaceutical pollution, and that the current water treatments do not remove such types of products from the water (Danelon et al., 2021). Given the limitations of this study, mainly due to the lack of more local data on medicines RL schemes, it is recommended that future research should provide qualitative information on the results of the NMRL system, from the stakeholders of the supply chain (representatives of industry, distributors and retailers) as well as consumer groups, pharmacists and public agents about their own interpretation of the current results. This should include whether and, if so, how they intend to change the way in which the system currently works, and what are their proposals to increase the consumers participation? Future research should also investigate the motivation for medicines returns and, in particular, identify the influence of effect related to knowledge of whether returned medicines will be reused, where possible, rather than simply sent to disposal.

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Comparative Techno-Economic and Life Cycle Assessments of Single And Intercropped-Mixed Feedstock Based Biorefineries For Production Of Energy

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Abstract

The role of intercropped mixed-feedstocks (IMF) in advancing biorefineries is rarely studied. However, as opposed to conventional single feedstocks (SF) from monocropping system (MCS), the MFs could potentially enhance economic profitability by reducing cost of feedstock transportation and overall operations due to high feedstock yield/ha and less inputs e.g., diesel. In addition, IMFs could improve environmental performances by minimizing emissions associated with feedstock farming inputs (e.g., fertilizer), transportation (e.g., diesel, and tear & wear) and overall operational requirements. Furthermore, intercropping systems (ICS) could mitigate feedstock yield uncertainties and ensure stable feedstock supply because legumes (e.g., pigeon peas) are drought resistant and inhibit pests & diseases when intercropped with maize. Nonetheless, the actual benefits of IMFs must be quantified. Therefore, techno-economic and life cycle assessments were done, using Malawian economic context as a case study, to evaluate IMFs of maize stover (MS) and pigeon pea stalks and leaves (PPSL) for ethanol, electricity, and biogas production in biorefinery at 156 and 2184 kt/y. Four scenarios were investigated; (S1) MS from MCS, (S2) MS from ICS, (S3) MS and PPSL from ICS, where PPSL was dedicated for combined heat & power (CHP), and (S4) MS and PPSL from ICS where MS was dedicated to CHP. The biorefinery systems were simulated in Aspen Plus ® to obtain mass and energy balances (MEB) which were used in assessing economic performance via biorefinery gate feedstock cost (BGFC), net present value (NPV) and minimum product selling price (MPSP). BGFC was evaluated by aggregating the cost of buying feedstocks, labor, milling, baling, and transportation. Transportation cost was computed via summation of cost of fuel, driving labor, depreciation, and maintenance influenced by transportation distance and feedstock yield/ha. The MEBs were also used as input and output data in Simapro ® software to estimate emissions (per functional unit, FU i.e., ton of feedstocks) in terms of fossil resource depletion (FRD), global warming (GW), terrestrial acidification (TA) and freshwater eutrophication (FWE). The IMFs scenarios demonstrated better economic and environmental performances compared to SF scenarios, especially at large capacity. For instance, BGFC, MPSP & FRD for IMF's S3 were $228 million/t, $2.28/L & 135 kg oil eq/t respectively, compared to $258 million/t, $2.37/L, and 146 kg oil eq/t respectively for S1 at 2184 kt/y. Thus, IMF improved BGFC, MPSP & FRD by 12, 5 & 8 % respectively. Therefore, IMF biorefineries could be an attractive opportunity to investors passionate in advancing bioeconomy.

Keywords: *Intercropped multi-feedstock biorefineries; techno-economic & life cycle analysis; feedstock cost; and ethanol, biogas & electricity*.

1. Introduction

The high economic cost and environmental emissions associated with feedstock mobilization and overall operations remain one of the major hindrances to successful commercialization of biorefineries (Zhao et al., 2015; Whalley et al., 2017; Liu et al., 2021). Studies suggest that this problem mainly emanates from the reliance on the conventional supply of single feedstocks (SF), e.g., maize stover (MS) from monocropping systems (MCS) which normally have low yield/ha due to low soil nutrient and lack of resilience to pest, diseases and droughts (Whalley et al., 2017; Ngwira et al., 2020). The crop intensification and large inputs (e.g., fertilizer and pests & diseases control) may increase productivity and enable large availability of feedstocks/ha but such investments could exacerbate the overall cost of feedstocks and increase environmental emissions (Ngwira et al., 2020). Techno-economic studies (Whalley et al., 2017; Liu et al., 2021) reveal that the major portion of feedstock cost is transportation which depends on distance and the quantities of feedstocks available/ha. Therefore, the requirement for long-distance of feedstock mobilization when, utilizing SF, to fill biorefinery commercial capacities (600-5000 t/day) reduces the biorefineries' economic performance (Liu et al., 2021). In addition, the combustion of large fuel quantities coupled with wear and tear during long distance transportation of SFs from MCSs result in high environmental emissions (Liu et al., 2021).

Multi-feedstock (MF) processing has been recommended (Ashraf & Schmidt, 2018) as one of the potential remedies to enhancing biorefinery's economic and environmental performances by minimizing transportation (due to large availability of feedstock/ha). However, the differences in location, composition and moisture content of feedstock are some of the major challenges to multi-feedstock co-processing as their mixture may affect feedstock transportation logistics & storage requirements, processing conditions and product yields (Ashraf & Schmidt, 2018). Intercropping systems (ICS) produce more residues/ha than MCSs (Cardoen et al., 2015; Ngwira et al., 2020). Therefore, co-utilization of intercropped mixed feedstocks (IMF) could potentially reduce transportation and enhance biorefinery's economic and environmental performances. In addition, the composition of residues of legumes like pigeon pea stalks and leaves (PPSL) (i.e., 38.65, 11.76 and 17.50 % for cellulose, hemicellulose and lignin respectively) falls within MS composition range (i.e., 35 - 50% cellulose, 10 - 22 % hemicellulose & 11 - 25 % lignin) (Humbird et al., 2011; Zhao et al., 2018). Thus, IMF of MS and PPSL could be processed following the well-researched and commercialized process schemes for SF of MS (Liu et al., 2021). However, there is little to no effort to assess the referred potential in increasing economic and environmental performances for biorefineries. Therefore, this work conducted comparative techno-economic analysis (TEA) and life cycle analysis (LCA) of IMF of MS and PPSL alongside SFs of MS to uncover the true benefits of the former for production ethanol, biogas, and electricity. The TEA evaluated the biorefinery gate feedstock cost (BGFC), net present values (NPV) and minimum product selling prices (MPSP). On the other hand, the LCA evaluated the contributions on fossil resource depletion (FRD), terrestrial acidification (TA), global warming (GW), ozone layer formation (OLF) on human health, freshwater eutrophication (FWE), and land use (LU). The selected economic indicators and environmental impact factors were assumed that they would provide adequate basis for comparing the environmental performances of IMF and SF biorefineries after consulting the literature (Liu et al., 2021).

There seems to be no data in literature, on co-pretreatment conditions and sugar yields for MS and PPSL, that could be integrated with available downstream data on fermentation and anaerobic digestion for use in Aspen Plus ® simulation modeling to enable TEA and LCA. Therefore, experiments were conducted to determine co-pretreatment conditions and yields from MS and PPSL by screening through a range of literature values for pretreatment agent (NaOH) loading (i.e., 0.6 - 5.6 % w/v) and solid loading (i.e., 7 - 20 % w/v) at 121 °C and 1 atm following a similar procedure reported in literature (Sawisit et al., 2018). Since the sugars (e.g., glucose and xylose) obtained from mixed feedstocks are not unique to MS and PPSL, the data on downstream processing conditions and yields i.e., fermentation and anaerobic digestion was obtained from literature (Humbird et al., 2011; Zhao et al., 2018).

2. Methodology

2.1. Feedstock characterization and pretreatment

Feedstocks of MS and PPSL were collected from Malawi and transported to Stellenbosch University (South Africa) for characterization and pretreatment experiments based on literature (Sluiter et al., 2012; Sawisit et al., 2018). Moisture content was determined using moisture analyzer (KERN DLB Version 1.0, 04/2011 GB) that computes the moisture content by comparing the mass of the samples before and after heating to constant mass. The protein composition was determined using Dumas protein analyzer (Dumatherm DT N40+14-0000) which combusts the samples and computes the amount of protein using nitrogen to protein ratio of 6.25. The extractives were determined by Soxhlet extraction (KDM-A Soxhlet extraction) after 24 h extraction. Ash content was determined after total ignition of samples in the muffle furnace (Nabertherm GmbH, SN299182). Lignin was characterized as total of acid soluble lignin and acid insoluble lignin. The cellulose (based on glucose) and hemicellulose (based on xylose) were determined using HPLC (Dionex 3000 ultimate, Biorad Aminex 8.7-H column, 0.005 H2SO4 eluent) after hydrolysis. The milled MS and PPSL (2 mm) were mixed at a ratio of 2:1 (MS to PPSL, the ratio is according to feedstock generation in ICS) then added to 90 mL solution of sodium hydroxide at different concentrations in a 250 mL Schott bottle (i.e., from 0.6 – 5.6 % w/v NaOH and from 7 - 20 % w/v solid loadings)(Sawisit et al., 2018). The samples were subsequently autoclaved at 121 °C and 1 atm for 60 mins before washing, drying (at 60 °C) and re-characterization.

2.2. Process description

Aspen Plus® V11 software was used to model processes for production of ethanol, biogas and electricity at a small capacity of 156 kt/y (C1) and large capacity of 2184 kt/y (C2) based on existing commercial scale lignocellulosic biofuel plant sizes (i.e. 600 to 5000 t/day) (Liu et al., 2021). Four scenarios were evaluated: (S1) MS from MCS, (S2) MS from ICS, (S3) MS and PPSL from ICS, while using PPSL for combined heat and power (CHP), and (S4) MS and PPSL while dedicating MS to CHP. The activity-thermodynamic property method, electrolyte non-random two-liquids (ELEC-NRTL) with Redlich-Kwong equation of state and STEAM-TA were selected due to their abilities in estimating properties in Aspen plus ® (Humbird et al., 2011; Davis et al., 2018). Pretreatment (at 2.7 % (w/v) NaOH 121 °C and 15 % w/v solid loading) dissolves 61 % of lignin, 10 % cellulose, 37 % hemicellulose and 99 % of extractives, ash, and proteins (Sawisit et al., 2018). The solids are separated from the liquid before undergoing enzymatic hydrolysis at solid loading of 5.1 %, enzyme loading of 0.04 kg/kg feedstocks, and temperature of 50 °C to yield 93 % and 85 % for glucose and xylose respectively (Zhao et al., 2018). The cocktail of enzymes (endoglucanases, exoglucanese, and β-glucosidase) are produced on site (Humbird et al., 2011; Davis et al., 2018). After hydrolysis, ethanol fermentation is performed at solid loading of 8.4 % and temperature of 37 °C with 96 % and 93 % yield of glucose and xylose respectively (Zhao et al., 2018). The solids from fermentation are filtered and fed to an anaerobic digestion (AD) unit while the beer is pumped for distillation (Humbird et al., 2011; Zhao et al., 2018). The stillage and wastewater undergo anaerobic digestion (AD) to produce biogas and treated water (Humbird et al., 2011; Zhao et al., 2018). A portion of feedstocks is combusted to heat water into steam which is used to drive the generator and produce electricity part of which is used within the plant while the balance is sold to the main grid (Humbird et al., 2011; Davis et al., 2018).

2.3. Feedstock cost

The costing methodology follows a similar approach in literature (Zhao et al., 2015; Whalley et al., 2017) where feedstocks from the fields are transported to primary processing centers (PPC) for milling before transporting them to the biorefinery. The BGCF was calculated using Eq. 1-2 (Zhao et al., 2015; Whalley et al., 2017).

$$BGCF = \text{FMM} + \sum_{n=1}^{N}\sum_{j=1}^{J} C_j \qquad (1)$$

$$C_j = C_{trans} + C_{Labour} + C_{Depr} + C_{Maint} + C_{energy} \qquad (2)$$

Where FMM refers to the salary (i.e., 5 % of C_j) of feedstock mobilization manager (FMM) who oversees feedstock mobilization process, N, is the number of collection centers, j refers to transportation, labor, depreciation, maintenance, or energy. C_{Labour} is the cost of labor based on $/labor-day, C_{Depr} is the cost of depreciation (14 %/y), C_{Maint} is maintenance cost (given as 0.26 $/t) and C_{energy} is the cost of energy for milling the feedstocks (0.11 $/kwh). C_{trans} is the cost of transportation given by Eq. 3-9 (Zhao et al., 2015; Whalley et al., 2017).

$$C_{trans} = C_{trans\ to\ PPC} + C_{trans\ to\ BR} \qquad (3)$$

$$C_{trans\ to\ PPC} = \int_0^{R_n} 2\pi Y_n\, \alpha_n \beta_{fc} F_{fc} r^2 dr + W_{driv\ to\ PCC} \quad (4)$$

$$F_{f-pcc} = F_{eco} * R_n * N_c * P_n \quad (5)$$

$$F_{pcc-B} = F_{eco} * d_{ntoBR} * Q_{ntoBR} \quad (6)$$

$$C_{trans\ to\ BR} = Q_{ntoBR} d_{ntoBR} \beta_{toBR} F_{pcc-Br} + W_{driv\ to\ BR} \quad (7)$$

$$d_{ntoBR} = R_n * N * \beta_{fc} \quad (8)$$

$$R_n = \sqrt{\frac{C_n}{100\pi Y_n \alpha_n}} \quad (9)$$

Where $C_{trans\ to\ PPC}$ is the cost of transportation from the field to the PPC, $C_{trans\ to\ BR}$ is the cost of transportation from the PPC to the biorefinery, Y_n represents biomass yield/ha, R_n refers to the feedstock collection radius of PPC, F_{fc} refers to fuel cost/t-km, d_{ntoBR} is the distance between the biorefinery and PPC, C_n is the quantity of biomass at PCC. Q_{ntoBR} is the quantity (t) of feedstocks transported from PCC to biorefinery, F_{Pcc-B} is fuel consumption L/t-km, β_{toBR} and β_{fc} (i.e., 0.5) refer fraction of cultivated land/useful land, α_n (i.e., 1.4) refers to the ratio of real road length to direct distance. $W_{driv\ to\ PCC}$ and $W_{driv\ to\ BR}$ refer to the wages for the driver from field to the PPC and from PPC to the biorefinery, respectively.

2.4. Capital and operating costs

The base costing year is 2021 and the project life 30 years. Chemical engineering plant cost indexes (CEPCI) and scaling exponents provided in literature (Humbird et al., 2011; Davis et al., 2018) were used to extrapolate cost of equipment to project year. Furthermore, an installation factor (i.e., with values ranging from 1 to 3.1) is used to adjust the purchase cost of equipment to an installed cost. Cost of utilities, storage, warehouse, site development, and additional piping were estimated as 7 %, 5 %, 4 %, 9 %, and 4.5 % respectively of the ISBL. On the other hand, prorateable expenses, field expenses, project contingences, and other costs were each estimated at 10 % TDC while the cost of construction was estimated at 20 % of the TDC (Liu et al., 2021).

2.5. Net present value and minimum product selling price

The net present value (NPV) was calculated using Eq. (10).

$$NPV = -TCI + \sum_{t=-2}^{30} \frac{Pb_t * Qb_t + Pe_t * Qe_t + P_{EtOH} * Q_t - F_t - MC_t - Lnt_t - T_t}{(1+i)^t} \quad (10)$$

Where TCI is total capital investment, P_{EtOH} is the selling price for ethanol, Q_t is ethanol production in a year t, Pb_t is the price of biogas i.e., 0.87 \$/L, Qb_t is biogas production in a year t, Pe_t is the price of electricity i.e., 0.11 \$/kWh, Qe_t is electricity production in a year t, F_t is the feedstock cost in a year t, MC_t is the operating expenses, Ln_t is the loan repayment with interest i.e., 23.9% in 10 years, T_t is an income tax rate i.e., 30.5 % paid by the plant in year t, i is the discount rate i.e., 15 %. Total loan is 60 % of the TCI (payable in 10 years) while 40 % was equity.

The MPSP for ethanol was calculated from Eq. 10 by letting NPV equal to zero. The operating expenses where determined as summation of fixed expenses i.e., salaries, labor burden (90 % of total salaries), maintenance (5 % of ISBL) & property insurance (0.7 % of FCI) and variable expenses i.e., cost of chemicals and waste disposal (Davis et al., 2018). The project start-up time was 3 months (i.e., 0.25 years) hence only 75 % of variable costs, 50 % of feedstock use, 50 % of revenues and 100 % fixed cost were applicable to the first year of the project. A declining balance depreciation of 200 % and 150 % were applied to the general plant and CHP respectively (Davis et al., 2018).

2.6. Life cycle analysis

The LCA was conducted in Simapro ® V9.2 using ReCiPe mid-point (H) method and following guidance by international standardization organization (ISO) 14040 and 14044 on defining goal, scope, inventory analysis, impact assessment and interpretation of results (Liu et al., 2021). The goal was to compare the environmental emissions contributed by each biorefinery scenario (S1-S4) at C1 and C2 (from cradle-to-gate perspective) to identify any environmental advantages of IMF scenarios over the SF scenarios. The scope of the analysis covered the environmental inputs and outputs from farming, transportation of feedstocks and biorefinery (Liu et al., 2021). The system boundary excludes biorefinery product use and recycling but will include MS and PPSL farming, harvesting, primary processing, baling of residues, transportation, storage, and conversion of residues to products.

Since this work deals with multi-products the "per ton of feedstock processed" was selected as suitable functional unit (FU) as guided by literature (Liu et al., 2021). The allocation in Simapro ® was done on mass basis for the transportation and main processes at the biorefinery because all the emissions concerned the biorefinery. On the other hand, economic allocation was used for data from farming in order to capture emissions related to MS and PPSL and leave out emissions related to the harvested grains (Liu et al., 2021). The data for farming systems applies to small holder farming system where farming is done using human manual labor and no mechanization is involved e.g., for land clearing and planting (Ngwira et al., 2020). The fertilizer requirement for maize MCS in Malawi is 92, 20, 10, 12 kg/ha for Nitrogen, P_2O_5 and K_2O respectively in addition to pesticide i.e., dimethoate requirements of 5 kg/ha. On the other hand, the fertilizer requirement for ICSs is 46, 10, & 5 kg/ha for urea, P_2O_5, and K_2O, respectively. The diesel fuel requirement for transportation (using trucks)/t was calculated using Eq. 5-6 as 5.1, 4.8, 3.9 and 3.9 L/t for S1-S4 respectively at C1 56.7, 53.4, 43.1 and 43.1 L/t for S1-S4 respectively at C2 (Zhao et al., 2015; Whalley et al., 2017). The MEBs from Aspen plus ® were used as input and outputs during processing at the biorefinery. Steam and electricity were assumed not to contribute to emissions because they were produced onsite.

The impact categories on which the scenarios were compared include FRD (kg oil eq/FU, GW (kg CO_2 eq /FU), TA (kg SO_2 eq/FU), OLF on human health (kg NOx eq/FU), FEW (kg P eq/FU) and LU (m2a crop eq/FU) (Liu et al., 2021). The interpretation of the selected environmental impacts were assumed that they would provide adequate basis for comparing the environmental performances of scenarios (S1-S4) after consulting the literature (Liu et al., 2021). Since the crops consume CO_2 during photosynthesis, the biogenic CO_2 was selected from Simapro data bank. This implied that the CO_2 emissions did not contribute to the environmental emissions.

3. Results and discussion

3.1. Feedstock composition and pretreatment

The composition of cellulose, hemicellulose, lignin, ash, protein and extractive were found to be 39.99, 18.65, 19.04, 6.93, 2.88 and 12.50 % for MS and 38.65, 11.76, 17.50, 4.54, 5.24 and 22.32 % for PPSL respectively which is within literature range (Humbird et al., 2011; Zhao et al., 2018). At pretreatment conditions of 15 % solid loading, 121 °C, and 2.7 % w/v NaOH loading the delignification of 61 % w/w was achieved in experimental sample D (Fig. 1). In addition, 90 & 63 % w/w of glucan and xylan respectively were recovered (Fig. 1) in D. At higher NaOH loading beyond 0.18 g NaOH/g substrate (i.e., sample A, E, F, G, H & J), higher lignin removal is achieved but this high delignification extent is accompanied by excessive sugar losses (Fig. 1). Thus, a compromise needs to be reached so that while high delignification is targeted, it must be accompanied by high sugar retentions (Sawisit et al., 2018).

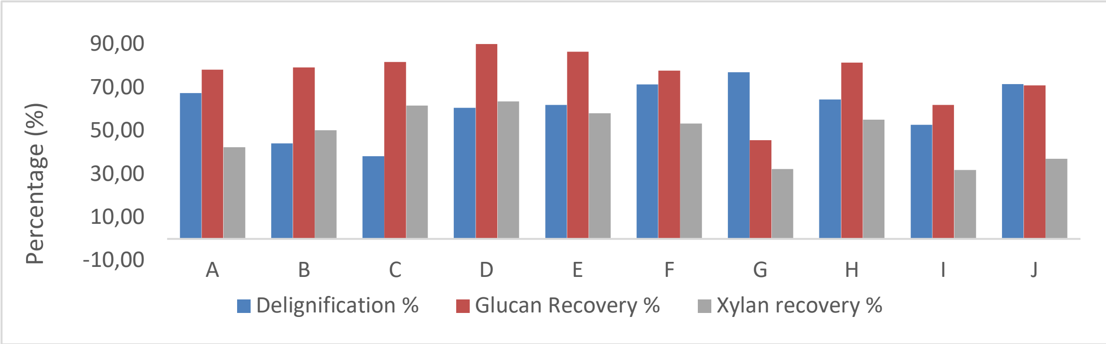


Figure 1: Delignification and glucan & xylan recovery from pretreatment experiments at different solid and NaOH loading. The solid and NaOH loading were: 15 & 3.0 % for, 15 & 3.0 % for B, 20.0 & 1.6 % for C, 15.0 & 2.7 % for D, 22.0 & 3.9 % for E, 7.9 & 1.4.0 % for F, 15.0 & 4.8 % for G, 10 & 4.2 % for H, 15 & 0.6 % for I, and 20 % & 5.6 % for J respectively.

3.2. Feedstock cost

The IMFs have a lower BGFC compared to SFs especially at large biorefinery capacity, C2. For example, (at C2) the total BGFCs are $228 & $245 million for IMF's S3-S4 respectively compared to BGFCs of $258 & $250 million for SF's S1 & S2 respectively (Fig. 2a). Hence IMF reduced BGFC by 12 % at C2. On the other hand, at C1, the BGFCs are 9.13 & 10.30 million for S3-S4 respectively compared to BGFCs of $9.11 & $9.07 million for (S1-S2) respectively (Fig. 2b). Therefore, the benefits of IMF are more noticeable at C2 than C1 attributable to differential influences of cost of transportation, labor, and energy , depreciation and maintenance in feedstock supply chain (Zhao et al., 2015; Liu et al., 2021). Chiefly, at C2, the transportation cost dictates the BGFC since the feedstocks require long transportation distances (TD) i.e., a total of 727, 686, 561, and 561 km for S1-S4 respectively (Eq. 8). On the other hand, at a C1, the IFMs still involve smaller total TD than SF, but variations (in TD) are minimal i.e., 52, 49, 40, and 40 km for S1-S4, respectively. Hence, at C1 the savings in transportation cost of IMF (due to their higher yield/ha compared to SF) are not sufficient to offset the higher labor and energy associated with mixed feedstock processing. For example the energy demand is for chopping and milling is 49 kWh/t for IMFs (of MS and PPSL) compared to 11 kWh/t for SF of (Manjunath et al., 2019). Nevertheless, biorefineries are usually designed to operate at large capacities (e.g., C2) to meet the large demand for products. Therefore, transportation cost is dominant in the biorefinery's operating expenses (Liu et al., 2021). Thus, IMFs are a more economically viable option than SFs.

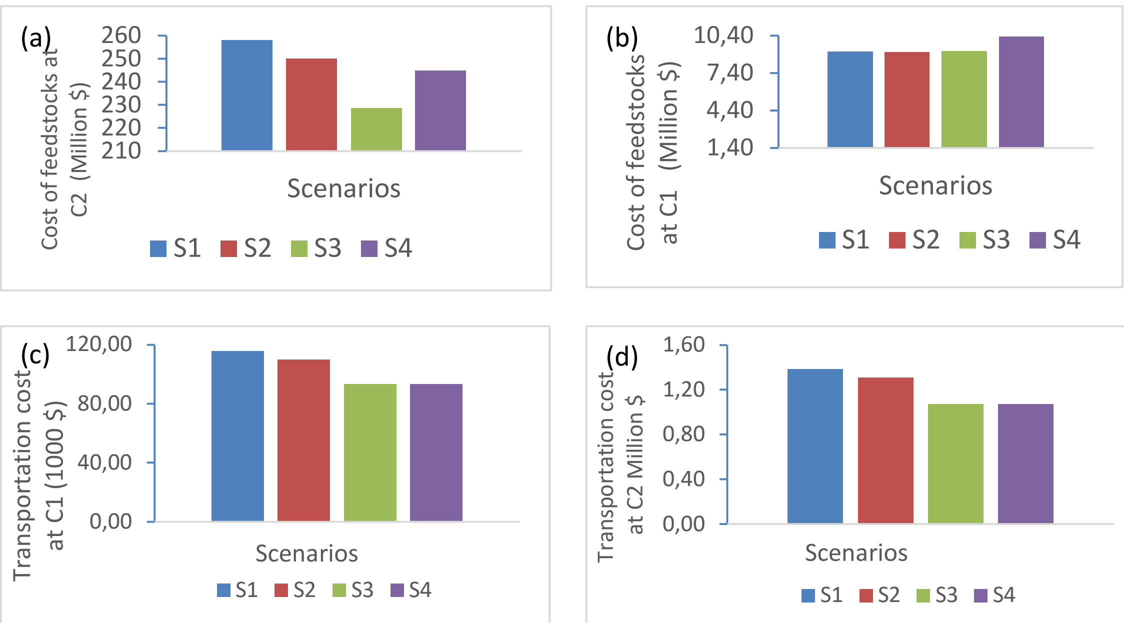


Figure 2: (a) Total cost of feedstocks at 2184 kt/y (C2), (b) total cost of feedstocks at 156 kt/y (C1), (c) cost of transportation at C1 and (d) cost of transportation at C2

3.3. Operating and capital costs

The IMF lowers the operating expenses of the biorefineries especially at high capacity. For example, at C2 (Fig. 3a), the operating costs for the IMF's S3-S4 are $753 & $769 million respectively compared to $783 & $775 million for S1 and S2, respectively. The low operating expenses for the IMFs are attributed to the low cost of feedstock which is a dominant component of operating expenses (Zhao et al., 2015; Davis et al., 2018; Liu et al., 2021). On the other hand, at C1 (Fig. 3b), the operating expenses for IMF's S3-S4 are $49 and $50 million compared to $49 million for MSF'S S1 and ISF's S2. Therefore, the benefits of IMF are more noticeable at C2 than C1. The results also show that CHP sections have the highest capital cost, attributable to high cost of equipment for operation at high temperature and pressure (Davis et al., 2018; Liu et al., 2021). The AD section requires second largest investments compared to the rest of other sections like pre-treatment, hydrolysis, and purification attributable to the large volumes of wastewater that is handled at AD section (Davis et al., 2018; Liu et al., 2021).

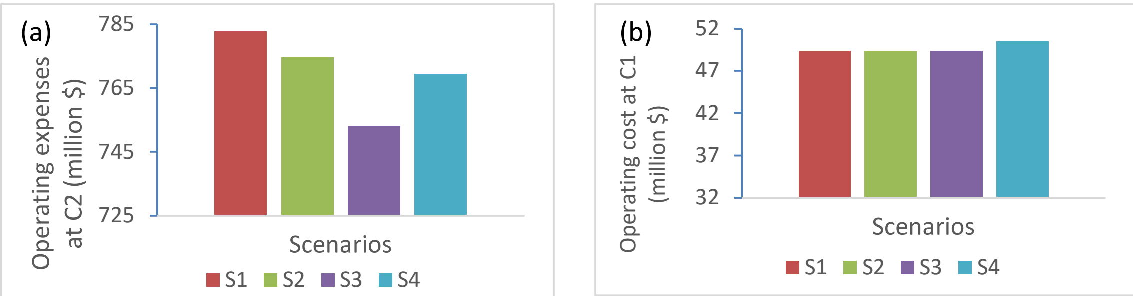
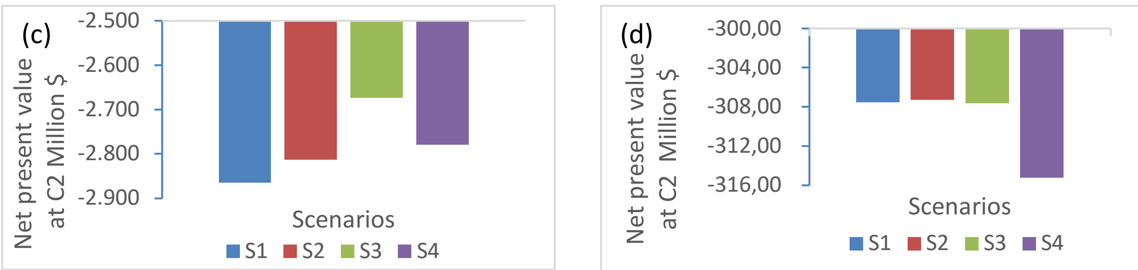


Figure 3: (a) operating cost for 2184 kt/y, (b) operating costs for 156 kt/y

3.4. The net present value and minimum product selling prices

The IMF biorefineries are more economically viable compared to SFs especially at C2 i.e., NPV of -$2674 & -$2780 million for S3-S4 respectively compared to -$2865 & -$2813 for million for S1-S2 respectively (Fig. 4a). On the other hand, at C1, S3-S4 have NPVs of -$307 and -$315 million respectively compared to NPV of -$307 for MSF's S1 and S2 (Fig. 4b). However, negative NPVs imply that the processes would not be economically profitable if ethanol is sold at the market price of $0.91/L. Therefore, the MPSP for ethanol was computed to determine the prices at which the sales would lead to profitable investment. Notably, at C2, the MPSPs for S3-S4 are 2.28 & 2.33 $/L receptively (Fig. 4c) compared to 2.37 & 2.34 $/L for S1-S2 respectively (Fig. 4d). On the other hand, at C1, the S3-S4 have NPVs of 2.99 & $3.00 S/L respectively (Fig. 4d) compared to 2.99 $ for S1 & S2 respectively (Fig. 4d). Thus, IMFs have potential to enhance economic profitability of biorefineries especially at large capacity due to the lower operating expenses influenced by the low cost of feedstocks (Liu et al., 2021). Therefore, the IMF would likely attract interest from investors seeking to advance the bioeconomy.



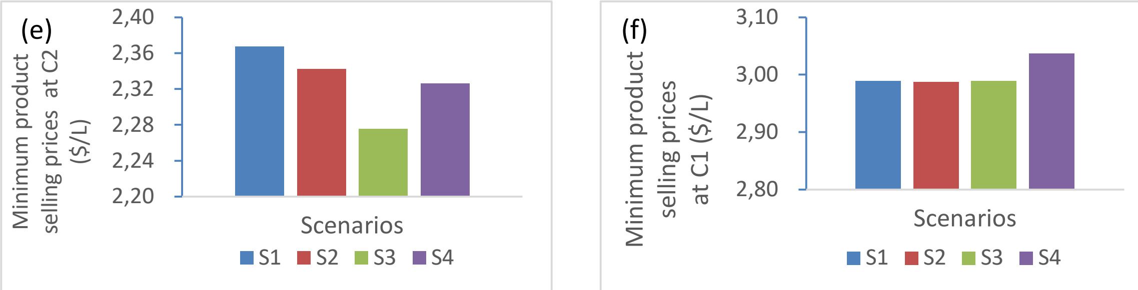


Figure 4: (a) net present value for 2184 kt/y, (b) net present value for 156 kt/y, (c) minimum product selling prices for 2184 kt/y and (d) minimum selling price for 2185 kt/y

3.5. Sensitivity analysis

The variations in ethanol production capacity & selling price and yearly operating period (within 25 %) have more direct influence on NPV compared to fixed capital investment, biogas selling price and electricity selling price. The variations are slightly more elastic at SF (S-S2) (Fig. 5a) than IMF (Fig. 5b). Therefore, it would be more economically stable to utilize IMFs than SFs.

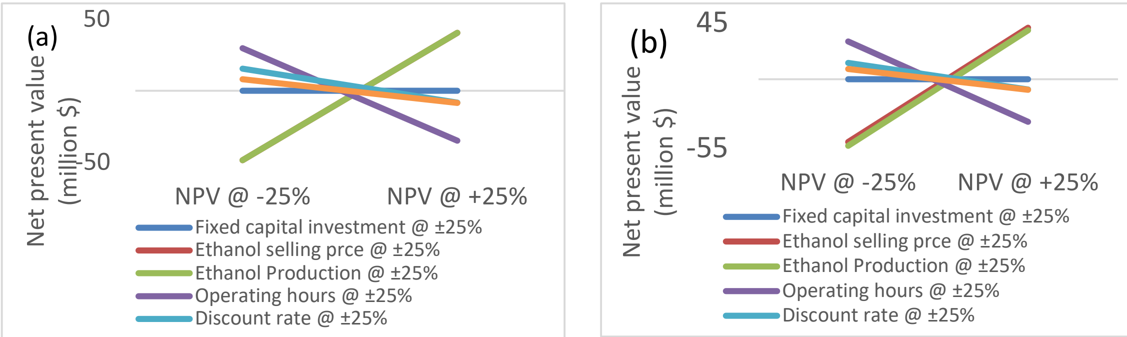


Figure 5: Sensitivity analysis of (a) single feedstocks and (b) intercropped mixed feedstocks

3.6. Environmental benefits of intercropped mixed feedstocks

The IMFs enhance environmental performance (EP) of SF biorefineries. For instance, the S4 reduce S1's FRD from 146 to 135 kg oil eq/FU (Fig. 6a), TA from 2.62 to 2.55 kg SO2 eq/FU) (Fig. 6b), GWI from 753 to 744 kg CO2 eq /FU (Fig. 6d) and FWE from 0.128 to 0.126 kg P eq/FU (Fig. 6e). A similar trend is observed at both C1 and C2. The higher environmental performance of IMFs is attributed to the 50 % less use of fertilizers and plant protection chemicals (Ngwira et al., 2020) and reduction in transportation distance & fuel requirement (Liu et al., 2021). Therefore, the IMF biorefineries would attract interest from investors passionate in advancing bioeconomy. The large environmental emissions observed in AD (Fig. 6) are attributed to the large collection of waste streams from all plant sections for biogas production and water recycling (Liu et al., 2021). The other major emissions are observed in enzyme and pretreatment sections (Fig. 6) are related to the historical processes related to the production of production glucose (from corn starch) and NaOH (from NaCl, via electrolysis) respectively (Liu et al., 2021).

Figure 6: Emissions for (S1-4) at C1 & C2 in terms of (a) Fossil resource depletion, (b) Terrestrial acidification (c) Ozone formation on human health, (d) global warming impact (e), Fresh water eutrophication and (f) land use.

Conclusion

The IMFs enhance the economic and environmental performance of the biorefineries. For example, BGFC, MPSP & FRD improved from $258 to $228 million/t, $2.37/L to $2.28/L & 146 kg to 135 kg oil eq/t, respectively. Hence IMF biorefineries could be an attractive opportunity to investors with passion in advancing bioeconomy and cleaner production. However, further research should be done on reducing the MPSP of ethanol to the market price of 0.91 $/L e.g., by diversifying energy products with high value products (e.g., lactic acid).

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Contribution of family farming practices to a social FEW Nexus from the perspective of Actor-Network Theory (ANT)

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Abstract

With the emergence of the Sustainable Development Goals (SDGs), new approaches have emerged seeking to solve complex problems resulting from climate change. One such approach is the FEW Nexus (Nexus food-energy-water) which considers that food, energy, and water should be managed, analyzed, and thought about interdependently. However, when looking at the current FEW Nexus studies, there is a lack of use of social approaches and a local focus. In this sense, the practices of family farmers were considered as a possible way to develop a new approach. Thus, the research question of this essay is: how can the social practices of family farmers contribute to an articulation and local organization of the FEW Nexus? As a theoretical background, it used the Actor-Network Theory, therefore, the central objective of this essay was to discuss how the social practices of family farmers can contribute to a new construction of FEW Nexus from the perspective of the Actor-Network Theory (ANT). To achieve this objective, a literature review was carried out in the main databases, seeking to describe the practices of family farmers in the FEW Nexus elements. Subsequently, such practices were interpreted under the lens of ANT. Lastly, it was proposed a FEW Social Nexus as a result. At the end, theoretical and social contributions of the study were highlighted. The main ones are: the proposition of an equitable relationship between human and nature in the theoretical FEW Nexus approach; the importance of family farming and the strengthening of public policies for the sustainability and achievement of the SDGs aimed at combating poverty and food insecurity.

Keywords: Actor-Network Theory. Family farming. FEW Nexus. Social Practices. Sustainability.

1.Introduction

New approaches have emerged seeking to solve complex problems resulting from climate change as Sustainable Development Goals (SDG). Another important approach is the FEW Nexus (Nexus food-energy-water) which considers that food, energy, and water should be interdependently managed, analyzed and thought. However, when looking at the current FEW Nexus studies, there is a shortage of social and local focus in the literature. At the same time, as the relevant social actor for sustainability, the family farmers were considered as a possible actor to develop Nexus approach.

Thus, the research question of this article is: **how can the social practices of the family farmers contribute for articulation and local organization of the FEW Nexus?** As a theoretical background, the Actor-Network Theory (ANT) was used, as it considers a sociological theory that equates natural and non-natural elements in its analysis, something that resembles the FEW Nexus logic in relating food, energy, and water aspects with human interaction. Therefore, the main objective of this essay is to discuss and to propose how the social practices of family farmers can contribute to a new construction of FEW Nexus from the perspective of the Actor-Network Theory (ANT). The text's main argument is that the social practices of family farmers, in line with the FEW Nexus approach discussion, could serve as a basis for advancing public policies for rural food security and sustainable agriculture.

2. Literature Review

From recently the literature, it is important to point out that family farming plays a relevant role in achieving the SDGs, consequently, its practices. Firstly, by operating through short agrifood chains (relationship system with the fewest possible intermediaries between producer and consumer), family farming reduces transport displacement, thus, greenhouse gases emissions. Moreover, direct marketing between the consumers and the producers also helps to preserve local and territorial culture (Malak-rawlikowska et al., 2019). In the social aspect, family farming serves and generates income for the poorest layer of population. In addition, its management is based on community and collaborative principles, promoting gender equity and rural succession (FAO, 2019; Godoy-Durán, Galdeano-Gómez, Pérez-Mesa & Piedra-Muñoz).

Seeking to explain the eating practices of family members, the Actor-Network Theory was chosen as the theory is based on the ontology of relational materiality. It means that the studied environment does not have a construction per se, as it crystallizes only when there is an interaction of two or more actors- that can be human and non-human as elements of nature. Thus, the ATN consider a multiplicity of possible realities (Latour, 2007).

One of the main concepts of the theory is the enactment, relational action that brings the object and/or actor into existence. In that sense, everything that is real in ANT is enacted, in the other words, every entity that relates to another can be considered as an actor. In organizational processes, this concept makes sense from the moment that enacting is considered to mean the same as how different objects "become" or "are structured" (CAMILLIS; ANTONELLO, 2016). Using this concept, the study of Ferreira (2022), in an ecovillage in Rio Grande do Sul, questions the single and mainstream concept of sustainability by observing a subjective meaning constructed through heterogeneous relationships of non-human aspects with community practices and the collective (human).

Another relevant concept is that of synergy, which, according to Latour (1999), seeks to understand factors/actors responsible for uniting/synchronizing other factors and authors, for a given purpose, in a respective context. Latour (1999) cites the example of the act of flying when describing that such an action only occurs with the symmetry of various entities such as pilots, plane, weather, and airport. In the rural part, the study of Silva et al. (2020) observes that the symmetry between family agricultural ideology, market and public sector are the public policies of institutional food. In another words, without public policies, in Brazil, the family farming do not survive.

3.Methods

The main practices of family farming were researched in the main international academic repositories such as: Web of Science, Scopus, Scielo, Google Scholar, Catalog of Theses & Dissertations – CAPES *(Coordenação de Aperfeiçoamento de Pessoal de Nível Superior)* and Lume UFRGS Digital Repository. Moreover, the main keywords used were a combination of FEW Nexus elements (water, energy and food) with signs that represent family farming. Among the main ones are: "*agricultura familiar";* family farming; small farmers and family; smallholder farming.

Subsequently, the main practices were described, highlighting the main topics. In the construction of the framework, the theoretical aspects of ANT were used to propose a new social approach to FEW Nexus.

4.Results

4.1 Water

When analyzing the main reports in the literature, it was observed that the action of family farmers has a significant highlight regarding the response against the drought. These initiatives are built in a community way, being related to both domestic use and production. Among the studies researched is the recovery of the spring, through community efforts carried out by the farming families themselves. This example is in rural community of Cana Verde - located in the municipality of Palestine de Goiás, Brazil - which arises due to the decrease in water availability, a result of the erosive process of the soil and the degradation of riverside vegetation increased by the rampant livestock activity (Fuzeti, 2019).

Additionally, there is also the development of social technologies which, according to Fabri, Freitas and Poletto (2020), is a set of innovative techniques, methods and actions developed and applied by the population that use to improve their living conditions. Among the main studies highlighted are the development of a high-depth water pumping system (up to 100 meters), developed in Africa and replicated in Brazil (ASA, 2008). Another initiative is the development of cisterns that helped farmers based on an implementation process that allowed the farmers themselves to learn collectively (Cavalcante; Mesquita; Rodrigues-Filho, 2020).

Another relevant factor for water management is the cooperative character. One of the studies that proves this aspect is that of Chiodi, Ribeiro, Anjos Augusto and Sampaio. (2015) on an association of family farmers located in the North of Minas Gerais. According to the study, family farmers, through the association, were able to access public policies for the construction, financing and use of projects related to infrastructure and management of water resources. From another perspective, water can be the guiding thread of spontaneous social movements. An example of this is the struggle of Peruvian agricultural communities that mobilized against mining due to the impact that this economic activity had on water quality and quantity (Li, 2016). In addition to the cooperative issue, other relevant factors for water management are family succession and female participation. In a study carried out with family farmers in Almería, Spain, it was demonstrated that the most efficient use of water occurs when young people and women participate in the production decision-making process (Piedra-Munoz, Vega-Lopez, Galdeano-Gomez & Zepeda-Zepeda, 2018).

4.2 Energy

About energy in social practices, it is noted that the presence of photovoltaic energy in small properties for automating the irrigation process – relevant action for improving efficiency in the use of water resources (Lefore; Closas; Schmitter, 2021). In addition, the role of photovoltaic energy in rural properties is essential for agricultural production, as it ensures greater energy stability (Soares; Silva, 2022a). However, it is important to highlight that the feasibility of implementing renewable energy on family farms only happens with the presence of structured public policies and with the action of universities, public institutions responsible for designing and analyzing the feasibility of projects (Soares; Silva, 2022b).

The State also encourages and generates income for family farming through renewable sources. Within scope, one of the first public programs to stimulate the agricultural renewable energy sector in Brazil was the National Program for the Production and Use of Biodiesel. Created in 2004, the program allows family farmers, through state intermediation, to sell their food to private companies that produce biodiesel (Santana, 2021). In this context of public policies, another entity that assumes an important role in the sustainable transition of family farming is the community through the formation of cooperatives and unions. First, it should be noted that the formation of unions and cooperatives of family farmers are fundamental for access to public policies such as the PNPB (Santana, 2021). There are also consumer cooperatives. One of the most relevant examples occurs in countries such as Ghana and Ethiopia, where there are structuring of photovoltaic energy cooperatives responsible, preferably, for serving medium and small agricultural properties (Lefore; Closas; Schmitter, 2021).

Another social issue, which has energy as its guiding principle, is the articulation of movements. One of the main cases is the struggle of riverside and indigenous family farmers against the construction of large hydroelectric plants (Alves, 2013). According to studies of Fainguelernt (2020) and Passos and Praxedes (2013), mega hydroelectric plants brought silting up of the land, changes during rivers, uncontrolled population growth and poverty in the region. In this regard, Alves (2013) points out that energy, to be sustainable, cannot only be renewable, but needs to be debated and developed "from the bottom up" so that it is, in this way, an action to reduce poverty and inequalities, and no longer an instrument of capital accumulation.

4.3 Food

Regarding food, there is a link between habits passed down from generation to generation and agricultural preservation practices. This is seen in cases such as the preservation of Creole seeds through the construction of agricultural community houses. According to the study by Junior et al. (2021), these houses favor the strengthening of the agrobiodiversity of rural family communities since farmers have availability and easy access to seeds that are genetically more resistant to pests and extreme weather events such as drought and floods. Other micro-scale practices are related to agroecology and its techniques to reduce the carbon footprint of food. In a study carried out in the city of Lagoa Seca, in the state of Paraíba -Brazil, Souto, Malagodi, Maracajá & Xavier (2011) described that the main conservation practices of natural resources are reforestation and preservation of native forest; the non-use of fires; the rational use of water; land cover for water preservation and nutrient loss.

Such a decrease in the carbon footprint of food can also be seen from a macroscale perspective. The main representation of this refers to the way in which food is sold through short agrifood chains. According to Lopes, Basso and Brum (2019), it is understood as short agrifood chains when there are no, or there are few, intermediaries between producer and final consumer. This form of trade reduces the environmental impact of food, as it shortens travel distances, thus reducing the amount of energy (fuel) and avoiding possible losses in storage and distribution (Malak-Rawlikowska et al., 2019). At the same time, they contribute to the appreciation of local products since there is a more intense exchange, through proximity, between producer and consumer (Cassol & Schneider, 2017). Subsequently, the Brazilian institutional market, represented by public institutional purchasing policies, further strengthened the construction of local and regional markets, also contributing to the diversification of family farming products (Nunes, Morais, Aquino & Gurgel 2018). Moreover, through the National School Feeding Program, family farmers ensure the food security of students, who have substituted ultra-processed products for in natura foods (Nascimento, Nascimento & Oliveira, 2019).

Organization with political significance also permeates the relationship between family farmers and food. First, cooperatives, associations and non-governmental entities are constituted seeking to demand compliance with public policies aimed at the development of family farming (Soares; Silva, 2022a). Additionally, the political struggle of family farmers addresses other relevant issues. The first concerns agrarian reform, redistribution policy and democratization of access to productive land to meet the constitutional principles of the social function of properties (Law n. 8.629, 1993). One of the family farming organizations on this agenda is the Landless Rural Workers Movement (MST). With a peasant ideology, the organization's land occupations, in addition to claiming agrarian reform, are carried out as a way of contesting the authoritarianism of capital that generates social inequalities and harms public health by using too many pesticides in its production (MST, 2023). Such a fight against the production of food with poison becomes a milestone in social justice on the part of family farming, especially regarding sustainable agricultural transition.

The summary of practices, and another that was not cited, can be view in Table 1.

Water	Energy	Food
-Actions articulated with public and social entities to combat drought; -Collective organization for the recovery and preservation of springs; -Collective organization to access	-Photovoltaic energy Implementation in the agricultural irrigation process and energy stability; -University and public policies as fundamental factors for the viability of photovoltaic energy;	-Agricultural preservation practices from generation to generation; -Community seed houses; -Empirical knowledge sharing for pest and insect management;

public policies for the construction of social technologies; -Cooperativism as a water management model; -Social movement for the preservation of water and landscape; -Introduction of guidelines related to Gender equity and family succession as efficiency factors for water use.	-Wind energy as an element of income generation; -Rural electrification cooperatives organization; -Social movement against the construction of large hydroelectric dams.	-Agroecological preservation techniques; -Marketing through short agri-food chains; -Claims for access to public institutional purchase policies through cooperatives; -Operation, policy and commercialization by cooperative organization; - Advocacy for Agrarian Reform.

Tab.1. Summary of practices of family farmers related to FEW Nexus

From the practices described in the literature, it is noted that family farming performs differently from capitalist farming. By interacting daily with natural assets, such as water, energy and food, family farmers modify and adapt to the various transformations of nature, such as climate change. That is, there is a form of synergy in the relationship between natural goods and human beings. In addition, the practice of struggle and mobilization of farmers, and rural families as a whole, are fundamental for the construction of a new ontology of management and perception, of the elements of the FEW Nexus.

In this reasoning, family farming manages its activities through cooperative management. Unlike the bureaucratic structure, cooperative-based management values the collective, solidary objectives and horizontal decision-making (Barros & Oliveira, 2019). This form of organization it is fundamental for family farmers, as well, for the transition to sustainability, operational viability of their commercial activities, and strategic production planning. However, family agricultural cooperativism can only be structured, especially in the Brazilian context, thanks to the public policies that enable investments, generate stable income, promote energy sustainability and the preservation of natural resources (Soares & Silva, 2022a).

Based on these arguments, Figure 1 was constructed seeking to establish a social FEW Nexus based on the practices of family farmers.

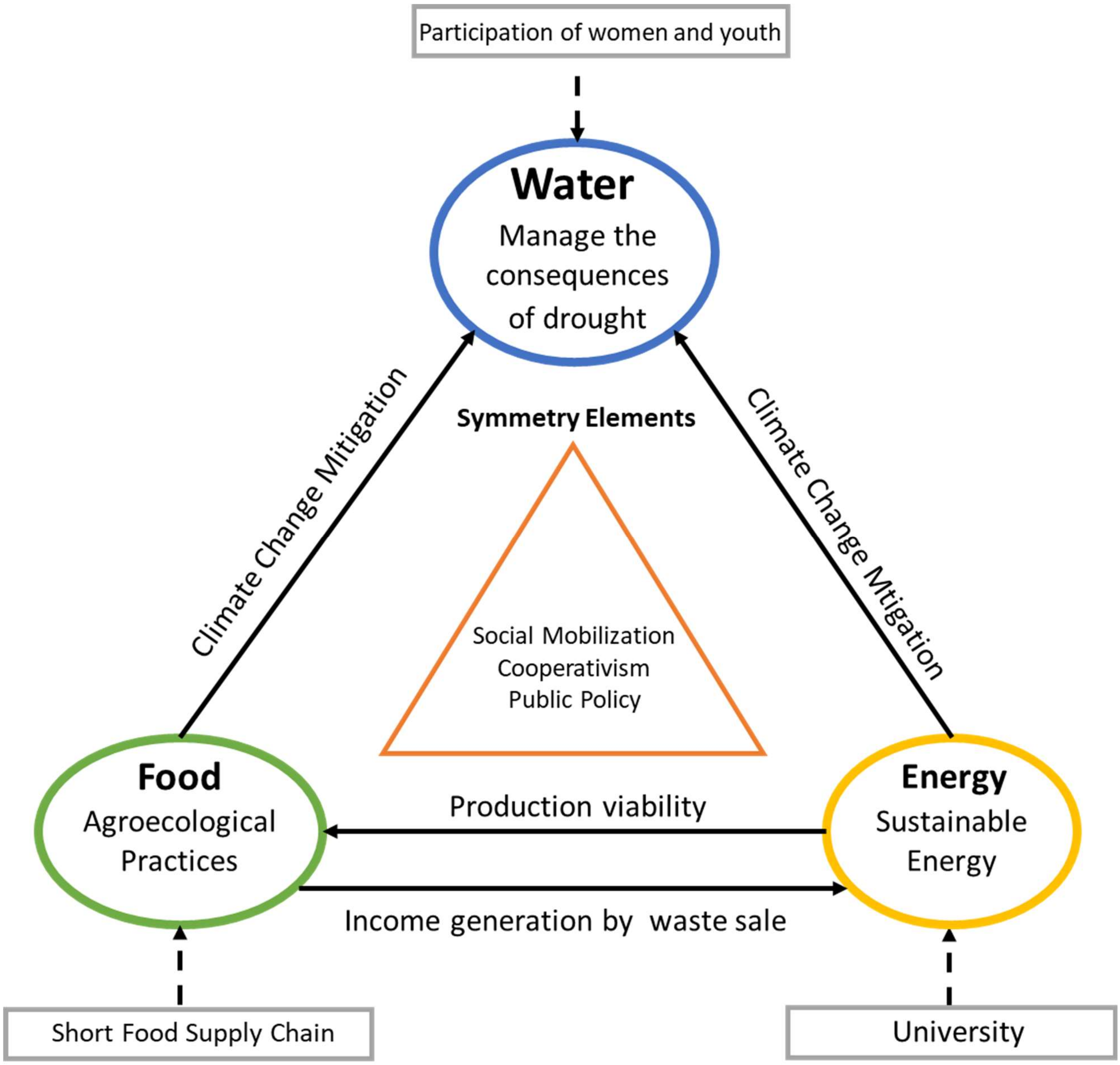

Fig. 1. Social FEW Nexus based on the practices of family farmers

As previously described, the symmetry elements of the FEW Nexus are: social movement, cooperativism and public policies. They are elements of symmetry because are essential for existence family farming practices and their interaction with water, energy, and food. The central element is water which must gain prominence, since it is a resource that cannot be produced by human beings. Thus, the focus should be practices combating drought, actions that affected directly by climate change.

Moreover, as seen in Figure 1, practices in the food element (represented by "Agroecological Practices") and in the energy element (represented by "Sustainable Energy) contribute to the mitigation of climate change, consequently, for managing the consequences of drought. In addition, I add influencing points in each of the elements as a relational factor for the materialization of the central practice of each of the elements, in other words, to enact it. In the case of the water resource, the influencing point is the participation of women and young people – essential actors for building resilient structures and efficient use of water resources (Piedra-Munoz et al., 2018).

The energy element is centered on sustainable energy, essentially represented by photovoltaic energy – primarily responsible for enabling sustainable production in remote areas (Soares & Silva, 2022a). As influencing point are universities, the actor responsible for research, development and the sustainable viability of renewable energy projects that started for family farming practices (Campos & Alcantara, 2018; Lopes, Lourenzani, Santos & Santos 2020; Soares & Silva, 2022b).

Finally, agroecological practices are a central element for a new perspective on food management. Through pest control, reforestation, preservation of native seeds, among other actions, agroecology is a fundamental philosophy for a change of perception in food production. Moreover, with management based on agroecology, the producer can take advantage of his waste to generate income through energy (biomass and biogas, for example) (Santana, 2021). Concomitantly to this, the influential point for the materialization of agroecological practices is the operation and commercialization of products through short agrifood chains.

5.Conclusion

The main objective of this theoretical article was to discuss how the social practices of family farmers can contribute to a new construction of the FEW Nexus from the perspective of the Actor-Network Theory (ANT). To achieve this objective, a literature review was carried out. Firstly, there were presented concepts involving family farming, FEW Nexus approach and the Actor-Network Theory (ANT). Subsequently, because of the discussion of family farming practices, a social FEW Nexus was developed and proposed with ANT as a theoretical lens.

Additionally, it should be noted that the study presents relevant theoretical and social contributions. The theoretical contribution lies in the fact that a development of FEW Nexus Social centralizes, as a fundamental aspect of the Nexus approach, an equitable relationship between human and non-human social actors. From a relational and non-overlapping reading, the FEW Nexus approach will be able to contribute more realistically to studies and future theories that aim to discuss sustainability and its various complexities in a deeper way. Moreover, through its construction based on the practices of family farmers, the FEW Nexus Social demonstrates the relevance of family farming for the discussion of natural resource management. In this sense, the result of this study is also a theoretical contribution to future research related to the organizational management of Nexus elements.

On the other hand, the social contribution lies in the fact of highlighting the importance of public policies for family farming, consequently, for the sustainability and mitigation of climate change. Moreover, the study can influence the development of actions and policies that integrate the three elements of the Nexus in their conception. From this integration, States and organizations will be able to outline more concrete plans and goals about the SDGs.

The limitations of this essay are that only certain number of search keywords and a database to research family farming practices were adopted. In addition, the family farming practices described in this work did not consider the possible cultural differences that exist in different regions of Brazil and the world. In this line, it is considered that climate change affects each region in different ways, mainly in continental countries such as Brazil. Thus, it is considered necessary to carry out a greater depth of these different impacts and reactions of family farmers themselves. With that, the sequence of the present proposal is precisely to evaluate this question empirically.

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Deep Learning-Enabled Temperature Simulation of a Greenhouse Tunnel

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Abstract

Agriculture is poised to suffer greatly from the effects of climate change. Prediction models, using deep learning, have been developed that can simulate and predict conditions in open field farming to combat the climate variability from climate change. However, deep learning used in precision agriculture, specifically greenhouse tunnels, is under-researched despite also being affected by this variability. Utilising tunnel data collected over 42 days, two hybrid deep learning models were designed. Specifically, a hybrid of convolutional neural network (CNN) and Long Short-Term Memory (LSTM), and a hybrid of CNN and Bidirectional LSTM (BLSTM). The models are designed to forecast the internal temperature of the tunnel to support its management. The cooling wet wall state, solar irradiance, inside and outside temperature of the tunnel are input variables to the developed deep-learning models. Two scenarios are discussed with the results, the first scenario includes all the external variables as input, while the second scenario only considers the internal temperature as input. Results show a performance improvement of 48% and 14% computation time for the CNN-LSTM compared to the CNN-BLSTM model for the two scenarios, respectively. In terms of the measured loss metrics, both models had varied performance and model fitness, with an average mean square error of 0.025 across the models and scenarios.

Keywords: Internet of Things, Deep Learning, Precision Agriculture, Climate Change, Thermal Modelling

1. Introduction

Due to climate change, farmers have adapted their growing practices to accommodate sudden changes in rainfall and temperature patterns that can directly affect their growing cycles. This change, however, has come at the expense of productivity and, potentially, yield (Malhi et al., 2021; Yang et al., 2022). At a global scale, any climate variability is a risk to food security (Fujimori et al., 2022). Although this variability is unique to each country, Africa as a continent is poised to suffer the most as crop irrigation is largely dependent on rainfall (Tadese et al., 2022). As the effects of climate change are generally focused on a global scale, Weber et al., 2018 presented the potential effects of climate change and global warming in an African context. Weber et al. showed that in the Western Cape (in South Africa), a 2°C increase in a global temperature average would lead to 9% fewer rainy days, 35 more hot nights (temperatures in the 90th percentile of minimum temperatures experienced at night), and nine more days considered to be heat waves per year. This combined with a variability in climate could be devastating for farmers.

To combat this variability, prediction algorithms using deep learning can be used. According to (Lecun et al., 2015), deep learning is a layered approach to machine learning, with each layer being a higher abstraction level with new features and information to be found. Extending this knowledge of deep learning, Emmert-Streib et al. (2020) then describes the ability of using deep learning algorithms for predictions and forecasting. For example, using Long Short-Term Memory (LSTM) for predictions uses this layered approach, with the output of the final layer being the predicted value. The main benefit of using an LSTM is the feedback connections to previous layers it creates which helps the algorithm remember important information within the applied data.

Although there are many applications for deep learning for prediction (Emmert-Streib et al., 2020), most are aimed at image or video processing. For agriculture, however, the use of deep learning has lagged behind. Zhao et al., 2021, however, derive a novel deep learning algorithm for temperature prediction specifically for agricultural purposes, specifically extreme weather forecasting for farmers. Their model, a combination of a Convolutional Neural Network (CNN), a Gated Recurrent Unit (GRU), and a Relative Position-based Self Attention Mechanism (RPASM), provided accurate results compared to their independent counterparts. They were able to predict 24-hours ahead to a mean absolute error (MAE) of 1.95°C.

Despite this being used in open field farming, precision agriculture cannot benefit from this advancement. Deep learning models specifically predicting conditions within greenhouses with minimal input data are under-researched. In this paper, a deep learning method for temperature simulations in a greenhouse tunnel is proposed to address the variability of external conditions to African greenhouses and understand how this affects conditions inside these greenhouses.

1.1 Related Works

Climate forecasting techniques can assist farmers in preparing their crop for specific seasonal conditions. However, due to climate change causing variability in these conditions, forecasting techniques trained on historical data are leading to inaccurate models. Han et al., 2019 developed a tool that aims to avoid these inaccuracies by combining historical data with probabilistic models to not only predict the climate, but also the probability of its variability. This tool was developed specifically for Uruguay but can easily be adapted for any climate. Machine learning models, mainly regressor models, were investigated by Nyasulu et al., 2022 to determine the best model for different climate (minimum and maximum temperature, relative humidity, and rainfall) predictions. They used an ensemble learning algorithm that trained and tested multiple models sequentially to determine the model best for each climatic parameter. The CatBoost Regressor, Gradient Boosting Regressor and Light Gradient Boosting machine learning algorithms were stacked and used to forecast the climatic parameters as a sliding window of one-time step ahead. Although useful, both previous examples (Han et al., 2019; Nyasulu et al., 2022) are particularly focused on external conditions. PA systems, as the one that is studied in this paper, can generally form part of protected agriculture where the crop is covered by plastic tunnels (Shi et al., 2019).

For this paper, related work focussing on greenhouse tunnel temperature forecasting or simulation are more valuable as a baseline. Petrakis et al., 2022 developed a neural network model for temperature forecasting in a greenhouse, in particular a multilayer perceptron neural network (MLP-NN). Their input feature selection included wind speed, outside temperature, solar irradiance, outside relative humidity, inside relative humidity (at different previous timesteps), and inside temperature (at different previous timesteps). For their temperature prediction, they achieved a mean absolute error (MAE), root mean squared error (RMSE), and R^2 of 0.218°C, 0.271°C, and 0.999 respectively. Although the results appear accurate, each simulation iteration did not use previous predicted results, but measured previous results, thereby aligning the model with the measured results after each timestep. Codeluppi et al., 2020 used artificial neural networks (ANN) in a similar manner to Petrakis et al., however, the model is executed on an edge device in the greenhouse in real-time. Further, instead of arranging their dataset as a time series, the authors use only the model for prediction which eliminates errors that can occur if data is corrupted or missing. Along with their ability to predict other input features, the authors can predict and forecast any temperature in time. Their results are more indicative of a true forecasting model with an RMSE, MAPE, and R^2 of 1.50°C, 4.91%, and 0.965 respectively. The study in this paper hopes to fill the gap of temperature forecasting methodologies in a South African context and extend the use of deep learning in agriculture for improved temperature simulations in a greenhouse tunnel.

2. Method

2.1 Experimental Setup

This study occurred in a closed tunnel at the Welgevallen Experimental Farm (Stellenbosch University, South Africa) and data was captured between 18 November and 30 December 2022 (42 days). The tunnel is dome-shaped and is 28 meters in length, 9 meters in width, and 3 meters in height.

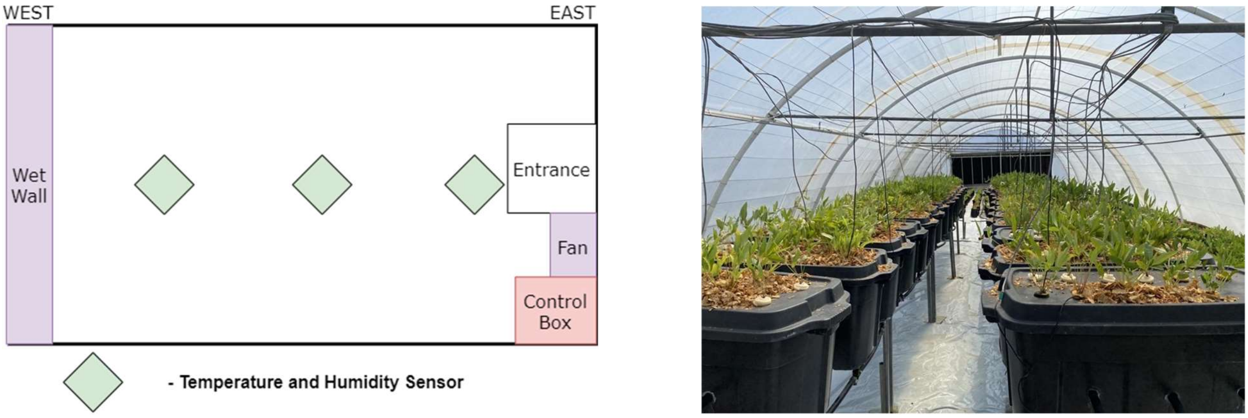


Fig. 1 A system diagram of the tunnel and the actual tunnel. A.) Sensors are placed equidistant apart beginning at the entrance of the tunnel; B) Containers occupy the first

Three Sensors were placed twelve meters apart, starting from the entrance of the tunnel to the wet wall on the opposite end. The fan occupies approximately one-third of the wall space next to the entrance of the tunnel and a control box housing the electronics is next to the distribution board (DB) (Fig. 1A). The system is designed to capture sensor data in three sections of the 28-meter-long tunnel: the front, the middle, and the back (Fig. 1B). The DHT22 temperature and humidity sensor was chosen for its low-power capabilities and low price and is compatible with most microcontrollers. It has the added benefit of simultaneous temperature (-40°C to 80°C) and humidity (0% to 100%) sensing. The sensor's accuracy is 0.5°C for temperature and 2 to 5% for humidity, which was acceptable for the purposes of the study. A Raspberry Pi Model 3B was chosen for sensor data aggregation, internet connectivity, CSV (Comma Separated Value) file formulation, and multiple General Purpose Input Output (GPIO) pins for future expansions and interfacing with control mechanisms. Each sensor captured humidity and temperature reading every minute for five minutes. After five minutes, an average was calculated for each parameter and stored in a CSV file on the Raspberry Pi. Further, the middle sensor was chosen for fan and wet wall control, as the front and back sensors were biased by both apparatuses respectively. Ten readings were made every minute and the median of those readings was chosen to control the fan and wet wall. Along with the environmental readings, the time that the reading was recorded, and a binary value (0 or 1) was stored representing whether the fan and wet wall were turned on during that period. At the end of each day, the CSV file was uploaded to Dropbox™ (Dropbox Inc., 2023) for remote access to the day's data. Furthermore, each sensor's temperature and humidity and the fan and wet wall's state were broadcasted to a Telegram™ (Telegram FZ LLC. & Telegram Messenger Inc., n.d.) channel for real-time monitoring.

2.2 Deep Learning Modelling

The deep learning algorithms used for the forecasting of the internal temperature of the tunnel are described in this subsection. Each of the deep learning algorithms are first explained, followed by the developed hybrid model for the tunnel temperature forecasting.

2.3.1 Convolutional Neural Network (CNN)

Data feature extraction is a preliminary step that ensures the reduction of the parameters needed for forecasting, this reduces the network computation and orchestrates the prediction accuracy. Convolutional Neural Network (CNN) is mostly skilful at extracting complex features in a dataset while storing varied irregular trends. CNN has hidden layers consisting of a pooling layer, a convolutional layer, and an activation function. The convolutional layer is the first input layer that converts the input data into features map to be sampled by the pooling layer in a bid to further reduce its dimensionality.

Given an input vector $x_1{}^m = \{x_1, x_2, \ldots, x_n\}$, , where $x^m, m \in M$ is the input vectors, including the solar irradiance, outside and inside temperatures, and the wet wall state (fan off or on). n is the normalised half-hourly unit per window of observation. Feeding these input variables into the first convolutional layer of the CNN framework will result in the output expressed in (*1*).

$$y_{ij}{}^{m(k)} = \sigma(b_j{}^{m(k)} + \sum_{m=1}^{M} w_{m,j}{}^{m(k)} \; x^0{}_{i+m-1,j}) \qquad (1)$$

Where σ is the activation function, $b_j{}^{m(k)}$ is the bias for the j^{th} feature map and k^{th} convolutional layer, w is the weight of the kernel for the CNN framework. This output is fed into the next layer of the CNN, the pooling layer to downsample the activation from the feature maps, thereby reducing the parameters and the computation costs. The output of this layer is expressed in (*2*).

$$P_{ij}{}^{m(k)} = \max_{r \in R} y^{k-1}{}_{i \times T + rj} \qquad (2)$$

Where T is the stride to decide input data length. The output $P_{ij}{}^{m(k)}$ is fed to the input of the next deep learning architecture in the hybrid model.

2.3.2 Long Short Term Memory (LSTM)

LSTM was proposed by Hochreiter and Schmidhuber, 1997 to address the vanishing gradient of recurrent neural networks (RNN) to preserve long-term dependencies. LSTM is skilful in learning temporal dependencies in a sequence of information. Utilisation of memory cells and gates like the input, forget and output gates in LSTM addresses the RNN vanishing gradient challenge. In LSTM, the input gate preserves the input data, forget gate determines the unused data, memory cells store the processing states, and the output gate delivers the LSTM operation output. This process is expressed in the following equations.

$$i_t = \sigma(W_i, [h_{t-1,} x_t] + b_i \qquad (3)$$
$$f_t = \sigma(W_f, [h_{t-1,} x_t] + b_f \qquad (4)$$
$$o_t = \sigma(W_o, [h_{t-1,} x_t] + b_o \qquad (5)$$
$$\bar{C}_t = tanh(W_c, [h_{t-1,} x_t] + b_c \qquad (6)$$
$$C_t = f_t \times C_{t-1} + i_t \times \bar{C}_t \qquad (7)$$
$$h_t = o + t \times tanh(C_t) \qquad (8)$$

In the equations, i_t, f_t , and o_t represent the input, forget and output gates respectively, while W_i , W_f , W_o are their respective weights. W_c is the weight for the memory cell. The bias of each gates are b_i , b_f , b_o , b_c . Other variables are, x_t , the input vector at time t ; h_t , the hidden state; $\bar{C}_t$, C_{t-1} , and C_t , the candidate memory, previous cell state and new cell state, respectively.

2.3.3 Bidirectional Long Short Term Memory (BLSTM)

Utilisation of the cells and gates in the LSTM enables it to address the vanishing gradient of RNN. However, LSTM only considers the previous state of information and losses the next state information. To address this challenge, BLSTM combines information in both forward and backward directions. Architecture of BLSTM is similar to LSTM gates and cells represented in (3) through (5), but in both directions. The hidden state, cell state and the output of the BLSTM concatenate for both direction are expressed in (9), (10) and (11), respectively.

$$c_t = f_t . c_{t-1} + i_t . \sigma(W_i, [h_{t-1,} x_t] + b_i \qquad (9)$$
$$h_t = o_t . \sigma(c_t) \qquad (10)$$
$$\bar{y} = \sigma(W_y h_{t,} + b_y) \qquad (11)$$

2.3.4 The Architecture of the Hybrid Models

In forecasting the internal temperature of the tunnel to support its management, two hybrid learning models are developed, comprising of a CNN-LSTM architecture and a CNN-BLSTM architecture. The CNN-LSTM and CNN-BLSTM models are presented in Table 1 and Table 2, respectively. The output of the CNN layer is fed into the input of the LSTM and/or the BLSTM input gates. The CNN extracts important features from the dataset and the LSTM and BLSTM layers are for information analysis and sequence predictions.

The hyperparameter values, detailing the number of neurons, parameters and the layers for the models are derived following an extensive experimentation of varied values to achieve the optimal performance for our requirements.

Table 1 CNN-LSTM and its definition

No	Layer Type	Neurons	Param
1	Input	8	8
2	Convolution1D	64	1 600
3	Convolution1D	64	12 352
4	MaxPooling1D	64	0
5	Time Distributed (Dense)	64	0
6	LSTM	100	66 000
7	Dense	100	10 100
8	Dense	7	707

Table 2 CNN-Bidirectional LSTM and its definition

No	*Layer Type*	*Neurons*	*Param*
1	*Input*	*8*	*8*
2	*Convolution1D*	*64*	*1 600*
3	*Convolution1D*	*64*	*12 352*
4	*MaxPooling1D*	*64*	*0*
5	*Bidirectional*	*128*	*66 048*
6	*Dense*	*100*	*12 900*
7	*Dense*	*7*	*707*

2.3.5 Evaluation Metrics

To evaluate the deep learning models for the internal temperature of tunnel forecasting, several error metrics are utilised. Such as, mean squared error (MSE), root mean squared error (RMSE), mean absolute error (MAE) and the computation time, which includes the training and testing time of each model. The MSE, expressed in (12), represents the mean of the squares of the difference of the predicted and the actual values.

$$MSE = 1/n \sum_{1}^{n} (y - \bar{y})^2 \qquad (12)$$

where y is the observed value over the number of n observed dataset, and $\bar{y}$ is the predicted output. Similarly, the RMSE, the root mean square error and MAE, the measure of the absolute difference of the actual and predicted values, are expressed in (13) and (14), respectively.

$$RMSE = \sqrt{1/n \sum_{1}^{n} (y - \bar{y})^2} \qquad (13)$$

$$MAE = 1/n \sum_{1}^{n} |y - \bar{y}| \qquad (14)$$

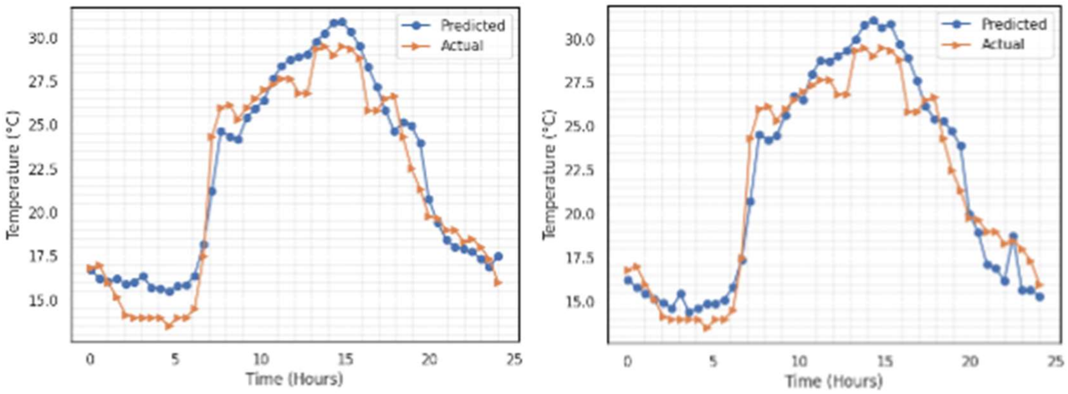
3 Results

3.1 Simulation environment

All computations were developed on Google Colaboratory (https://colab.research.google.com) using an Apple M1 Pro Laptop with 32GB Memory. After extensive experiments, and in addition to the hyperparameter values in Tables 1 and 2, the system optimisation parameters selected were a learning rate of 0.01, 80 epoch, 160 batch-size, 0.33 validation split, and a ReLU activation function.

3.2 Model Comparison

To evaluate the two models, two scenarios were created. The first scenario integrated all the input variables, the solar irradiance, internal temperature, outside temperature and the fan and wet wall state. The second scenario only uses the internal temperature as an input. This scenario is specifically relevant when all contributing factors to a particular data of interest are not available. Fig. 3 illustrates the output from the CNN-BLSTM model for the two scenarios.



A) B)

Fig.3 The 24-hour actual vs. predicted internal temperature output. A) CNN-BLSTM utilising all the input variables; B) CNN-BLSTM utilising only the internal temperature variable.

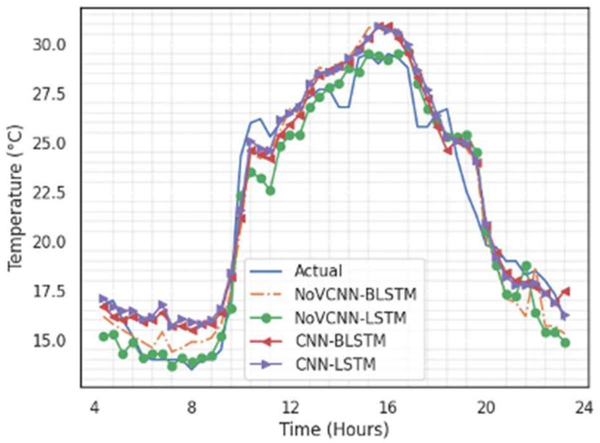


Fig.4 The 24-hour actual vs. predicted internal temperature output for the two hybrid models for the two scenarios. CNN-BLSTM and CNN-LSTM are the two models with all external variables.

NoVCNN-BLSTM and NoVCNN-LSTM are the models with only the internal temperature as input.

Surprisingly, in the 0:00am and 6:00am period, the model with the internal temperature achieves a greater predicted accuracy, while between 6:00am and 23:59pm the case with all the external variables achieves better accuracy. Fig. 4 illustrates the predicted and actual summary of the two models and the two scenarios models. This result illustrates that the predicted values for all models are very narrow with a good fitting.

3.3 Model Evaluation Metrics

An example representation of the training and validation loss function of the tunnel data is shown in Fig. 5. This is illustrated for the MSE and RMSE of the CNN-LSTM model for the second scenario. To verify the effectiveness of the deep learning models. a comparative summary of the MSE, RMSE and MAE for the two models under the two scenarios are shown in Fig. 6.

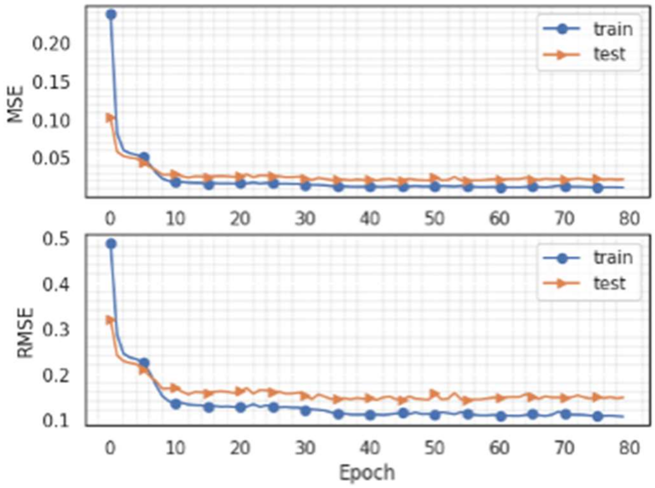


Fig.5 The training and validation loss during training for the CNN-LSTM model utilising the internal temperature as an input.

Interestingly, the performance of the models for the two scenarios varies. For MSE, the CNN-LSTM utilising all the external variables achieves the lowest MSE but a high MAE. While the CNN-LSTM model for the second scenario archives the lowest RMSE and MAE.

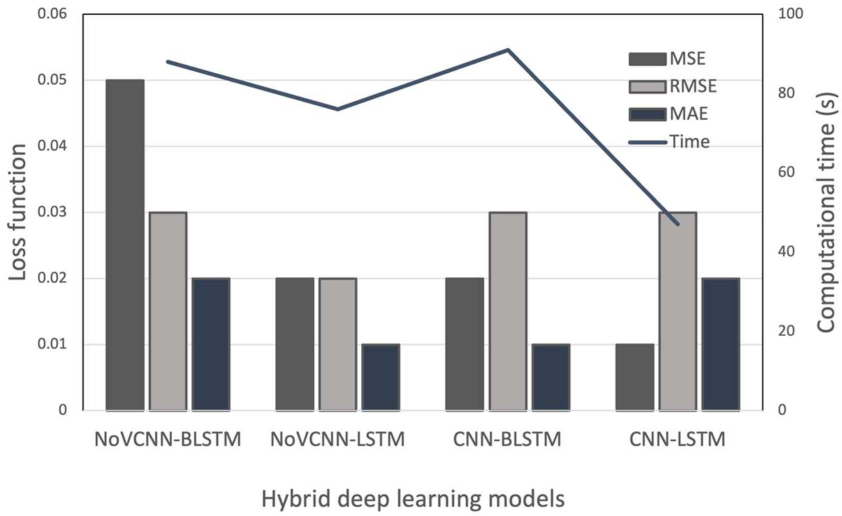


Fig.6 The performance comparison of the evaluation metrics for the two hybrid models. The left axis is the 'Column' Loss function, while the right axis is the 'Line' Computation time (s).

Comparing the computation time for the case of all the external variables, as expected the CNN-LSTM model has lower computation time compared to the CNN-BLSTM model. This is also similar for the second scenario. Specifically, the CNN-LSTM achieves a 48.0% performance increase to CNN-BLSTM for the first scenario and a 13.6% for the second scenario. The computation performance is particularly of interest in memory constrained IoT devices in tunnel modelling.

4 Conclusion

This work developed two hybrid deep learning models, a CNN-LSTM and a CNN-BLSTM to forecast the internal temperature of a greenhouse tunnel utilising the tunnel data collected over 42 days, The effectiveness of the models were analysed based on error metrics, MSE, RMSE and MAE, as well as their computation time. Results show performance improvement of 48% and 13.6% computation time for the CNN-LSTM compared to the CNN-BLSTM model for the two scenarios created, respectively. Also, an average mean square error of 0.025 was observed across the models and scenarios. Through this research, two deep learning algorithms have been developed that will directly benefit precision agriculture in an effort to combat climate variability. This will allow better understanding of the effects of external conditions on internal variables in a greenhouse tunnel and will allow for better decision making in crop production in the future.

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Dimensions to Evaluate Circular Economy Maturity in SMEs

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Abstract

Small and Medium-Sized Enterprises (SMEs) are making strenuous efforts to implement a Circular Economy (CE). However, some challenges keep these businesses from switching from a 'take-make-dispose' linear economy to a closed loop with zero waste. In this strand, one such complex issue is related to the companies' requirements to understand the level of circularity in their processes. Maturity models are used to address complex scenarios and applied in different fields. Nevertheless, there is a lack of models or frameworks that support the CE maturity level. Thus, the primary purpose of this research is to identify the dimensions to measure CE maturity in SMEs. Characterized as exploratory network analysis, scientific contributions were retrieved from Scopus database, totaling in 355 papers without period restrictions. Data was analyzed by network analysis software CiteSpace. The overall contribution of the research is to promote efforts to develop studies related to CE maturity in SMEs, which can be managed in an integrated manner and engaged in ways that allow companies to reach higher levels of circularity.

Keywords: Sustainability. Maturity Models. Bibliometric Analysis.

Introduction

SMEs have been challenged to rationalize ways of promoting new products at competitive prices while ensuring higher quality levels in a sustainable way. A CE is a global switch from a "take-make-dispose" linear economy to a circular one that seeks to eliminate waste and extend resources. Transitioning SMEs towards CE is crucial to using and reusing natural capital efficiently, adding value throughout the life cycle of finished products, improving both developed and developing countries economies and reducing negative environmental contributions. However, barriers can be identified across the implementation and utilization of CE in SMEs as the users do not use a well-established framework to measure the level of maturity of CE practices, methods, and tools.

The CE concept is gaining awareness among government, society, businesses, and academia. Following the traditional Supply Chain to increase the efficiency of the business supply chain and maximize economic benefits, the fundamentals of the CE (STAHEL, 2016) were structured from Closed-Loop Supply Chain Management (CLSCM) fields. CLSCM also yearned for economic maximization, reducing energy consumption and emissions to balance economic benefits, social effects, and environmental impacts (KUMAR and SATHEESH KUMAR, 2013; MORSELETTO, 2020; BANDEIRA et al., 2023). Similarly, CE provides effective resource management and strengthens the supply chain to optimize its use and reduce greenhouse gas emissions and waste generation (POMPONI and MONCASTER, 2017). Subsequently, the Ellen Macarthur Foundation (2013) emerge to redefine the current industrial model, which values extractive collection and waste, aiming to reshape growth with a focus on positive benefits for the entire society. The CE gradually decouples economic activities from consuming finite resources and eliminating waste from the whole system. CE is typically represented by nine loops of recovery (URBINATI et al., 2017), also called the R9: (R0) refuse, (R1) reduce, (R2) reuse, (R3) repair, (R4) refurbish, (R5) remanufacture, (R6) repurpose, (R7) recycle, (R8) recover and (R9) re-mine.

The importance of SMEs for countries' economies is widely known, and the management theory and principles were adapted to address the specificness of SMEs and their environment (D'AMBOISE and MULDOWNEY, 1988). Among the OECD countries, SMEs represent between 70% and 95% of all existing companies (OECD, 2017). Beyond providing economic prosperity, SMEs contribute expressively to countries' Gross domestic product (GDP), employment generation, and distribution (PRABAWANI, 2013), both in developed and developing economies. However, SMEs are facing problems related to resources that harm business sustainability. In the field of SMEs, sustainability is already addressed by numerous studies. Some researchers identified that the desired environmental protection that SMEs can provide depends on external (context) and internal (within SME) drivers to pursue sustainable practices or internal and external factors affecting sustainable value (PRABAWANI, 2013). It is already proved that SMEs could achieve positive financial results through sustainability-related factors like corporate social responsibility, innovation, and training (BURLEA-SCHIOPOIU and MIHAI, 2019).

In many countries, from developed to undeveloped economies, SMEs companies play a crucial role with numerous contributions to GDP. Even though both themes were developed in the literature, the interrelations between CE and SMEs remain a development field. CE literature has grown and has been established as a prominent research field in recent decades (FERASSO et al., 2020; PRIETO-SANDOVAL et al., 2018). However, few researchers in the field focus on developing CE Maturity Models (MM) or other tools in SMEs, which results in entrepreneurs being unable to validate or assess their current CE maturity and benchmark it with others. As such wise, this research intends to fulfill this necessity by identifying the dimensions to measure the CE level of maturity in SMEs. Based on the presented concepts, the main research question emerges: "What are the dimensions to assess the current level of CE maturity in SMEs?". The rest of the paper is structured as follows. The next section describes the methodological procedures for the network analysis of metadata. Section 3 presents the results and dimensions, while the paper ends with a concluding remarks section and cited references.

Methods

The approach adopted in this research is an exploratory network analysis in CE and the relations with SMEs and MM. Data collection was conducted in December 2022 on Scopus scientific database. Considering all fields of study, the searching procedures were limited to articles written in English and searching in the papers' titles, abstract, and keywords. In this exploratory strand, we used as Boolean search keywords "Circular economy" AND "SME*" (to include SMEs) AND "Maturity Model" Then, the searching parameters were: "TITLE-ABS-KEY ("Circular economy" AND "SME*" AND "Maturity Models") AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English"))". This search resulted in 355 documents, without any period restrictions. The metadata from all 355 documents was stored in *.RIS and *.CSV files for further analysis.

The data analysis was conducted in the second strand of the research. We followed the network bibliometric approach Ferasso et al. (2020) and Bandeira et al. (2022) used. To explore the structure of scientific knowledge in the field, a co-citation network was built using the software CiteSpace 5.8.R1 version (CHEN and SONG, 2019). A network of citations can identify key references, the strongest linkages, clusters of references, and the shape of each cluster.

The *.RIS file served as an input file in CiteSpace for data conversion. The software recognized 13,851 references from the 355 papers in the sample. From these, 13,851 were successfully converted at an acceptable rate of 96.0%, considering the loss range between 1%~5% from the original *.RIS file. The converted data was scanned using the frame period from December 1970 to December 2022, text processing: title, abstract, author keyword; node types: references; links: Cosine; scope: within slices; g-index, scale factor k = 25; top N levels of most cited references in each slice = 50 (top N% = 10.0%); no pruning procedures; visualization: cluster view static + merged network. The re-run procedure revealed empty spaces, and the range period changed automatically from 2012-2022.

Results

The selected 355 papers allowed the identification of commonly addressed bibliometrics information. The citation metrics (shown in Fig. 1) showed that publications increased after 2019. 225 of the analyzed papers (70.70%) were published in the last five years and 187 (52.67%) over the previous three years (2020-2022). These results indicate that this thematic is gaining momentum among scholars in the field. Seeking to understand all papers' impact, the number of citations per cited publication was calculated for each year. In the sampled documents, 297 (83.66%) received citations. The citations per cited publication indicated substantial growth in 2019 and 2020. Moreover, 1982 citations were noticed in 2022, among which Fatimah et al. (2020) and Priyono et al. (2020) received a remarkable performance, respectively, 166 and 144.

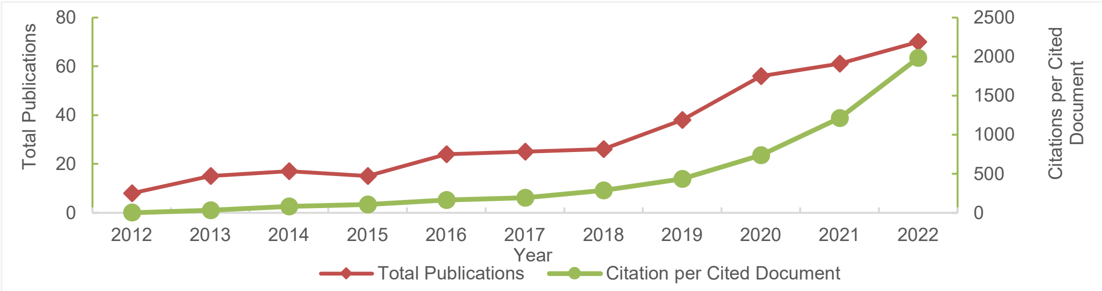

Fig. 1. Distribution of total publications and citation per cited publication. Source: Scopus.

A worldwide analysis of the sampled papers shows that 37 countries received publications centered in Italy, the United Kingdom, China, Spain, the USA, and others. Despite the substantial diversity, which includes Asia, Europe, and American scholars, there is a lack of academic efforts in prominent regions such as Africa (e.g., Ghana) and Latin America (e.g., Uruguay and Bolivia). The highlighted collaboration efforts across countries show a frequent collaboration between the Czech Republic and Slovakia, Brazil and the United Kingdom, Italy and France, the USA and Germany, and Spain and Portugal. This cooperation demonstrates a global interest in collaboratively promoting CE and MM for SMEs.

A network analysis was also performed, including co-occurrence and co-citation, which is crucial for understanding complex systems and relationships by uncovering hidden patterns and connections. Co-occurrence analysis identifies patterns of association between entities, while co-citation analysis focuses on relationships between sources. These analyses provide valuable insights into the intellectual structure of a domain, the evolution of knowledge, and relationships within complex datasets, leading to unfolding key aspects for developing a framework. First, a co-citation network analysis was developed to identify the theoretical roots and key influential papers frequently cited by CE, SMEs, and MM studies. As seen in Fig. 2, the co-citation network was built using CiteSpace software version 6.1R6. The network included 5,727 nodes and 7,892 links from 4,199 distinct references from the sample.

Strong references are identified based on their number of total citations and the linked references in the network. The nodes also represent the main cited documents, in which the links are formed based on the nodes' centrality. Thus, centrality measures the ability of the connections between nodes in the sample (CHEN and SONG, 2019).

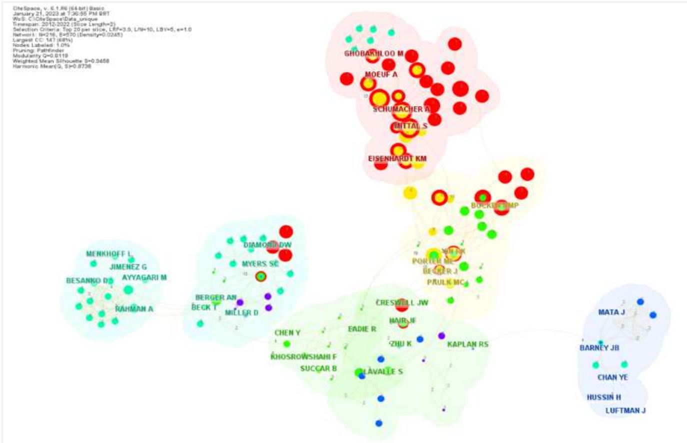

Fig. 2. Co-citation network in CE, SMEs, and MM research field.

In this research, Mittal et al. (2018) is the most cited article in the network. This paper critically reviews current Smart Manufacturing (SM) and Industry 4.0 maturity models following SMEs' specific requirements. The second influential paper is by Yin and Fai (2014). The study mainly focuses on the methodological approach to evaluating study cases in SMEs. The third most cited paper is from Ghobakhloo et al. (2011), the study analyzed internal and external issues affecting the IT adoption process in SMEs proposing a framework involving the main stakeholders, such as managers, vendors, consultants, and government, to build a successful model.

A co-occurrence network was elaborated to reveal the significant thematic clusters in the CE, SMEs, and MM domains based on the titles, abstracts, and keywords of the sampled publication. The term co-occurrence network identified three main themes. (1) The most prominent theme has 53 terms that are related to MM and the process to implement, assess and integrate them into organizations, (2) the second substantial theme has 49 terms mainly related to the effects and impact generated after companies apply MM. The last (3) theme has 16 terms related to the methodological and operational process of MM creation and design. Fig. 3. displays the term co-occurrence network created using VOSViewer software.

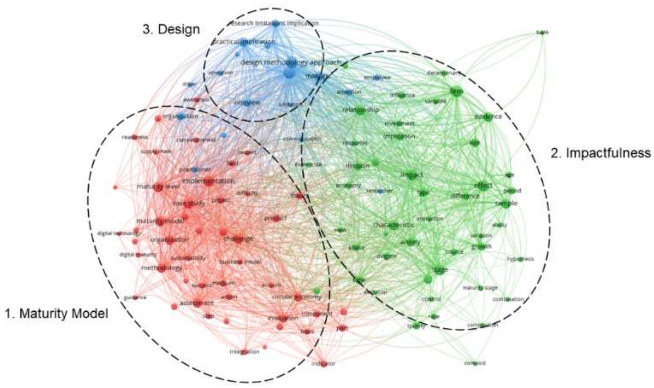

Fig. 3. Term co-occurrence network based on CE, SMEs, and MM studies.

The evolution of terms in the co-occurrence network is illustrated in Fig. 4. The terms Circular Economy, Digital Technology, Readiness, Assessment, Digital Maturity, Driver, Operations, Supply Chain, Product, Maturity Level, Sustainability, and Challenge has been subject to intense scrutiny by researchers in recent studies.

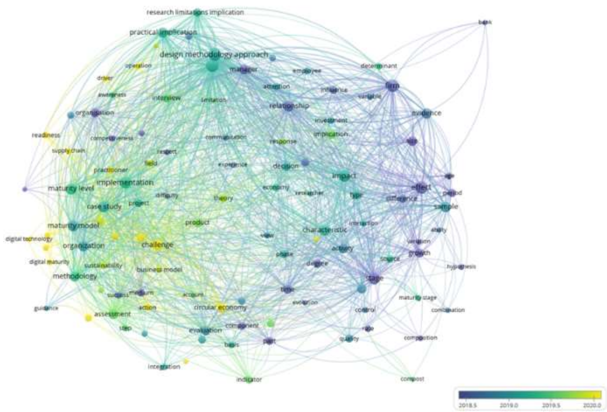

Fig. 4. The evolution of terms in the co-occurrence network.

After an in-depth analysis, the authors applied the exclusion criteria of selecting only papers related to CE, SMEs and MM based on sampled titles, abstracts, and keywords. Also, specific domain papers were removed since many articles were focused on engineering and computer science. For the criterion of specific domain papers, every title, abstract, and article's keywords were analyzed according to the aim and question of this research. As a result, 39 were selected as the foundation for creating the dimensions proposed by this research, as shown in Table 1.

Table 1 - Results of the SLR on ***CE, SMEs, and Maturity Models***, organized by authors.

Authors	Year	Title
Oliveira and Kaminski	2012	A reference model to determine the degree of maturity in the product development process of industrial SMEs
Ormazabal *et al.*	2016	An overview of the circular economy among SMEs in the Basque country: A multiple case study
Garzoni *et al.*	2020	Fostering digital transformation of SMEs: a four levels approach
Okreglicka *et al.*	2015	Business Process Maturity in Small and Medium-Sized Enterprises
Ganzarain and Errasti	2016	Three stage maturity model in SMEs toward industry 4.0
Moya *et al.*	2019	A new framework to support Lean Six Sigma deployment in SMEs
Diana *et al.*	2017	Putting environmental technologies into the mainstream: Adoption of environmental technologies by medium-sized manufacturing firms in Brazil
Sehnem *et al.*	2019	Circular business models: level of maturity
Ferreira *et al.*	2019	A Proposed Index of the Implementation and Maturity of Circular Economy Practices - The Case of the Pulp and Paper Industries of Portugal and Spain
Parra *et al.*	2019	Maturity model for the information-driven SME
Flynn	2018	Investigating the implementation of SME-friendly policy in public procurement
Adeniyi *et al.*	2019	Developing maturity levels for flood resilience of businesses using built environment flood resilience capability areas
Prashar	2017	Energy efficiency maturity (EEM) assessment framework for energy-intensive SMEs: Proposal and evaluation
Sardi *et al.*	2020	Evolutionary paths of performance measurement and management system: the longitudinal case study of a leading SME
Teixeira *et al.*	2015	Prioritizing quality problems in SMEs: A methodology
Pirola *et al.*	2020	Digital readiness assessment of Italian SMEs: a case-study research
Lizarralde *et al.*	2020	An Industry 4.0 maturity model for machine tool companies
North *et al.*	2020	Promoting digitally enabled growth in SMEs: a framework proposal
Kafel and Sikora	2014	The level of management maturity in the Polish food sector and its relation to financial performance
Bento and Tontini	2019	Maturity of lean practices in Brazilian manufacturing companies
Seidel-Sterzik *et al.*	2018	A Capability Maturity Model for Life Cycle Management at the Industry Sector Level
Brown *et al.*	2021	A tool for collaborative circular proposition design
Kaariainen *et al.*	2020	Applying the positioning phase of the digital transformation model in practice for SMEs: Toward systematic development of digitalization
Haezendonck and Van-den-Berghe	2020	Patterns of Circular Transition: What Is the Circular Economy Maturity of Belgian Ports?
Salo, Suikkanen and Nissinen	2020	Eco-innovation motivations and eco-design tool implementation in companies in the Nordic textile and information technology sectors
Yin and Fai	2014	Measuring knowledge management performance in industrial enterprises: An exploratory study based on an integrated model

Brendzel-Skowera	2021	Circular economy business models in the SME sector
Rauch *et al.*	2020	A Maturity Level-Based Assessment Tool to Enhance the Implementation of Industry 4.0 in Small and Medium-Sized Enterprises
Tontini *et al.*	2016	Maturity model of procurement and supply management in small and medium-sized enterprises: A benchmarking of hospitals and metal-mechanic companies
Depaoli and Scornavacca	2020	A model for digital development of SMEs: an interaction-based approach
Sehnem *et al.*	2020	Circular economy in the wine chain production: maturity
Sacco *et al.*	2021	Circular Economy at the Firm Level: A New Tool for Assessing Maturity and Circularity
Laureano *et al.*	2016	Maturity in management accounting: Exploratory study in Portuguese SME
Vásquez *et al.*	2021	A sustainability maturity model for micro
Vashishth *et al.*	2021	Integrated management systems maturity: Drivers and benefits in Indian SMEs
Fatima, Oksman and Lahdelma	2021	Enabling small medium enterprises (SMEs) to become leaders in energy efficiency using a continuous maturity matrix
Machado and Carvalho	2021	Maturity Models and Sustainable Indicators - A New Relationship
Kayikci et al.	2022	Assessing smart circular supply chain readiness and maturity level of small and medium-sized enterprises
Uhrenholt *et al.*	2022	Maturity Model as a Driver for Circular Economy Transformation

Source: The authors.

The analysis of the 39 selected articles uncovered that the research is focused on 5 journals containing 42% of the explored biography: Sustainability, Journal of Cleaner Production, Journal of Industrial Engineering and Management, Management Decision, and Journal of Manufacturing Technology Management. The remainder of the papers (58%) is distributed among 27 other journals. Also, a growing trend was observed in the journals after 2017, highlighting the subjects' importance in the presented field.

The selected articles from the SLR and works proposing MM, maturity levels, or assessment practices enable identifying the dimensions for evaluating CE maturity in SMEs. Five dimensions were selected to fulfill this research purpose (Table 2): (1) The "Take" dimension focuses on the current methods of resource extraction and utilization in SMEs' operations; (2) The "Make" dimension is related to the process of transforming resources into goods and services; (3) The "Distribute" dimension aims to analyze the methods of distribution and transportation within SMEs. The (4) "Use" dimension proposes evaluating products or services and their environmental impact. The last dimension being considered is the "Recover" dimension (5), allowing the verification of the waste management process, recovery methods, and reverse logistics systems.

Table 2 – Framework's Dimensions

Dimension	**Description**
Take	The dimension refers to how organizations extract and utilize resources and energy from the environment, focusing on efficiency and responsibility in using biological and technical resources by selecting suppliers and materials that align with environmental criteria.
Make	The dimension concerns transforming resources into goods and services, emphasizing sustainable methods, such as incorporating eco-innovations and advanced technologies.
Distribute	The dimension focuses on delivering a product or service to the customer, aiming to minimize environmental impact by ensuring efficiency and traceability of product distribution through optimizing transport routes, packaging, and implementing a sustainable logistics system.
Use	The dimension is centered on the consumption of goods and services by customers or other companies to minimize environmental impact by creating products and services that are powered by sustainable energy sources, promoting circular use of materials and resources, and offering services that extend the lifespan of products through repair, maintenance, and upgrades.
Recover	The dimension is focused on recovering and redirecting waste, materials, and energy from products at the end of their lifecycle, using eco-innovation processes, reverse logistics strategies and supply chain management. To minimize waste and promote the use of materials and resources, communication channels can be established with customers to retrieve and renew products, and materials can be recovered and recirculated from these products.

Source: The authors.

For each dimension, sub-dimensions were selected according to the literature that represents strategic items for SMEs. Table 3 was created to detail the purpose of each sub-dimension.

Table 3 – Framework's Sub-Dimensions

Dimension	Sub-Dimension	Purpose
Take	**Material Selection**	Evaluating the use of biodegradable or easily recirculated materials in various value chains to minimize resource usage and emissions.
	Source Selection	Analyzing the integration of sustainable suppliers and partners in the supply chain, promoting local sourcing without impacting economic performance.
	Inbound Logistics	Examining the implementation of circular principles, waste reduction, and sustainability in the inbound logistics process.
Make	**Circular Design**	Assessing the incorporation of circular design principles in product and service lines to enhance sustainability through environmental and social aspects.
	Energy Management	Assessing the effectiveness of energy-efficient processes and sustainable energy sources in reducing the environmental impact of production.
	Lean Practices	Evaluating the implementation of Lean practices and waste reduction in internal processes to optimize efficiency and cost savings.
Distribute	**Sustainable Logistics**	Examining the implementation of sustainable logistics practices, such as low-emission vehicles, efficient routes, and innovative packaging solutions to minimize the environmental impact of transportation and distribution.
	Outbound Logistics	Analyzing the implementation of sustainable outbound logistics practices to minimize the environmental impact of outbound logistics.
	Inventory Control	Evaluating the implementation of sustainable inventory control practices to minimize the environmental impact of inventory control.
Use	**Repair**	Analyzing the availability of repair and maintenance services to extend the life of products or services.
	Reuse	Examining the promotion of the reuse of products or services to extend the life of products or services.
	Carbon Offsetting	Assessing the implementation of carbon offsetting to minimize the environmental impact of products or services.
Recover	**Waste Management**	Evaluating the implementation of waste management to minimize waste and promote the use of materials and resources.
	Recycle	Measuring the effectiveness of recycling to recirculate materials and resources.
	Reverse Logistics	Examining the implementation of reverse logistics to recover products that are no longer in use or that customers want to return.

Source: The authors.

Conclusion

This research aimed to identify the dimensions that allow SMEs to assess their current and desired level of CE maturity. The SLR, based on 355 articles, indicated that the areas of CE, SMEs, and MM are gaining prominence in the academic, corporate, and government sectors. Significant efforts are being made toward creating new methodologies, cutting-edge designs, and structures influencing the entire value chain. Post-2018, the theoretical foundation saw an increase in the overall number of publications and the number of cited works. This trend was observed globally, as 37 countries joined forces to concentrate on studying these areas and advance groundbreaking research through key collaborations worldwide after conducting a comprehensive and in-depth analysis of 50 papers to identify dimensions, sub-dimensions, maturity levels, objective evidence, and assessment mechanisms. Key five dimensions were carefully chosen: (1) Take, (2) Make, (3) Distribute, (4) Use, and (5) Recover. These dimensions provide a clear roadmap for organizations to achieve a higher level of CE maturity.

The significance of the study can be comprehended through theoretical and practical highlights. Due to this study from an academic perspective, five key dimensions and fifteen sub-dimensions emerged, allowing assessing CE maturity. All dimensions promoted a simplified view of the pillars of word-class practices referring to CE and enabled the development of a framework for evaluating CE maturity based on the specific needs of this type of organization. From a practical perspective, this study has contributed to the support sought by SMEs to improve their CE from five structured dimensions. These firms play a critical role in driving economic growth and innovation. However, in a rapidly changing and increasingly competitive market, SMEs face significant challenges transitioning from a linear economy to a circular one.

This research also has limitations inherent in the methods used. Regarding the SLR, the chosen keywords and the selected database moderately restrict the results found. The inclusion or parallel comparisons with other scientific databases may lead to different results, which could also be a suggestion for future bibliometrics studies. Also, an in-depth qualitative or mixed-method study is needed to identify better concepts, taxonomies, elements, and contexts where CE is studied in the context of MM and SMEs. By identifying and structuring five key dimensions this research offers a comprehensive understanding of the directions for evaluating the current level of circularity, empowering organizations to act and drive positive change related to CE.

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Expansion of Photovoltaic Module Production in South Africa

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Abstract
This paper explores the potential benefits and environmental considerations of expanding photovoltaic (PV) module production in South Africa. The country's heavy reliance on fossil fuels while it experiences an abundance of natural sunlight makes it well suited for discussions concerning the growth of solar energy. The expansion of local production of PV modules can lead to accessibility, affordability, and employment opportunities while reducing the negative environmental effects associated with traditional fossil fuels. The global landscape of PV module production is discussed, with China being the dominant player in the industry, followed by Europe and the USA. Environmental concerns related to PV manufacturing are addressed, such as emissions and leakages during production and disposal. The importance of careful scrutiny of environmental impacts caused by the production process itself is emphasized. The end-of-life management of solar PV modules is identified as a growing environmental issue, and the benefits of recycling will also be highlighted. Mitigation strategies for reducing environmental effects throughout the lifecycle of solar PV systems are proposed such as increasing system efficiencies and implementing scientific end-of-life recycling and disposal practices. The expansion of PV module production in South Africa holds great potential for sustainable economic growth and environmental protection.

Keywords: solar, renewable, energy, environment, photovoltaic

Introduction
South Africa is a developing economy with great potential for growth and expansion. For a long time, the country has relied heavily on coal-fired electricity. A strategy that may gain traction and can contribute to solving the current national issues, is the expansion of photovoltaic (PV) module production in South Africa. PV modules are a type of solar technology that can be used to generate renewable energy and have proven to be an attractive alternative to other forms of energy. South Africa is well-situated geographically to benefit from the increasing demand for renewable energy sources because the country has an abundance of natural sunlight and is in a convenient location to take advantage of the rapidly expanding global market for solar energy. PV modules are becoming increasingly popular due to their environmental benefits and their potential to generate electricity without depending on any fossil fuels which may pollute the environment. Local production of photovoltaic (PV) modules will eliminate the cost of shipping and other associated costs of importing them from other countries (i.e customs duty), making them more accessible and affordable for local markets and solar projects. Local PV panel manufacturing can also provide employment as it will ultimately strengthen the local economy. Furthermore, this will reduce the negative environmental effects associated with traditional fossil fuel energy generation methods, such as air pollution, soil degradation, and increased carbon emissions, as more people will now gradually prefer to use renewable energy.

1. Overview of photovoltaic power generation
Renewable energy is generated from sources that can be replenished over a short period of time. Renewable energy sources include solar, wind, water, biomass, and geothermal energy. Despite continued significant reliance on fossil fuels for transportation, heating, and power, the oil crises of the 1970s pushed for more investment in alternative energy sources. The negative effects of climate change have increased public demand for non-fossil fuel-based energy, aided by government incentives (Burclaff, 2023). Globalization processes increased at an unprecedented rate in the 1990s. Most global markets had already established a rather homogenous socio-economic system at the beginning of the 21st century, connected by a network of complex interdependencies. In most economies around the world, dynamic economic expansion accompanied the systematic development of globalization processes, which aided in the rise of social development and changed consumption patterns. A notable increase in energy demand is a result of systematic economic development. Unfortunately, the non-renewable energy sources that are currently available will run out within the next 20 years. Furthermore, generating energy from non-renewable sources is getting more expensive and is detrimental to the environment. As a result of these shifts, most economies are seeking alternatives to fossil fuels (Iglinski, et al., 2022).

Based on the systematic growth of the renewable energy systems (RES) industry as well as parallel changes in the labour market and consumption patterns, it can be argued that the majority of countries are presently going through an energy transition. Depending on the geographical location and climate in the region, suitable RES sources are being adopted. However, each nation's energy transition needs to move forward in a direction that eventually results in an optimal energy mix that relies on feasible renewable energy systems. In the pursuit of economic efficiency, social responsibility, and environmental protection, the development of the renewable energy sector has been a critical element in the idea of sustainable development. Governments and international organizations have taken responsibility for this development by creating several cooperative initiatives and international agreements to minimize any long-term negative consequences on the economy, society, and environment. The International Energy Agency, which is a significant participant in this evolution, defines sustainable energy as an energy sector with a long-term, global vision of development (Iglinski, et al., 2022).

South Africa started transitioning towards renewable energy in 2003 and established a renewable energy policy. The Department of Mines and Energy developed the Renewable Energy White Paper (REWP 2003) to set a target for renewable energy contribution that was greater than the renewable energy contribution then. The country showed its commitment by creating a practical strategy for renewable energy as part of REWP 2003. The renewable energy resources of South Africa have a large and vital potential that can make significant contributions to its energy sector, society, and economy at large. The cost of energy plays a significant role in deciding how effective renewable energy solutions are from a financial viewpoint. One of the renewable energy sources in South Africa with the greatest potential is solar energy. Photovoltaic (PV) and concentrated solar power (CSP), often known as solar thermal energy, are the two most well-known technologies for producing solar energy. To operate conventional steam turbines or engines that generate electricity, CSP plants use mirrors to concentrate solar energy onto the pipes carrying the fluids. The steam created by the thermal energy is then used to power the conventional turbine. Photovoltaic modules use silicon to directly convert solar radiation into electrical energy (Aliyu, et al., 2018). Aliyu and Modu suggested a rapid transition to photovoltaic technology in South Africa, but ten years after the release of the white paper, the country has yet to reach its full potential in this industry.

2. Benefits of photovoltaic power generation

In this section, various benefits of photovoltaic (PV) power generation are discussed, drawing attention to why this research into the expansion of PV module production is important to the South African economy. Despite its low conversion efficiency, the photovoltaic (PV) cell is preferred due to its high reliability, low maintenance, and lack of noise. Additionally, solar energy is considered a clean and environmentally friendly energy source. Solar energy concepts have been essential in promoting the green economy, and its usage and demand is widely accepted in the residential sector. Multiple environmental and economic sustainability indicators indicate that solar PV systems are an attractive option, and their economic viability is further strengthened with the inclusion of subsidies (Choudhary & Srivastava, 2019). Coal-fired power stations are the major cause of greenhouse gas emissions in China for example. Therefore, having fewer coal-fired power plants and more renewable energy sources will effectively lower greenhouse gas emissions and significantly slow down global warming. The combustion of coal generates significant amounts of ash, dust, sulphur dioxide, nitrogen oxide, carbon dioxide, and other pollutants, and waste gas must be processed before emission. Even flue gas emissions that comply with regulations contain small, detectable pollutants. These pollutants will accumulate over a long period of time and might eventually reach significant levels, which can cause negative effects. While biomass power generation requires plenty of land space, strong wind power has geographical limitations. Hydroelectric generation harms the ecological environment by submerging hundreds of square kilometres of land. Solar photovoltaic technology generates clean energy without harming the environment or the ecosystem, so it tends to be the most reasonable option for countries to invest in. (Liqiang & Zhang, 2017).

PV systems are a versatile energy source with many benefits. They have no moving parts, are modular, and can be expanded or even transported conveniently. These systems are independent from the energy grid, and produce no noise pollution. Additionally, they require minimal maintenance and tend to have long lifespans. PV market growth and expansion will have significant positive environmental implications. There are no "greenhouse gases" or harmful gas emissions produced during PV system operations. Solar photovoltaic technology primarily involves the creation of photovoltaic modules, less waste emissions are produced during this process than during the operation of coal- and oil-fired power plants (Liqiang & Zhang, 2017).In addition to contributing to meeting the increasing global demand for electricity, PV energy can do so without having to incur the substantial environmental costs associated with burning fossil fuels (Fthenakis, 2000).

The main reason for installing solar photovoltaic modules (PV) is to lessen the carbon footprint emitted by current electricity production (Anctil, 2021). Solar PV cells provide a reliable, clean, and green source of energy, with no need for a continuous supply of raw materials and low maintenance costs. Its versatility caters to multiple uses, including remote locations, while its contribution to smart energy networks helps

reduce the production of electricity at centralized power plants and the environmental impacts associated with it. It also has the potential to reduce costs significantly, making it an attractive and economically viable alternative. Moreover, its silent operation is ideal for urban areas and residential applications (Mo Solar Apps, 2023).
Solar photovoltaic (PV) modules can not only generate electricity but also act as external shading devices for buildings (Zhang, et al., 2017). Building-integrated photovoltaic (BIPV) is a configuration where photovoltaic modules or systems are incorporated into the building envelope, becoming part of the infrastructure components such as façades, roofs or windows. This way, BIPV serves a dual purpose, as both an efficient means of converting solar energy into electricity, and a component of the building skin providing weather protection, thermal insulation, noise protection, daylight illumination, and safety (Government of Canada, 2023). Solar PV shadings have the ability to significantly reduce solar heat gain through windows. Photovoltaic (PV) technology can be directly integrated into building envelopes to create building-integrated photovoltaics (BIPV) systems, in contrast to wind power, which requires large open spaces for the construction of wind farms. In addition to locally generating power, a well-designed BIPV system can successfully lower the cooling burden on buildings (Zhang, et al., 2017).

3. How photovoltaic modules work

Photovoltaics is the direct conversion of light energy into DC electrical energy at the atomic level. Certain materials exhibit the photoelectric effect, which is the absorption of photons of light and the release of electrons. When free electrons are captured, an electric current is produced that can be used as electricity (Knier, 2002). A photovoltaic cell is made of semiconductor materials that absorb the photons emitted by the sun and generate a flow of electrons. Elementary particles known as photons travel at a speed of 300,000 km/s, carrying solar radiation (Planete energies, 2019). The same semiconductor materials, such as silicon, are used to make solar cells. A thin semiconductor wafer is specially treated to produce a positive and negative electric field on one side for use in solar cells. Electrons in the semiconductor material are displaced from their atoms when light energy strikes the solar cell. The electrons can be captured in the electric current if electrical conductors are connected to the positive and negative sides, creating an electrical circuit. A load can then be powered by this electricity (Knier, 2002).

Electrons must move in the same direction to create an electric current. This process is made possible by the use of two different forms of silicon. The silicon layer that is exposed to the sun is doped with atoms of phosphorus, which has one more electron than silicon, while the other side is doped with atoms of boron, which has one less electron. The layer with extra electrons is the negative terminal (n), whereas the side with less electrons is considered the positive terminal (p). At the intersection of the two layers, there is an electric field formed. When the photons excite the electrons, an electric field sweeps them to the n-side while the holes move to the p-side. An anti-reflective coating is applied to the top of the cell to reduce photon loss due to surface reflection. The electrons and holes are directed to the electrical contacts attached to both sides before flowing to the external circuit in the form of electrical energy (Knier, 2002). Figure 1 below shows a summary of how a solar cell works.

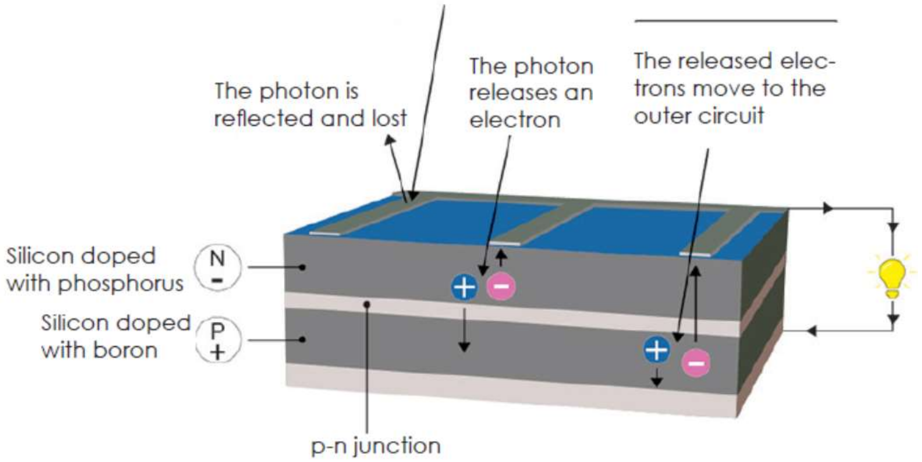

Figure 1: How a photovoltaic cell works (Planete energies, 2019)

4. Silicon extraction

There are various types of solar cells, which include monocrystalline, polycrystalline, and amorphous silicon cells. Polycrystalline solar cells are usually a preferred choice because of their competitive pricing and conversion efficiency (Liqiang & Zhang, 2017). Sand mining for quartz is the first step in the production of

Si-PV modules. To produce "metallurgical grade" silicon (MG-Si, at least 98% purity), the silica in the quartz sand is reacted with carbon electrodes, wood, charcoal, and coal in an electric arc furnace. The MG-Si can be processed further into "electronic grade" (EG-Si, 9 N purity) or "solar grade" (SoG-Si, 6 N purity) silicon to satisfy the more demanding specifications in the electronics and solar industries. The "Siemens" or "modified Siemens" processes are used to achieve this. In the original Siemens process, trichlorosilane gas decomposes and deposits more silicon onto silicon rods at 1100–1200 °C, whereas in the modified Siemens process, silane is used as an input gas and the decomposition temperature is maintained at roughly 800 °C. Manufacturing silicon ingots involves making mono-Si and multi-Si wafers, which is then followed by wafer sawing. Ribbon-Si wafers, on the other hand, are directly pulled or cast from liquid silicon, resulting in significantly improved material efficiency by avoiding sawing losses. For all three Si-PV technology types, the cell production and subsequent module assembly procedures are almost identical. The PV modules are enclosed with ethylene-vinyl acetate and glass sheets, which shield them from the environment while they are in use. Aluminum frames are usually incorporated into the assembly for additional strength and easy mounting (Dajun, et al., 2014).

5. How photovoltaic modules are made

To establish a firm understanding of this study, it is crucial to comprehend the processes carried out to manufacture solar modules. Solar module technology is advancing rapidly, which has resulted in a huge increase in demand. However, despite the technological advancements, the fundamental design of photovoltaic modules has not altered much over the past few years. Most photovoltaic modules continue to be manufactured from a grid of silicon crystalline cells positioned between a front glass plate and a rear polymer plastic back-sheet supported by an aluminum frame (Knier, 2002). Figure 2 below shows the six main components used in assembling photovoltaic (PV) modules.

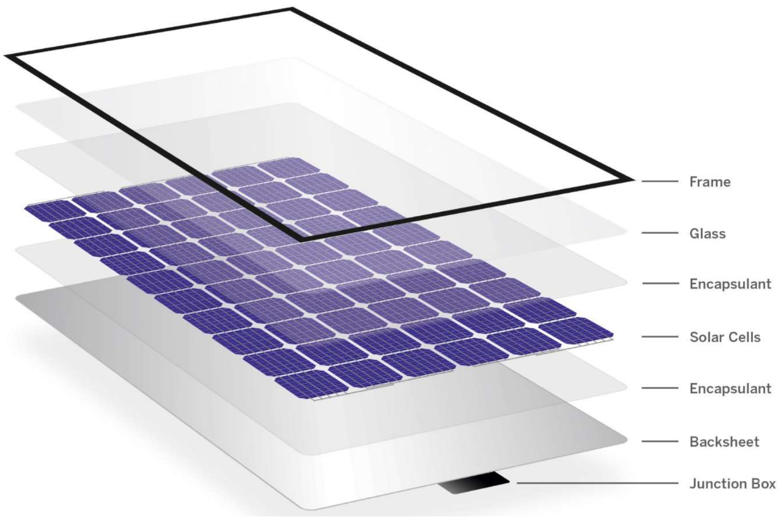

Figure 2: Components of a photovoltaic (PV) module (Indiamart, 2023)

The process of manufacturing conventional mono and polycrystalline silicon PV cells begins with the use of very pure, semiconductor-grade polysilicon, which is derived from quartz and is a commonly used material in the electronics industry. This polysilicon is heated to its melting point, and trace amounts of boron are added, creating P-type semiconductor material. Ingots, or blocks of silicon, are then formed either by growing a pure crystalline silicon ingot from a seed crystal taken from the molten polysilicon or by casting the molten polysilicon into a block, creating a polycrystalline silicon material. Wafers are then cut from the ingots with wire saws and subjected to a surface etching process. After they are cleaned, they are put in a phosphorus diffusion furnace, forming a thin N-type semiconductor layer on the entire outer surface of the cell. An anti-reflective coating is then applied to the top surface of the cell, and electrical contacts are imprinted on the top (negative) surface. An aluminized conductive material is then deposited on the back (positive) surface of the cell, restoring its P-type properties. Finally, each cell must be tested electrically (University of Central Florida, 2023).

6. Global landscape of PV module production and environmental considerations

First world countries such as Germany, Japan, and USA have initiated large scale projects to advance the PV industry. "The global demand for PV power increased from 1 GW in 2004 to 57 GWs in 2015: an annual growth rate of more than 20%, faster than any other industry, including other emerging renewable energy industries" (Yan, et al., 2018). The manufacturing of PV modules has shifted to China, it has been estimated that a Chinese-made crystalline silicon (C-Si) PV module installed in southern Europe would need to be used 20–30% longer than a similar European-made module to generate enough electricity to offset the carbon emissions from its production. This is because the energy generation mix in China uses a higher proportion of coal (Sunderasan & Vamshi, 2018). Though Europe and the US are at the leading edge of research and development for PV technology, most PV modules (approximately 80%) are produced in Asia. China alone makes up 62% of global output. Only 4% of PV modules are made in the United States, while 10% of PV modules are produced by European manufacturers (Dajun, et al., 2014). The location of silicon manufacturing is changing rapidly. Figure 3 shows the location of polysilicon cell and panel production in 2013 compared to 2019. Chinese production has increased for each manufacturing stage, particularly for polysilicon (30%), while installations have decreased (5%). In comparison, most of the manufacturing in the USA was for polysilicon production, and its share has reduced by 13% over the same period, while installations have remained constant. The USA still produces polysilicon, but it is exported to produce cells and panels in other countries (Anctil, 2021).

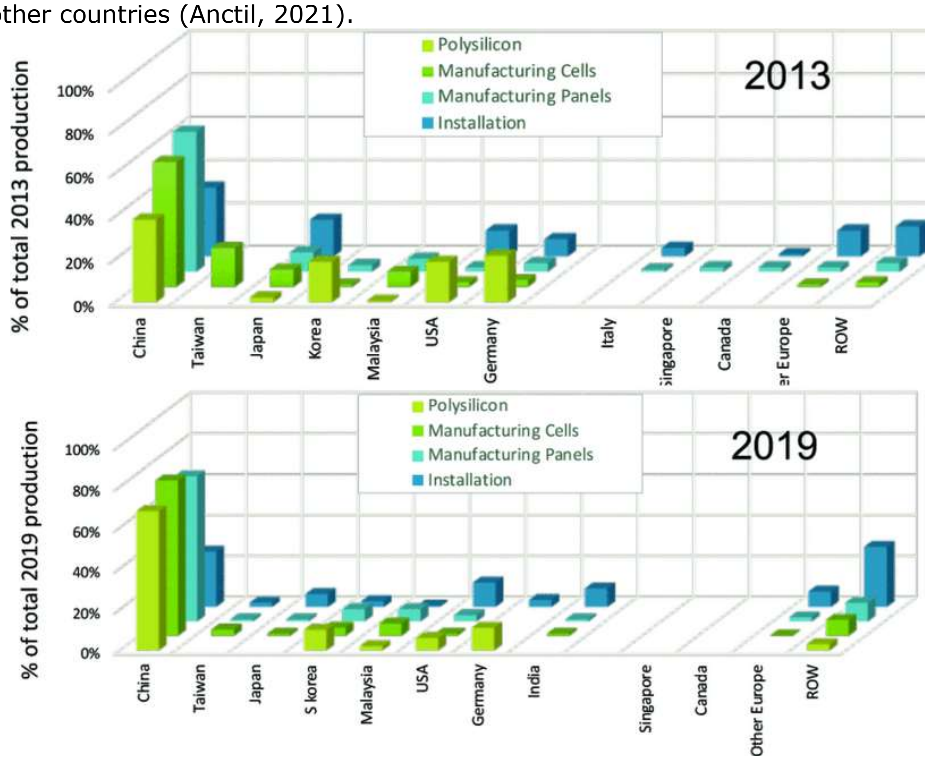

Figure 3: Global locations of polysilicon cell and panel manufacturing in 2013 vs 2019 (Anctil, 2021)

Apartments that are completely powered by solar PV systems, commonly referred to as "net-zero energy apartments," frequently ignore the energy input and environmental effects of producing PV cells and modules, transporting them, and assembling the systems. Recycling and disposing of solar PV modules and other system parts that are no longer useful also tend to be ignored. At each stage of the production, installation, use, decommissioning, recycling, and disposal processes, materials and energy inputs are needed. These stages generate effluent as well. Sunderasan and Vamshi argue that when compared to the emissions from the traditional energy generation alternatives that PV aims to replace, the lifecycle emissions of GHG and heavy metals from multi-crystalline, mono-crystalline, ribbon silicon, and thin-film Cadmium-Telluride modules do not differ considerably (Sunderasan & Vamshi, 2018). The location of a manufacturing plant has a significant impact on the overall carbon footprint of the module because silicon manufacturing requires a large amount of electricity for operations (Anctil, 2021). China has different energy and industry structures with more lenient environmental regulations. Therefore, PV modules made in China will have distinct energy and environmental profiles than those made in Europe or North America (Dajun, et al., 2014)

7. Environmental concerns of PV manufacturing

Investments in solar PV systems are often viewed as a step towards improving environmental sustainability and as an alternative to conventional options that significantly increase greenhouse gas emissions. Emissions and leakages from the production, consumption, and disposal of solar PV systems are regularly overlooked and taken to be zero due to the substantial differences in the emission profiles between PV and conventional energy sources, particularly coal-fired power generation. Arguments in favour of large-scale solar PV installations usually neglect the environmental effects of mining metal ores for thin-film cells and quartz sand for silicon cells. The potential for a substantial increase in the volumes of photovoltaic (PV) systems around the world means that any environmental impact from solar PV modules, no matter how small it may seem, deserves careful scrutiny. It is also necessary to conduct separate analyses of the significant environmental effects associated with the mass production, use, and disposal of battery banks, power electronics, and other system components (Sunderasan & Vamshi, 2018).

Manufacturing crystalline silicon, creating solar batteries, and assembling a solar photovoltaic power generation system are all elements of the production of solar photovoltaic equipment. Businesses that use crystalline silicon, which constitutes a significant portion of the photovoltaic industry, cause serious negative environmental effects. These businesses consume a lot of energy, produce a lot of pollution, and involve a low level of repeated construction. Technologies used in polysilicon production primarily utilize Siemens, improved Siemens, and silane pyrolysis techniques (Liqiang & Zhang, 2017). Despite having low concentrations in solar panels, metals like cadmium and lead may result in hazardous waste materials. Separating these metals from the glass, which makes up the majority of a solar panel, is a reasonable way of solving this issue. Separating the hazardous metals from glass and metal frames may result in a significant reduction. By using physical techniques such as a hammer mill, sandblasting, or pyrolysis, these metals can be stripped of glass and plastic in small-scale operations. Chemical stripping using appropriate solvents, such as acids and oxidizers is the most effective way to recover the metals (Vasilis, 2000). Unfortunately, there are still no specialized solar panel recycling facilities to make up for the Si and other raw materials used in the production process, even though recovering silicon and other raw materials from scrap solar panels may be a viable approach. Since there is now no efficient system for collecting or disposing of the growing number of waste solar panels, the necessity for environmentally sound management of these panels has now become critical (Yan, et al., 2018).

The production of solar photovoltaic systems can have negative consequences for the environment, particularly in terms of wastewater and waste gas pollution. These pollutants often contain toxic substances such as fluorine, chromium, hydrogen fluoride, and silicon tetrachloride gas. Improper disposal of solar cells at the end of their useful lifespan further increases negative environmental implications, which may include the emission of undesired smells and the destruction of soil structure and quality. The process of solar photovoltaic production generates waste gas that is difficult to eliminate, as well as wastewater pollution. When a solar photovoltaic system reaches the end of its useful life, it becomes waste that can potentially pollute the environment. The manufacturing of crystalline silicon solar cells involves the use of various chemicals such as acid, alkali, phosphoric acid, hydrofluoric acid, and sodium hydroxide. These chemicals are used in processes such as silicon wafer surface corrosion and velvet preparation, which aim to remove phosphorus from the silicon glass. The use of these chemicals results in the production of alkali and organic wastewater, which contains chromium and silicon compounds. While chemical and biological methods can remove the most toxic substances during wastewater treatment, certain residuals may remain in sewage treated with silicon and fluorine materials. Even though there is a low concentration of pollutants in processed sewage, the crystalline silicon solar cell industry is continuously expanding. Different stages of the manufacturing procedure result in the creation of effluent gases and possibly dangerous runoff (Liqiang & Zhang, 2017).

The possibility of their contribution to global warming has been highlighted when cleaning Si and nanocrystalline-Si thin film module lines with nitrogen trifluoride (Sunderasan & Vamshi, 2018). The cleaning of solar panels to maintain good performance usually leads to the production of wastewater containing chromium. This chromium wastewater consists mainly of hexavalent and trivalent chromium compounds. Chromium adversely affects crop growth, and using wastewater containing chromium for irrigation reduces crop yield and results in soil hardening, thus reducing soil quality. Over time, chromium will accumulate in plants and enter the food chain, affecting animals and humans. Hexavalent chromium can cause various diseases, such as rhinitis, respiratory ailments, digestive tract disorders, and corrosion of the skin and internal organs. Drinking water regulations specify a maximum allowable concentration of total chromium at 0.05 mg/L, with a further limitation of 0.01 mg/L for hexavalent chromium. Long-term consumption of water containing chromium can lead to skin cancer (Liqiang & Zhang, 2017).

To maintain its commitment to environmental preservation, the PV industry has chosen a proactive and long-term strategy. Manufacturing solar panels presents some health, safety, and environmental (HSE) concerns, which have been the focus of numerous studies at Brookhaven National Laboratory, under the supervision of the US Department of Energy's National Photovoltaic Program (Vasilis, 2000). Noise pollution is an inevitable by-product of glass production in the factories since the machinery and equipment used in the process are often loud. Manufacturers can mitigate noise pollution by employing low-noise or noise-reduced equipment with acoustic isolation (Liqiang & Zhang, 2017). Product quality for solar PV modules is fairly simple to assess. For instance, to assist investors and developers in making wise investment and procurement decisions, DNV GL conducts a variety of tests to evaluate PV module quality and long-term reliability and publishes supplier-specific PV module reliability scores. These tests do not provide adequate information about risks related to production processes however they are an effective framework for quality control to employ in the meantime (Sunderasan & Vamshi, 2018).

8. End-of-Life Management

The decommissioning of solar cells at the end of their useful life is a problem that could have an impact on the environment (Vasilis, 2000). The solar panels themselves also pose a problem for the environment; after their useful lives, they turn into hazardous waste. The recycling of used solar modules was not an issue during the first 25 years of their development because they have a long service life. However, plenty of the initial batch of installed solar modules are now being retired, and proper end-of-life management of solar panels is gradually becoming a significant environmental issue. The energy and cost required to recover silicon from recycled solar panels are only one-third of what would be required to produce silicon directly. This makes solar-module recycling particularly beneficial for the environment because silicon production is a process that consumes significant amounts of energy. There are only a few PV module recycling facilities around the world because end-of-life solar PV module management is a newly emerging field that needs further research and development (Yan, et al., 2018).

"The lifespan of solar photovoltaic equipment is approximately 20 years, and a solar component that has exceeded its lifespan becomes solid waste" (Liqiang, 2017). The negative environmental effects from solar PV module production, utilization, and disposal can be mitigated through increasing system efficiencies, reducing material consumption, employing changes in the upstream energy mix and in material production techniques, and through scientific end-of-life recycling and disposal of all system components. In comparison to 300 GWp in 2016, the International Renewable Energy Agency (IRENA) predicted that installed global PV capacity might approach 4500 GWp by the year 2050. According to estimates, the reuse and recycling of end-of-life PV modules could theoretically provide roughly 78 million metric tons of usable material, or the equivalent of about 2 billion PV modules (Sunderasan & Vamshi, 2018). It is apparent that glass and aluminium make up a significant amount of PV modules, proving that every type of PV module loses potentially reusable resources. Another result of the non-recirculation of PV modules, is the loss of rare metals, particularly indium, gallium, and germanium. Amorphous silicon and copper-indium gallium selenide modules contain indium. Copper indium gallium selenide, concentrating photovoltaic (CPV) modules, and new PV module technologies all contain gallium. Germanium is present in amorphous silicon, concentrating photovoltaic (CPV) panels, and emerging panel technologies. Even though the volume of these rare metals in PV panels is under 1%, their value is significant (Yan, et al., 2018). However, metals such silicon, lead, cadmium, phosphorus, and flame retardants are not treated properly or recycled. These compounds will accumulate over time and cause adverse effects on water, soil, air, and human health (Liqiang, 2017).

Newer solar PV modules are being made of expensive materials such as silver, carbon fibre, and tin, which tend to be difficult to recycle. Reducing the use of these exotic materials in modules would make solar PV more environmentally friendly. Most of the PV modules that are collected for recycling are often those that have been damaged during installation or transportation, whereas modules that have reached the end of their useful lives make up just 1% of the total (Sunderasan & Vamshi, 2018). When PV systems reach the end of their useful lives, recycling them increases the benefits for the environment and may even increase market support. Additionally, recycling addresses the public's concerns about damage to the environment. Recycling costs will decrease as the recycling technologies mature, whereas the landfill disposal costs are constantly increasing (Vasilis, 2000) At the moment, there are three common methods of processing waste solar panels which are: component repair, module separation, and the removal of silicon and other rare metal elements from among the components (Yan, et al., 2018). A feasible recycling program needs to pay close attention to the economics of collecting the materials, as well as the experiences of related businesses. "The basic viability of any recycling program often hinges on the geographic concentration of the goods and their proximity to appropriate recycling facilities, and on their content of valuable materials" (Vasilis, 2000).

9. Policy and regulatory framework

In the United States, even if waste has been disposed of in accordance with current procedures and regulations, the generator of the waste is still responsible for the cost of any site remediation that may be required in the future. It is challenging, however, to estimate the cost of this potential obligation; one method is to give it a value comparable to the current price of disposing of hazardous waste, which in the US averages $800 per ton. Economic incentives might not be enough to persuade the PV industry to transition to voluntary recycling right now. This could, however, change in the future since additional financial incentives could be introduced for developing environmentally friendly technologies and reducing carbon dioxide emissions (Vasilis, 2000). To protect the environment, governments should implement strict regulations for the battery industry. Governments should create policies that promote and guide the growth of solar photovoltaic technology. Recycling units should raise awareness of environmental preservation and make an effort to run as environmentally conscious companies in order to standardize, rationalize, and recycle solar PV equipment waste while reducing any adverse environmental effects (Liqiang & Zhang, 2017). The use of feed-in tariffs, tax credits, and other instruments might demonstrate the commitment of a policy while increasing a project's capacity to obtain capital. In a "zero-subsidy" environment, there is no apparent system to acknowledge and reward the PV module manufacturers with greater environmental credentials in comparison to their competitors in the industry. The Silicon Valley Toxics Coalition awards 'solar scores' to rate the environmental performance of manufacturers and to rank them in the order of their performance.

This study calculates the goodwill capital included in market valuations of listed PV module manufacturing companies and links the creation of such goodwill to the given solar scores (Sunderasan & Vamshi, 2018). The European Union officially amended the waste electrical and electronic equipment (WEEE) directive in July 2012. They added PV components as discarded electronic devices so that they could be included under the ten categories of WEEE. Solar PV components must be gathered and recycled because they are now part of the electronic waste management system. All solar modules that have reached the end of their useful lives must be properly disposed of, according to this directive on PV waste management. Additionally, all manufacturers of PV panels that supply components to the European market must pay a recycling fee. On the other hand, few countries outside the European Union are implementing such policies currently because there is a low volume of waste PV modules available for recycling in other regions, and the cost of recycling the modules is too high for the process to be considered cost effective (Yan, et al., 2018).

Conclusion

In conclusion, the expansion of PV module production in South Africa holds great potential for sustainable economic growth and environmental protection. PV power generation comes with numerous benefits because it is environmentally friendly. PV systems are versatile, modular, and independent from the energy grid, making them accessible and convenient. The cost of PV modules remains a barrier to widespread adoption, but the technology has the potential to become economically viable if it is implemented strategically. It is also crucial to analyze the environmental concerns associated with expanding PV manufacturing. Recycling and disposal practices to recover valuable materials and reduce the volume of waste generated should be carefully considered before implementing large scale production operations. Further research and development in end-of-life management is needed to establish specialized recycling facilities and improve recycling processes. By expanding PV module production while considering environmental implications and concerns, South Africa can greatly benefit immersely from the expansion of photovoltaic (PV) module production, create more employment opportunities, and contribute to environmental sustainability.

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Feasibility of the production of Refuse-Derived Fuel in Brazil: a case study in the state of Espírito Santo

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Abstract

Refuse-Derived Fuel (RDF), which can be obtained from Municipal Solid Waste (MSW) can be an alternative to reduce the emission of polluting gases in several industrial sectors, such as cement plants, due to its high calorific value and its moderate environmental impacts. The cement industry is energy intensive and uses highly polluting fossil fuels. Therefore, RDF stands out as a potential substitute for fossil fuels used in this sector, when associated with these industries through co-processing technology, which has the potential to mitigate their environmental impacts. However, there are still doubts as to whether RDF-producing enterprises are viable in the Brazilian context, given the high cost of production technologies compared to other disposal options. This study analyzed the economic viability of a MSW production plant in RDF, considering real data from the state of Espírito Santo (ES) located in Brazil. Using economic engineering tools, variables such as: capital and operating costs, Minimum Attractiveness Rate of Return (MARR), revenue generated by RDF sales, oil price and annual availability of waste were analyzed. The sensitivity analysis showed that the scenarios with 20% replacement of petroleum coke by RDF present a better Net Present Value (NPV) behavior compared to the others, and variables such as capital and operating costs do not have significant influences on the NPV variation of the cash flow. The project's uncertainties were evaluated through the application of the Monte Carlo Method (MCM), which showed that the scenarios that consider 20% of fossil fuel replacement by RDF have a better NPV behavior in the face of variations and are less likely to return negative NPV values. After analyzing the variables that most impact the cash flow, it was found that the MARR and the revenue generated on sales are those that most impact the viability of the RDF plant. Although this study considered data from a Brazilian state, the considerations allow a generalization to other locations, as long as the significant uncertainties for each region are incorporated. This study guides projects involving the production of RDF by the private sector highlighting their risks. The public sector can take advantage of this analysis if it wants to guide actions that encourage this use of MSW rejects.

Keywords: *Co-processing. Cement industries. Urban solid waste. Economic viability.*

1. Introduction

Climate change remains a critical issue for current and future generations. For the nations of the world to comply with international agreements aimed at mitigating global problems such as climate change, especially those that have committed to the Paris Agreement, they must reduce carbon emissions from fossil fuels (SIDDIQUI et al., 2020). In this sense, it is essential to consider alternative sources of energy, such as waste that can take advantage of waste, a specific portion of Urban Solid Waste (MSW), in addition to avoiding the use of fossil fuels (HARAGUCHI et al., 2019).

The release of waste into the environment, without any form of prior treatment and control, has been one of the main factors responsible for the contamination of groundwater and soil, which contribute to the release of polluting gases into the atmosphere, responsible for the greenhouse effect. Therefore, this issue has become one of the concerns of society and the public power in all its sectors, since this problem has intensified with industrialization and population concentration in large urban centers. (SIDDIQUI et al., 2020).

In this sense, a relevant milestone around waste management in Brazil was the National Solid Waste Policy, instituted by Law No. 12,305, which among the crucial issues to be achieved, is the demand energy recovery from waste (BRASIL, 2012) involving the generation of energy, heat, and value-added products (VOLK et. al, 2021). Lima et al. (2018) demonstrated that energy recovery and MSW treatment are more efficient in energy and environmental terms than the current landfill-based management systems that occur in Brazil.

Among these options for energy use is the transformation of MSW into Refuse-Derived Fuel (RDF) from thermal treatments, contributing to the generation of useful energy (CHAVANDO et al., 2022). It becomes an alternative product, produced from waste materials with high calorific value and low moisture content diverted from landfills. (REZA et al., 2013). RDF used as a substitute for fossil fuels leads to reductions in carbon emissions above expected levels (PALERMO et al., 2022), providing emission reductions from 2% to about 23% (SILVA et al., 2021).

Currently, research carried out in Brazil on the use of MSW to produce RDF is mainly focused on the resource potential and ecological impact using Life Cycle Assessment - LCA (STAFFORD et al. 2016; LIIKANEN et al, 2018; PALERMO et al., 2022). These studies have shown that the environmental impacts of MSW management can be reduced when the RDF produced is used in cement industries as a substitute for coal (LIIKANEN et al., 2018). Feasibility studies of RDF conversion systems from MSW for the Brazilian case were not identified. The financial viability of these plants is of great importance as it is typically cost barriers that restrict effective waste management in many regions. (HARAGUCHI et al., 2019).

Faced with the need to value MSW in the Brazilian energy market and the recent legislation encouraging this use, this study aims to evaluate the feasibility of using MSW to produce RDF, aiming at replacing fossil fuels in cement industries. It is intended to fill the gap of studies that investigate the parameters that influence the economic viability of MSW co-processing to produce RDF and its use in the cement industry. Furthermore, it is necessary to estimate the costs, capacity, and energy production of a waste-to-energy system, considering the specific composition of the MSW used. For this, the present study aimed to answer the following question: in relation to the generation of waste in the State of Espírito Santo, what is the viability for the collection and transport of MSW, production of RDF and its use as a substitute for conventional fuels used in cement industries through co-processing?

Aiming at the analysis proposed in this study, the reality of the state of Espírito Santo was considered, since this state launched its State Plan for Solid Waste (PERS) in 2019. Within this context, two studies in Espírito Santo were carried out. The first one investigated the implementation of public policies to produce RDF from paper and non-recyclable plastic waste and irreversible tires and their use in the region's cement industries (CHAVES et al. 2021a). The second one proposed a reverse logistics network indicating the best location for the implementation of the RDF plant, as well as determining the waste flows to produce the RDF and then its flow to the cement industries in the state (CHAVES et al., 2021b).

Continuing this analysis, this study aimed to carry out an economic feasibility analysis to evaluate the potential of using RDF produced from MSW to replace conventional fossil fuels in the cement industries in the state of Espírito Santo. For this, the interval between 2022 and 2040 was considered, the initial year of development of this study and the final year of PERS coverage, respectively.

The state of Espírito Santo produced an average of 1,028 tons of MSW in 2020 (ESPÍRITO SANTO, 2019), of which 87% were sent to landfills, while 13% were improperly disposed. There are 03 cement industries in the state, located in the municipalities of Cachoeiro de Itapemirim, Serra and Vitória, and only one of them is licensed to carry out co-processing. In addition, the current waste plan includes actions to encourage the energy use of waste. Therefore, it is considered that the state presents the necessary elements for the intended analysis and, therefore, was chosen as a case study.

2. Methods

2.1 Geographical background

Espírito Santo is in the southeastern region of Brazil, being the smallest and least populous state in the region. It occupies an area of 46,074.448 km² and a population of approximately 4,108,508 inhabitants, distributed among 78 municipalities, and presenting a demographic density of 76.25 inhabitants/km² (IBGE, 2021). In 2017, around 861,308 tons of MSW were generated in the state. Most of this waste is disposed of in sanitary landfills (87%), and of these, only 6.4% of the municipalities carry out some type of treatment system (sorting, composting and/or recycling) before being sent to landfills. In the state there are 78 Waste Pickers' Organizations distributed among their municipalities. They conduct the sorting of MSW and make its commercialization, consequently contributing to the reduction of waste sent to landfills, reducing municipal expenses with the grounding process (ESPÍRITO SANTO, 2019). A population increase in the state of Espírito Santo of around 15% is expected by 2040 (4,797,622 inhabitants), which will lead to an increasing increase in MSW generation that could reach around 1,196,961 tons (29% increase) (ESPÍRITO SANTO, 2019).

2.2 Research Procedures

To carry out an analysis of uncertainties about the economic viability of MSW conversion, this study was carried out in stages. In the first stage, for the development of the objectives proposed in this research, a documentary and bibliographical research was carried out. For this, sources of official publications from Brazilian public sector bodies were used, among them mainly the National Policy on Solid Waste, in addition to government reports and constitutional and legal materials about the disposal and treatment of waste in the Brazilian territory. The official guidelines of the state of Espírito Santo were also considered, mainly the State Policy on Solid Waste (PERS). In the second stage, a projection of the volume and gravimetric composition of waste was carried out until 2040, based on data collected in PERS on the amount of waste generated annually and its estimated gravimetric composition. For this, data provided by PERS on the population projection until 2040 were used.

In the third step, the annual energy conversion rate was calculated based on the availability of paper, non-recyclable plastic and MSW in the state. Total RDF productivity from MSW for the years 2022 to 2040 was calculated using the mass balance. The energy recovery potential (ERP) in gigawatt hours per year (GWh/year) can be calculated from Equation 01, where DW is the dry waste (in tons per year) and LHV is the Low Heating Value (in megawatt hours per ton). The LHV was estimated according to data provided by Chaves et al. (2022).

$$ERP = DW.LHV \quad (01)$$

For the fourth stage, from the search, recording and analysis of the data, these were treated with the aim of estimating revenues and costs for projecting the cash flow, considering the inflows and outflows of capital, and arranged in a time horizon. Thus, scenarios with 10%, 20%, 30%, 40% and 50% replacement of petroleum coke used in cement industries by RDF were simulated and the cash flow was estimated for each of these scenarios. Scenarios were also used with the use of own resources for the initial investment of the project, and with the possibility of financing 100% of this. Cash flow was estimated based on the following components: gross revenue, operating costs and expenses, taxes, as well as taxable income (JOSEPH; PRASAD, 2020). Thus, the economic tools used in this study were: (i) cash flow projection based on estimates of inflows and outflows; (ii) NPV method; (iii) Internal Rate of Return (IRR) method and (iv) Payback method.

The calculation of the RDF price for use as an industrial fuel as a substitute for petroleum coke was estimated according to Mamede (2013). The variation in the MSW composition affects the economic indicators, as its calorific value directly influences the calculation of the RDF sales revenue. Thus, the LHV of petroleum coke was used, and its respective sale price, making it possible to arrive at the value in reais per energy unit (kJ), which was multiplied by the amount of energy per ton of RDF.

In the fifth stage, a Sensitivity Analysis (SA) was carried out to measure the variation of important parameters in economic indicators: initial project investment, revenue generated from RDF sale, Capital Expenditure (CAPEX) and Operational Costs Expenditure (OPEX) and the Minimum Attractiveness Rate of Return (MARR). The sensitivity analysis provided uncertainty by measuring the influence of just one parameter on the economic indicators, seeking to understand how much it impacts the result if one of the variables changes. Therefore, it was possible to determine how much the NPV changed in view of the variation of the analyzed parameters. To perform the SA, a Microsoft Excel® spreadsheet was used.

From the variables that most influenced the NPV, those that most impacted the NPV in the analyzed scenarios were selected to measure the combined effect of these important variables on the economic viability of the project. For this, the Monte Carlo Method (MCM) was used. This method allowed identifying the variables that most impact cash flow and establishing estimates for a positive NPV, in addition to analyzing the replacement of fossil fuels by RDF in cement plants. Thus, the MCM sought, through estimated values, what could be considered a good decision for the investment. The values of interest for analysis were the NPV. Thus, the modeling took place by sampling the distribution of possible results for each event, defining the probability distributions of each input.

After these determinations, the simulation was performed in the @Risk 8.0 software based on the set of simulations performed, generating a distribution of the value per variable, being the output of the model. After applying the MCM, the data were statistically evaluated and classified according to the behavior of its variables. The mean, mode, median and standard deviation values of the samples were observed to observe how these variables behave.

3. Results

The analyzed project involved the reuse of the non-recyclable fraction of MSW, with the aim of eliminating the disposal of refused waste in landfills, valuing reusable materials using it as an energy input. The present study considered the implementation of an industrial plant that will carry out the mechanical treatment of MSW for conversion into RDF. Thus, the equivalent annualized investment cost of the following items was considered: industrial plant capacity, infrastructure work, equipment, and inputs for the operation of the plant, in addition to operational and administrative employees. In determining the costs for the implementation of a production system, it was necessary to analyze the viability of the MSW conversion plant into RDF for use in cement production kilns.

3.1 Sensitivity Analysis

The SA was performed for the variables: Sales volume of RDF, MARR, CAPEX and OPEX. After carrying out the SA, it was possible to observe that the initial investment variables and the plant's operating costs do not have much relevance on the variation of the NPV of the cash flow. According to Fig. 1, in case of an increase of up to 50% in these variables, it does not cause financial unfeasibility for any of the hypotheses evaluated by the sensitivity analysis, since in none of the situations the NPV presents a value lower than zero.

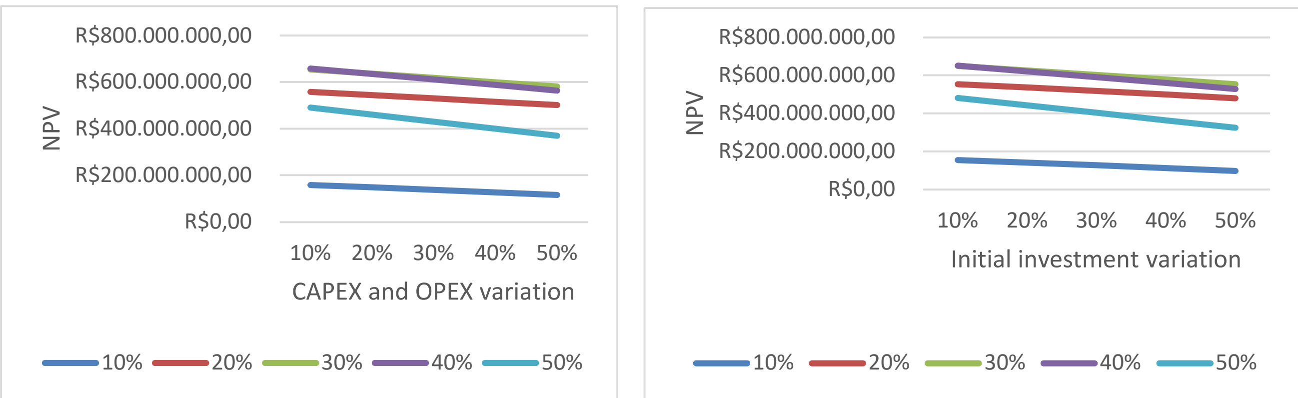


Figure 1 - Variation in NPV versus fixed costs and expenses (left) and NPV versus initial investment (right).
Source: Authors (2023).

In contrast, the MARR variables and revenue generated on RDF sales are sensitive to NPV. Gross revenue is dependent on the number of sales made annually. In the scenarios of 10%, 40% and 50% of fossil fuel replacement, the reduction in sales volume is even more sensitive, suffering a drop of 30%, 50% and 40% respectively. This drop causes a negative return on the NPV, making the project unfeasible.
In order to calculate the financial parameters, it was necessary to determine the MARR of the project, which was considered the Special System of Liquidation and Custody (SELIC) rate, which on December 30, 2022 was set at 13.65%, data provided by the Central Bank (2022). The MARR is a factor that strongly influences the NPV. It is also possible to observe that the MARR is inversely proportional to the NPV, since the lower the interest rates, the greater the value of the NPV, making it possible to obtain a greater financial return. Despite variations in profitability, these variations do not lead to negative returns. Fig. 2 presents the SA performed for these two important variables. These variables remained sensitive for cash flows without financing (Fig.2) and for cash flows with financing (Fig. 3).

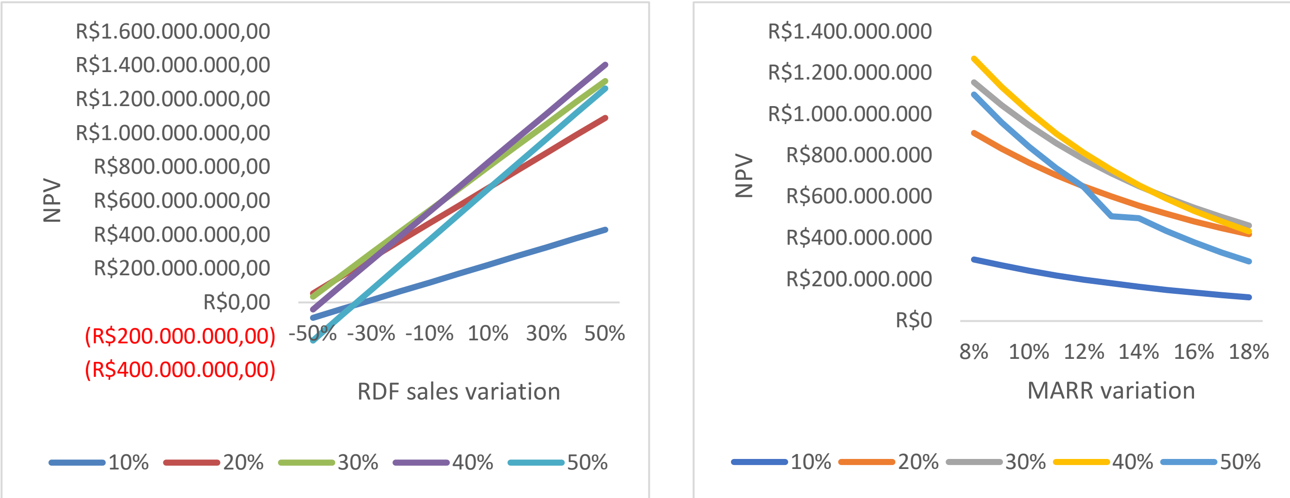
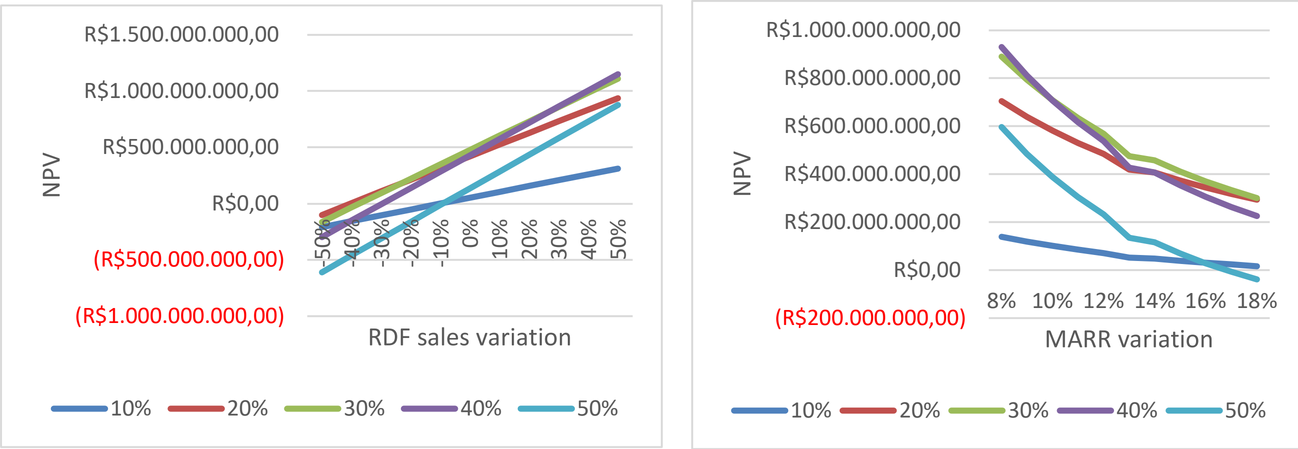


Figure 2 - Variation in NPV versus RDF sales volume (left) and NPV versus MARR (right) for unfunded cash flows.
Source: Authors (2023).

Figure 3 - Variation in NPV versus RDF sales volume (left) and NPV versus MARR (right) for financing cash flows.



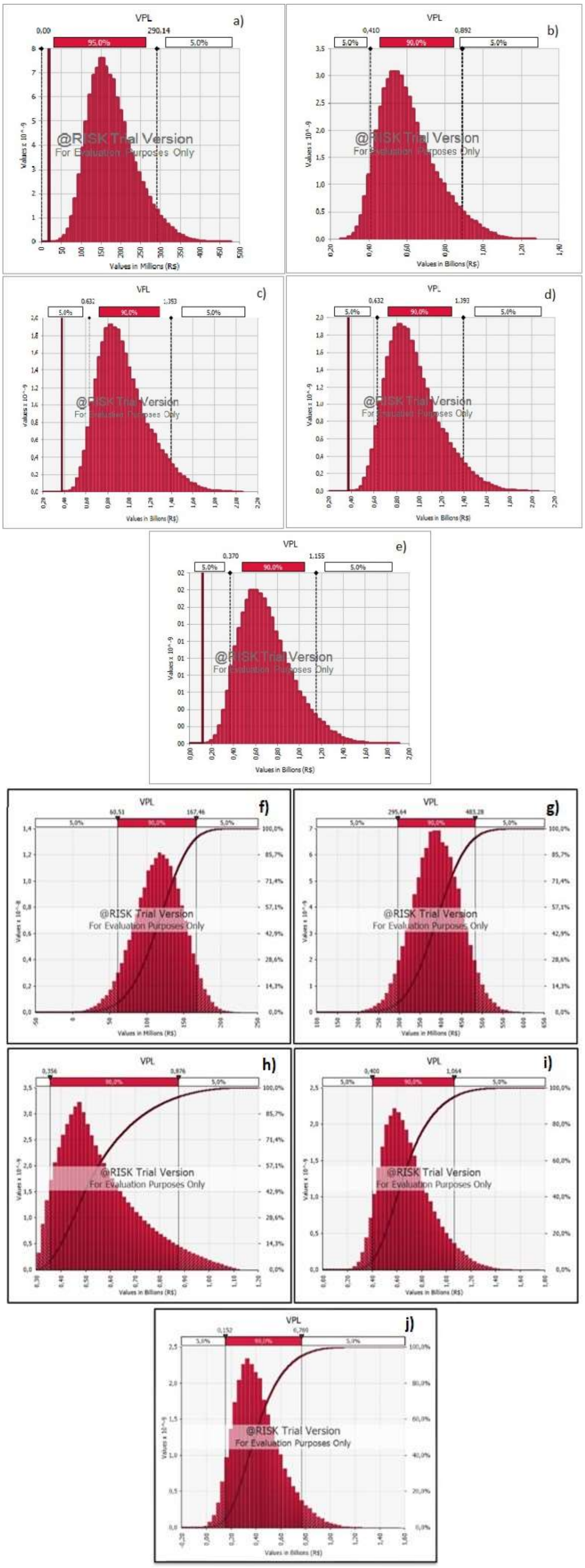
Source: Authors (2023).

With the sensitivity analysis, it is possible to identify that the variations for the scenario with financing are even more impactful than the scenario without financing. The monthly cost of the financing installments during the first 10 years of the project is high and puts the company's revenue at risk, because even if the plant's performance in a given period is not positive, the company is obliged to bear the cost of debt.

3.2 Monte Carlo Simulations

The Monte Carlo simulation was carried out for the cash flows without financing and with financing for the percentages of 10%, 20%, 30%, 40% and 50% of fuel substitution. The objective was to evaluate the probability of returning positive monetary values considering the uncertainty related to some variables involved. After identifying the variables that most impacted the project's cash flow, the variables oil price and annual availability of waste were also added to carry out the risk analysis of the project. The simulations occurred modifying all the analyzed variables and assuming that all of them can undergo modifications throughout the project's operating period. Through the simulations carried out, financial results were obtained, and their accumulated probabilities for the enterprise shown in Fig.4.

Figure 4 - Probability distribution of NPV in relation to the variables for unfinanced and financed cash flows for the five fuel substitution scenarios.


VPL
a)
0.00
290.14
95.0%
5.0%
Values in Millions (R$)
b)
0.410
0.892
5.0%
90.0%
5.0%
Values in Billions (R$)
c)
0.632
1.393
d)
0.632
1.393
e)
0.370
1.155
f)
60.51
167.46
g)
295.64
483.28
h)
0.356
0.876
i)
0.400
1.064
j)
@RISK Trial Version
For Evaluation Purposes Only

Source: Authors (2023). NPV probability distribution for the following replacement petroleum coke by RDF scenarios with financing: a) 10%, b) 20%, c) 30%, d) 40%, e) 50% and without financing: f) 10 %, g) 20%, h) 30%, i) 40%, j) 50%.

Regarding the scenarios without funding, the data show a relatively asymmetrical positive distribution to the right in relation to the mean value for all five simulated scenarios, that is, the values are concentrated at the lower end of the scale and are gradually distributed towards the upper end. For the 10% replacement scenario, although the project does not present a negative NPV probability for this analysis, it is a scenario that works with a small volume of waste, not justifying the high investment cost to operate with such a low volume waste. The scenarios that consider 20%, 30% and 40% replacement are those that manage to operate with a larger volume of waste since the initial years of project implementation. These scenarios present a uniform cash flow and average values and standard deviations proportional to their respective operating income streams. The scenario that considers 50% replacement presents a high investment value in the plant's facilities. In addition, when compared to the other analyzed scenarios, it presents a drop in the average value, indicating a greater tendency to lower NPV values, when subjected to more extreme oscillations of the variables involved in the project. In short, this points to the greater risk involved in undertakings in this scenario.

As for the scenarios with funding, the data show a skewed distribution to the right in relation to the mean value for the 30%, 40% and 50% replacement scenarios. This is evidenced by the fact that the mode values are smaller than the mean and median values. For the 30% scenario, the curve is even steeper towards the lower end of the scale compared to the 40% and 50% graphs. For the 10% replacement scenario, it is possible to observe an asymmetrical distribution to the left in relation to the mean value. Thus, the values are concentrated at the upper end of the scale and are gradually distributed towards the lower end. In relation to the 20% replacement scenario, this presents a symmetrical distribution in relation to the mean, that is, the values remain close to the mean in a higher probability. Thus, from the results obtained, it is possible to verify that they do not tend to extreme values, that is, values that make the project unfeasible.

4. Discussion

The application of the MCM for feasibility analysis of the project without funding, confirmed that the 20% and 30% replacement scenarios are more viable, along with the scenario that considers 40% replacement, as they are less susceptible to uncertainties that can act together. These scenarios indicate that the availability of waste is satisfactory to meet the plant's operation, and that the probability of a negative NPV is zero for the analyzed variations. With the existence of funding, only the scenario that considers 20% fuel replacement by RDF is considered viable. In this cash flow, the NPVs are more likely to vary around the mean, with always positive values for the variations analyzed in this study. Scenarios with 30% and 40% replacement show a greater tendency for accumulated NPV at the lower end of the scale, with a greater probability of presenting NPV lower than the average.

It was possible to identify the variables most sensitive to changes: MARR and revenue on RDF sales in all years analyzed, followed by RDF availability and oil price occupying the third and fourth position, respectively, of contribution to the NPV.

Despite being economically viable, having legislation that encourages, technologies and availability of waste to produce RDF, one of the great challenges for the implementation of RDF plants in Brazil are the political barriers. If there is demand for the commercialization of RDF in Brazil, they can compete with existing sanitary landfill companies, which have a low cost compared to other technologies, and which currently have strong influence with the public authorities.

The country also presents delays in relation to subsidies and financial incentives that favor the use of RDF. Although financial incentives for waste energy recovery projects are provided for by Decree number 10,117/2019, the country still has difficulties in effectively expanding the use of waste for this purpose. In addition, the petroleum coke used in the cement industry is linked to the price of petroleum. When the price under fossil fuels is low, it competes with RDF more advantageously, negatively affecting demand for RDF in cement plants (CHAVES et al., 2021b).

The feasibility of using RDF also depends on the reliability of its uninterrupted supply, both in quantity and quality, and with relatively stable and financially viable prices in relation to fuels already used in the market. In addition, some uncertainties regarding the parameters considered by the study must be considered. These uncertainties in relation to the PERS policies, whether they will be relatively implemented as foreseen by the document, and whether the cement industries will accept the RDF and license their cement kilns to carry out the co-processing. Therefore, the assumptions considered in this study are crucial to guarantee the effective viability of this production.

If they are not present, it would not be possible to guarantee the financial viability of the undertakings. This justifies the lack of projects of this nature today. This study considered a situation of waste generation and implantation defined by Chaves et at. (2021b) in which policies were partially implemented, discarding an optimistic and ideal scenario for the sector. In this way, it is expected that the barriers in the implementation of policies for the sector, which have historically been presented, may affect the success and effectiveness deadlines of the projected actions. Despite this precaution, there are still risks regarding the implementation of actions, which would compromise the viability of the projects identified in this study. Therefore, the results presented must be analyzed from this perspective.

However, it is worth highlighting a pioneering initiative to encourage the sector in Brazil that came from the Votorantim group in 2019, which replaced fuel with RDF in a cement factory. Of the three cement industries located in the state of Espírito Santo, none of them are licensed to co-process waste, although they are interested in replacing fossil fuels as long as it is economically viable (Chaves et al., 2021a). This is yet another factor that could compromise the viability of the enterprise for producing RDF, as without local demand, the logistical costs for delivery to more distant locations could make the business unfeasible. The more cement companies adhere to co-processing, the more stable the market becomes, thus making investments less vulnerable. Thus, the maturation of the market makes more investors interested in RDF production plant projects. Therefore, actions to encourage the decarbonization of the cement sector can be a motivator for these companies to make the necessary adjustments to guarantee this licensing.

5. Conclusions

This study investigated the feasibility of implementing an RDF manufacturing plant for use in cement industries as a substitute for petroleum coke. For unfinanced cash flows, the scenarios that consider 20% and 30% replacement of petroleum coke by RDF stand out against the others. Both present a NPV that best behaves in the face of simulated variations. Furthermore, both have a higher IRR and a shorter payback time. In the scenario with financing, only the scenario that considers 20% fuel replacement by RDF stands out.

The tools used, such as sensitivity analysis and Monte Carlo simulation, provide the decision maker with a variety of possible results and their probabilities of occurrence, however their nature is subjective, requiring more accurate ratification of the estimates considered in this study. One of the alternatives to increase the accuracy of the information is to collect data from companies that work with the product, and that are similar in size to the projected one, to identify changes in variables over time in the market.

For future studies, it is suggested that uncertainties related to the composition of these wastes and their variations in LHV are also investigated, since the variation in the composition of USW is quite significant for the economic viability of the scenarios. Therefore, if an enterprise is implemented, a factor to be constantly checked refers to the composition of the waste destined to RDF production.

The financial viability assessment presented in this study can be used to analyze the implementation of an RDF plant for other locations, the input variables having to be changed, according to the demand of each region. To assess plant viability in each location, it is crucial to consider significant uncertainties in future waste generation rates and demand from the cement industries in these regions. In addition, the distance from the plant to the collection points and from the industries and the gravimetric composition of the waste must be considered, as these variables can make the project unfeasible and generate a negative NPV. Also, it may happen that some specific location presents other variables involved in long-term planning, and these should be considered by the study.

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Industry 4.0 Technologies in Effluent Management: Advancements and Opportunities

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Abstract

The growing urgency to address complex environmental issues has expanded research on the application of Industry 4.0 technologies, aiming to develop solutions to mitigate the impact of production systems on the environment, including the domain of effluent generation and treatment. Water, a vital element, faces increasing pollution threats, giving rise to ongoing concerns. In this context, the need to adopt measures to reduce polluting activities while simultaneously enhancing water treatment systems becomes imperative. Effluents, residual liquids resulting from various human activities, range from improperly disposed industrial waste to untreated sewage and intensive agricultural practices. Irresponsible disposal of these wastes into water bodies without proper treatment contributes to degrading water quality, causing profound and sometimes irreversible impacts. Proper management of these effluents is crucial to mitigate adverse effects and ensure sustainable water use. This article primarily focuses on seeking innovative and effective solutions for effluent treatment within the context of Industry 4.0. To achieve this, a Systematic Literature Review was conducted using the Web of Science and Scopus databases, employing the search string "Wastewater" And "industry 4.0." Out of the initially retrieved 17 articles, a selection was made to establish connections between various Industry 4.0 concepts and water resource management. This article contributes to the identification of technologies that support the effluent treatment process, linking Industry 4.0 concepts with water and wastewater management.

Keywords: *Industry 4.0, water treatment, effluent treatment.*

1. Introduction

The uneven distribution of water across the planet, exacerbated by climate change (Miguelez et al., 2023), poses a challenge, manifesting in regions with water shortages or excesses. This underscores the inherent complexity in the global management of water resources. The remarkable ability of water to dissolve various substances makes it susceptible to pollution. The difficulty in accessing adequate water and the pollution caused by direct discharge of effluents into water bodies highlight the importance of effluent collection and treatment systems in urban areas.

Proper effluent treatment is essential to eliminate or reduce pollutants, such as excess nutrients, heavy metals, and pathogens (Matheri et al., 2023; Heo et al., 2021), ensuring conditions for reuse (Pandey et al., 2022). This process, undertaken by various companies, is crucial to minimize negative impacts and ensure water sustainability. Effluent Treatment Stations (ETS) play a pivotal role in this continuous and uninterrupted process (Miguelez et al., 2023).

Thus, effective management of effluent treatment requires enhancements (Pandey et al., 2022), aiming for quality and ongoing improvement of water supply chains that are imperative to promote environmental sustainability (Crisan & Korodi, 2018).

The perspective of Industry 4.0 emerges in an interconnected global context, transformed by Information and Communication Technologies (ICT). In this technological landscape, the Internet of Things (IoT), Internet of Services (IoS), and cyber-physical systems establish connections both within and outside the industry, interlinking supply chains (Bonilla et al., 2018). These innovations play a fundamental role in environmental preservation, enabling real-time monitoring, resource optimization, and the adoption of eco-efficient practices, as emphasized by Uwamungu et al. (2022).

Therefore, the purpose of this article is to analyze the impact of Industry 4.0 technologies on effluent treatment management, emphasizing their ability to enhance processes, elevate water standards, and promote environmental preservation.

1.1 The Effluent Treatment Process and Industry 4.0

By removing or reducing harmful substances and contaminants present in wastewater, such as excess nutrients, heavy metals, and harmful microorganisms (Matheri et al., 2021; Narendar et al., 2022), it becomes possible to prevent water pollution, minimize damage to ecosystems, and reduce risks to human health, thereby enabling the safe use of treated water in various activities. This approach not only contributes to environmental preservation but also facilitates the potential for responsible reuse of treated water. The stages of the effluent treatment process are illustrated in Figure 1.

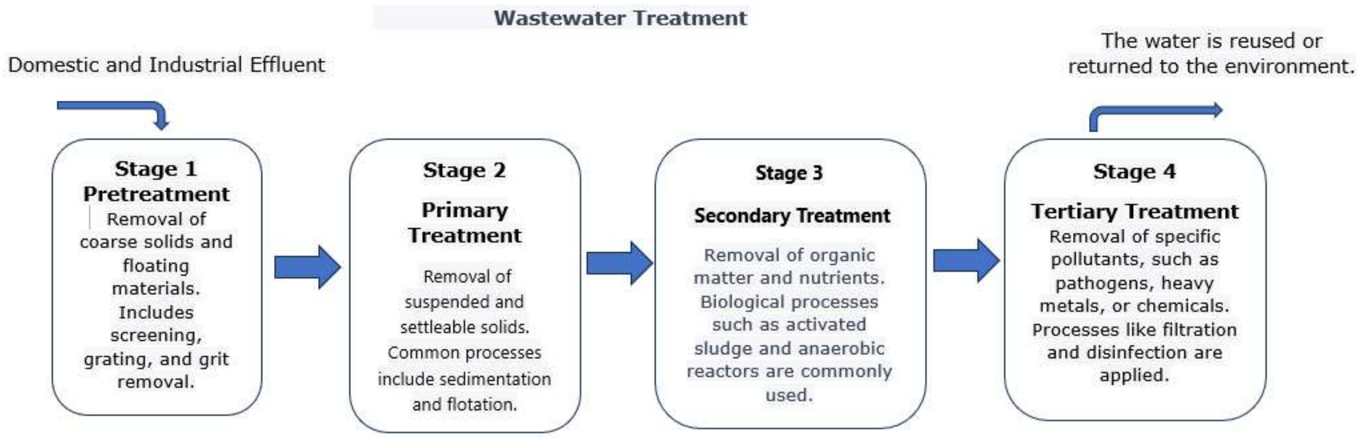

Figure 1 - Stages of Wastewater Treatment

Source: Adapted from Pandey et al. (2022)

In the management of effluent treatment, the perspective of Industry 4.0 emerges as a paradigm with the potential to enhance efficiency. This approach encompasses the integration of advanced technologies and intelligent systems within the industrial context, aiming to optimize production processes, streamline information communication, and acquire accurate and up-to-date data about operations (Ding, 2018; Pandey et al., 2022).

2. Method

This article is the outcome of a systematic literature review (SLR) aimed at identifying the relationship between Industry 4.0 and effluent treatment, addressing the following research question: How do Industry 4.0 technologies impact effluent treatment management? Okoli's studies (2015) served as the reference point. The search string "Wastewater AND Industry 4.0" was employed across all fields in the Scopus and Web of Science databases. The SLR protocol, as outlined by Okoli (2015), was executed in four stages, detailed below:

Stage 1: Planning

Objective: Identification and formulation of research question.

Protocol: Development of the research design.

Stage 2: Selection

Practical screening: Definition of search criteria, including databases.

Literature search: Scopus and Web of Science databases using the string: "Wastewater AND Industry 4.0."

Results: Scopus: 41 articles, WOS: 24 articles = Total: 65 articles

65 articles - 22 duplicate articles = 43 articles

43 articles - 5 articles not accessible = 38 articles

Stage 3: Data Extraction

Analysis and evaluation of articles based on the research question:

38 articles - 21 articles with a different focus than the research question = 17 articles

Stage 4: Execution

Conducting synthesis of articles:

• Implementation of structuring, merging, and analysis of articles.

Compilation of critical analysis and summary on the addressed topic.

3. Results

After the completion of practical screening and literature search, 17 articles were selected and are listed in Table 1, showcasing a direct relevance to the addressed topic.

Table 1 - List of Selected Articles in the Systematic Literature Review

Source: Prepared by the authors

Nº	Tema /Foco	Autores	Year
1	Relaciona os diferentes princípios da Indústria 4.0 com a administração de recursos hídricos, incluindo água e efluentes.	Shivam Pandey et al	2022
2	Examina diversas estratégias de Inteligência Artificial (IA) e sua aplicação potencial no processo de tratamento de água.	Jean Yves Uwamungu et al	2022
3	Renovar e proteger infraestruturas críticas que fornecem água e fornecem purificação de água	Cristina Villar Miguelez et al	2023
4	Apresenta uma estrutura de controle preditivo projetada para otimizar a eficiência energética em instalações de tratamento de águas residuais.	Ruben Crisan et al	2018
5	Obter uma melhor precisão deprevisão no modelo de tratamento de águas residuais	Narendar Singh D et al	2022
6	Propõe um modelo híbrido de previsão de influentes baseado em aprendizagem profunda	A. N. Matheri et al	2023
7	Propõe um modelo de previsão ME-DeepL proposto combina a força de vários algoritmos de aprendizagem profunda numa arquitetura de aprendizagem	SungKu Heo et al	2021
8	Faz uma análise da circularidade sustentável e das operações inteligentes baseadas em dados e do controle da estação de tratamento de águas residuais	Anthony Njuguna Matheri et al	2022
9	Propõe um modelo que monitora os sólidos suspensos totais (TSS) e sedimentáveis (SetS) nas águas residuais	Railson de Oliveira Ramos et al	2022
10	Apresenta um quadro baseado na IoT para monitorizar a produção de resíduos alimentares e a utilização de energia e água no setor alimentício	Sandeep Jagtapa et al	2021
11	Propõe modelo baseado em IA foi amplamente testado na gestão das operações de tratamento de águas residuais.	Anthony Njuguna Matheri et al	2021
12	Mostra a aplicação de Controlador de Modelo Interno baseado em Redes Neuronais Artificiais (RNAs)	Ivan Pisa et al	2020
13	Identifica as principais barreiras para implementar a circularidade no sistema inteligente de gestão de água	Qinglan Liu et al	2021
14	Fornece uma revisão abrangente da aplicação atual de ferramentas baseadas em IA na simulação de processos de tratamento sustentável de água e efluentes	Nguyen Duc Viet et al	2021
15	Propõe o monitoramento para prevenção por meio do monitoramento da infraestrutura de saneamento como águas residuais	Hana Efendić et al	2022
16	Propõe a aplicação de técnicas de TL para derivar novas estruturas de controle baseadas em RNA (Redes Neuronais Artificiais)	Ivan Pisa et al	2023
17	Propõe a otimização da biodegradação de poluentes orgânicos ecotóxicos encontrados em águas residuais industriais	Priya et al.	2023

3.1 Analysis of Articles Using VOSviewer

To facilitate the qualitative analysis of the articles, the VOSviewer software was employed. VOSviewer is a software tool for constructing and visualizing bibliometric networks, which was used on the data provided by Scopus and Web of Science to extract keywords and terms with frequent occurrences. The software generated the cluster shown in Figure 3.

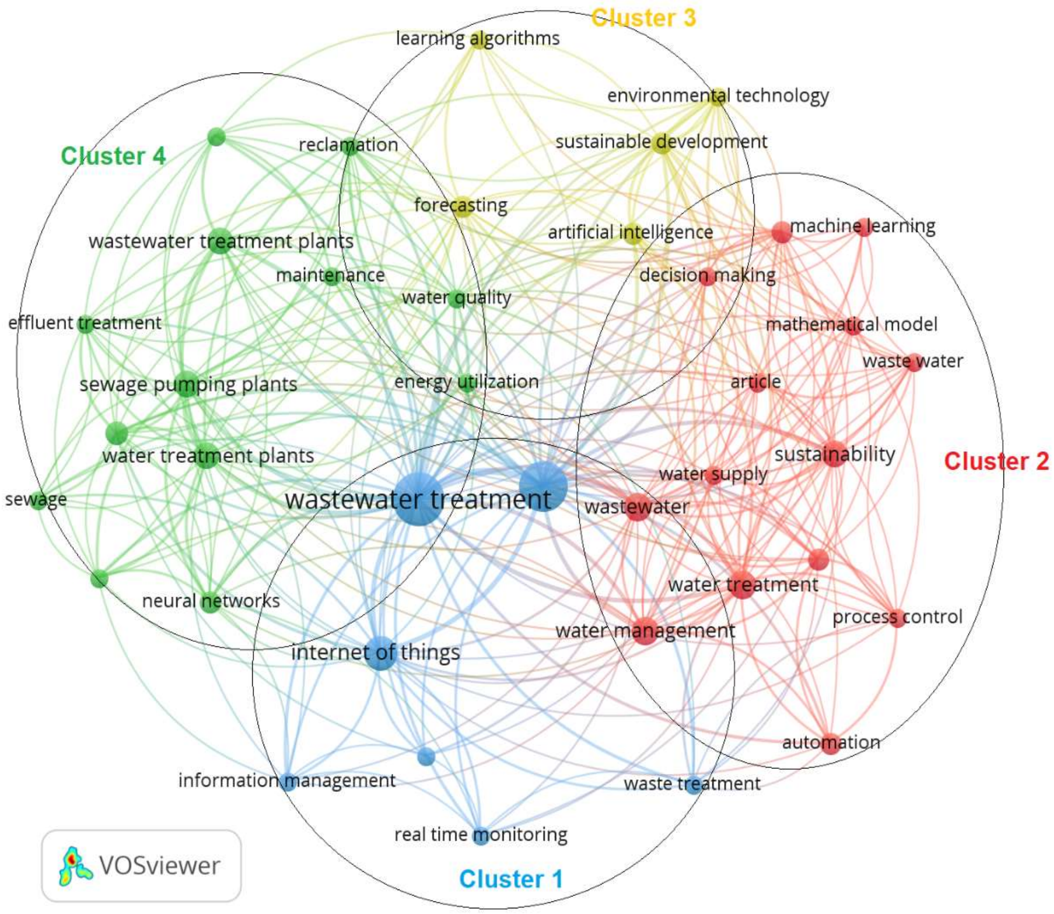

Figure 2 - Representation of Themes around Wastewater Treatment

3.2 Cluster Analysis and Discussion

Figure 3 highlights four clusters related to wastewater treatment:

Cluster 1 establishes a connection between IoT, information management, and real-time monitoring in the context of wastewater treatment.

Pandey et al. (2022) emphasize that the IoT system in wastewater treatment serves various functions, including data collection on wastewater, remote monitoring of post-treatment water quality, and the accessibility of this information through cloud and mobile devices in an easy and instantaneous manner. The rapid adoption of advanced technologies such as IoT and AI optimizes the efficiency of treatment facilities, enabling remote monitoring, real-time analysis, and responses to events, as well as continuous process optimization, including predictive control, as discussed by Crisan & Korodi (2018). Uwamungu et al. (2022) highlight that real-time information management empowers autonomous decision-making processes, asset monitoring, and operations.

In Cluster 2 - The themes encompass Machine Learning, Decision Making, Mathematical Modeling, Sustainability, Water Management, Process Control, Automation, and Water Treatment.

Matheri et al. (2023) suggest the use of machine learning algorithms to identify subtle contaminations, ensuring regulatory compliance and environmental and public health safety. Uwamungu et al. (2022) propose a mathematical prediction model for variables. IoT and automation, emphasized by Pandey et al. (2022), lead the evolution, enabling the elimination of hazardous tasks and a more proactive approach to reduce operational costs, as highlighted by (Jagtap et al., 2021).

The importance of digital twins in monitoring and management, particularly in the control of water treatment processes that optimize operation and response to changes, is highlighted by (Matheri et al., 2022). These approaches converge toward intelligent water management, especially in Smart Cities, as proposed by (Miguelez et al., 2023). The goal is to enhance efficiency, ensure regulatory compliance, and strengthen security in water resource management.

Cluster 3 - Highlights the themes: learning algorithms, environmental technology, sustainable technology, sustainable development, forecasting, decision making, energy automation, artificial intelligence.

The studies by Pisa et al. (2020) demonstrated a robust performance of prediction and control networks. Furthermore, Liu et al. (2021) emphasizes that IoT and big data are promising tools to enhance environmental care, promoting sustainability. The ability to anticipate issues and adjust operations proactively, as observed by Ramos et al. (2022), also plays a crucial role in reducing risks and financial costs. AI-based models have been widely employed for simulation and optimization of complex processes (Viet et al., 2021).

Cluster 4 - Highlights the themes: Reclamation, wastewater plants, maintenance, water quality, sewage pumping plants, water treatment plants sewage, neural networks.

There are notable advancements in water recovery technologies in water management, enabling the production of water of various qualities, as emphasized by Liu et al. (2021), suitable for both potable and non-potable uses. However, meticulous precautions in wastewater treatment plants (WWTPs) are crucial, as highlighted by Matheri et al. (2021), due to varied operational conditions that can have serious implications for public health and the environment, affecting flora and fauna. Furthermore, Matheri et al. (2023) stresses that water from sewage systems can anticipate disease outbreaks in urban populations, underscoring the need for surveillance and proper treatment. In this context, Heo et al. (2021) focus on the application of neural networks for automated extraction of key features from datasets, providing tools to address challenges related to public health and water issues.

4. Conclusion

The convergence of Industry 4.0 with wastewater treatment brings forth crucial opportunities and challenges. Advanced technologies such as the Internet of Things (IoT), artificial intelligence, and big data analytics have the potential to revolutionize water management and environmental preservation.

The adoption of Industry 4.0 technologies in industrial wastewater treatment offers substantial improvements, including enhanced operational efficiency, superior quality of treated water, and informed decision-making (Efendić et al., 2022). However, addressing challenges such as technological integration, regulatory compliance, and organizational adjustments requires strategic and collaborative approaches across multiple sectors.

In a context of growing water scarcity, the recycling of water from effluents gains relevance, further highlighting the role of Industry 4.0 (Pisa et al., 2023). Circular economy and responsible use emerge as vital strategies to ensure the future availability of this essential resource (Priya et al., 2023), aligning with global sustainable development goals.

This study contributes to the academic discourse on the relationship between Industry 4.0 and wastewater treatment through a systematic literature review. However, it is important to acknowledge that the scope of this field is broad and complex, extending beyond the boundaries of this study in terms of potential technological applications and discoveries.

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Life Cycle Assessment of Concrete Blocks Production From Fiberglass Residues: An Industrial Ecology Application

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Abstract

This article aims to study the environmental viability of using waste fiberglass in the manufacture of concrete blocks for civil construction, in an Industrial symbiosis (IS). According to the literature, the simulated percentage was 15% of the fiberglass residue replacing gravel and stone dust without this negatively altering its mechanical properties. Currently, these residues that are generated in the manufacture of reservoirs and their destination is the landfill. The study region is favorable since we have many factories of fiberglass reservoirs and concrete blocks in the region of the cities of Ribeirão Pires and Mauá, São Paulo, Brazil. Life cycle analysis (LCA) was adopted for this study, and impact categories GWP - Climate change, FFP - Fossil depletion and LOP - Natural land transformation.

Keywords: waste fiberglass, concrete blocks, Life Cycle assessment, ecology

1. Introduction

The planet's carrying capacity is limited and requires urgent action to preserve our future. As highlighted by Odum (2006), it is essential to reduce the consumption of materials and energy, as well as to generate less waste, in order to build a sustainable world. We must adopt a holistic approach to better understand the world as an integrated system, considering the environmental, social and economic impacts of our actions. Only then can we guarantee a prosperous future for present and future generations.

In this context, industrial ecology, circular economy and cleaner production emerge as key approaches to promoting sustainable development. According to Weizs (2015), Industrial Ecology is increasingly sought for a better understanding of the interactions between society, technology, resources and the environment. Ayres (2002) argues that industrial ecology seeks to create an industrial system inspired by the principles of natural ecosystems, where waste from one process becomes resources for another. For Geissdoerfer et al. (2017), combining industrial ecology with the principles of circular economy seeks to maximize the efficient use of materials and energy throughout the life cycle of products, reducing the extraction of natural resources and waste generation. Cleaner production, a concept introduced by Fiksel (2006), complements these approaches by emphasizing the minimization of environmental impacts during the production process, through the adoption of more efficient technologies and the replacement of toxic inputs with more sustainable alternatives. All these strategies contributes to reducing the consumption of non-renewable natural resources, as pointed out by Chertow (2004). The integration of these concepts brings significant economic and environmental benefits, since using the waste diverted to landfills as raw material for another process minimize resource dependency and improved the sustainability; among hundred others examples, see Agudo et al. (2022) for the photovoltaic equipment. The circular economy also provides innovative business opportunities, such as recovering valuable materials from discarded products (Bocken et al., 2016).

An essential aspect emphasized by the UN (2021) towards sustainability is that local and regional solutions are crucial to address the specific challenges of each region, considering local stakeholders in the process of implementing the sustainable development goals. By seeking solutions adapted to local realities, it is possible to take advantage of existing knowledge, resources and capabilities to drive significant change. Experience in small-scale industrial sectors shows that new solutions can grow and become part of the mainstream in markets and societies only after they have influence at least 20% on the market (Rockström, 2015). However, for effectively implementing cleaner production, circular economy and/or industrial ecology concepts, a change of mindset is required both companies and society. This involves creating public policies that encourage sustainable practices, as well as raising awareness and providing education/information about the benefits of industrial ecology, circular economy and cleaner production.

The combination of industrial ecology, circular economy and cleaner production represents a comprehensive and promising approach to address the current environmental and economic challenges. By adopting these concepts, more efficient production system are obtained, reducing the consumption of materials and energy at the same minimizing waste generation. From others economic processes, the civil construction industry presents itself as a prominent sector to put in practice these concepts for sustainability, since it intensively demands natural resources such water and abiotic materials, besides demanding energy direct and indirectly (Zhang et al., 2022). According to Lamba et al. (2022), to achieve environmental sustainability in the civil construction industry, the natural capital must be considered as a limited source of resources, and thus the production of more sustainable materials based on by-products from other industries has recently gained more attention.

Urbanization, in turn, is an increasingly evident trend due to the increase in the world population and migration to urban areas. This trend leads to an increase in demand for housing and urban infrastructure, resulting in increasing consumption of building resources. Urban growth exerts pressure on building materials production systems, with significant impacts on natural resources and the environment. Given this scenario, it is essential to seek local/regional solutions that allow reducing the environmental impact of civil construction and promoting sustainability. Civil construction is a sector that consumes a significant amount of materials, among them fiberglass tanks and concrete blocks are widely used. However, it is important to highlight that the manufacture of these reservoirs generates a considerable amount of inert by-product (waste) that is often sent to landfills. Applying the industrial ecology concept on this industry, one alternative is the inclusion of these residues into the concrete blocks, as suggested by Reis et al. (2021). This practice, known as incorporation of inert waste, contributes to reducing the demand for virgin raw materials and the amount of by-products diverted to landfills is reduced. In addition to the environmental benefits, this practice can also generate economic benefits, such as the costs reduction in acquiring raw materials and with the disposal waste. As highlighted by Tao et al. (2023), the incorporation of waste in concrete-based products can result in products with satisfactory technical characteristics, without compromising the quality and resistance of the material.

The objective of this study is to evaluate the environmental performance of reusing of inert waste from the fiberglass tanks manufacture as raw material for concrete blocks production. The life cycle assessment is the method considered to provide quantitative indicators supporting comparative discussions. It is expected that evaluated case can be validated from an environmental perspective looking for more sustainable civil construction industries.

2. Methods

2.1. Case study description

In the Brazilian region focused in this study, there are many companies of fiberglass tanks and concrete blocks. This region has high economic power, it is located close to the São Paulo metropolitan region (~22 million inhabitants), and it is currently under urban development, which explains the existence of such kind of companies producing important materials for construction of houses, buildings, and other important infrastructures for urban expansion. The proximity of producers and users results in savings for transportation processes, that is why those companies are located in such region. As represented in Fig. 1(a), the usual fiberglass and concrete production follows the traditional linear way of production. While producing concrete blocks generates zero solid waste (concrete waste is circulated back internally as raw materials), the fiberglass production generates solid wastes that are currently send to regional landfills for proper management according to Brazilian laws. Both production systems operates separated, showing a potential in applying industrial ecology concepts by considering the waste generated by fiberglass company as raw material for the concrete blocks company. This approach, as represented by Fig. 1(b), indicates a potential improvement on environmental issues, since a reduced amount of fiberglass is diverted to landfills, while the concrete blocks company is potentially reducing its environmental load by replacing some virgin materials (gravel and rock dust) by the fiberglass waste. Red lines in Fig. 1(b) indicates the relationship between both companies after implementing the industrial ecology scenario that would affect positively the material flows of raw materials to concrete blocks company, as well the waste generation by fiberglass tank company. Specifically for the region evaluated (including Ribeirao Pires and Maua cities), there are about seven fiberglass tanks companies producing about 384,000 kg/yr of tanks, and generating about 19.2 ton/yr of waste. Additionally, there are twelve concrete blocks companies operating, producing about 23,760 tons/yr of concrete blocks. These numbers shows the existing regional potential in using fiberglass waste as raw materials for concrete blocks.

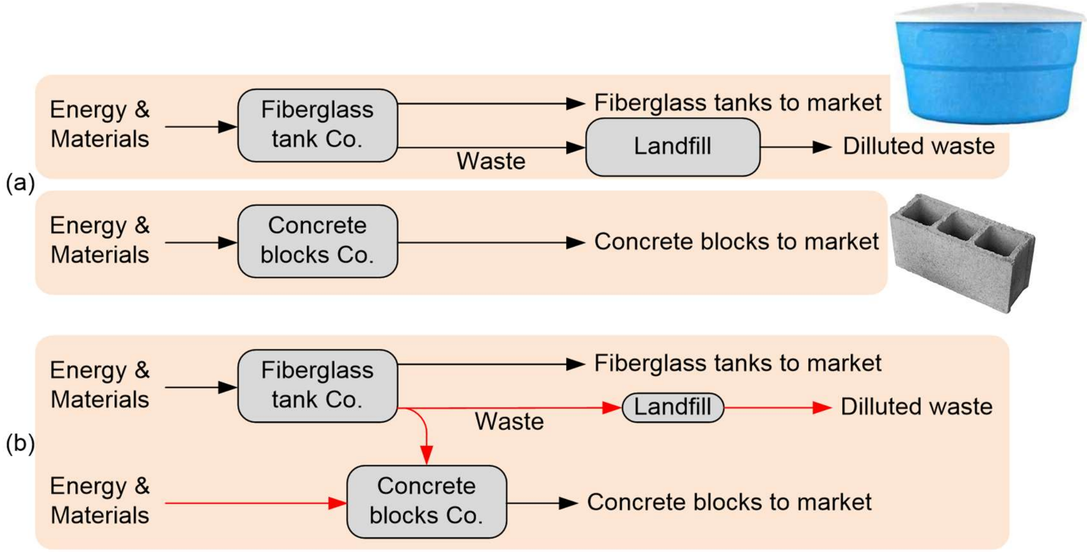

Fig. 1. Schematic representation of (a) traditional and separated way of producing fiberglass tanks and concrete blocks, and (b) an alternative way of synergic production when applying the concept of industrial ecology. Red lines in (b) represents the flows of energy, materials and waste affected after implementing the proposed eco-technology.

2.2. Life cycle assessment

Life cycle assessment (LCA) is the method considered in this study to quantify environmental burdens that would sustain a discussion about the environmental performance of the proposed synergic use of fiberglass waste as raw material for concrete blocks production. To accomplish the goals of this study, the spatial boundaries includes exclusively the concrete blocks Co., since the fiberglass waste considered as input for the concrete blocks production has 'zero burden' embodied. In other words, none environmental impacts are included in the fiberglass waste, since it is considered as a by-product of fiberglass tanks production that has no market value and would be diverted to landfills.

Exclusively primary data are used in this study, obtained from technical *in situ* fieldwork at fiberglass tank and concrete blocks companies. Although all data for inventory analysis are initially quantified considering a year as temporal boundary, and all infrastructure and equipment are quantified considering their life spam, the functional unit adopted is 1 ton of concrete block (ton_{block}) produced. Recipe midpoint (Hierarchist) is the LCI method applied, considering the following three impact categories: climate change (100yrs), fossil depletion and natural land transformation. These categories were chosen due to their representativeness in the cases studied (civil engineering area), as also considered by Colangelo et al. (2020) and Pešta (2022) in their LCA study of lightweight concrete block. All LCI coefficients comes from the Ecoinvent® database, version 3.8 (2021), considering the allocation at the point of substitution approach. Appendix A shows all LCI coefficients used in this study.

Since the fiberglass waste are diverted to concrete blocks production, there is no need for transporting the fiberglass until the landfill and even all associated environmental burdens in the landfill operations. This avoided emissions (or avoided environmental burdens) are accounted in this by using the numbers provided by Sulis et al. (2021). Specifically, the values of 8.31 kgoil-eq./ton waste (fossil depletion) and 202.52 kgCO2-eq./ton waste (global warming potential) are considered. These authors did not considered the impact category natural land transformation in their study, which is why it was disregarded also here. The landfill studied by Sulis et al. (2021) and the distance considered by them from waste source until the landfill location are somehow different from the ones evaluated in this present work, which will demand future efforts to improve their accuracy.

2.3. Sensitivity analysis for fiberglass waste transportation

A key aspect when dealing with by-products of one company that is considered as raw material for another company is related to the transportation phase. Uherek et al. (2010) state the importance of considering transport into the LCA calculations since burning diesel in road vehicles engines is a source of emissions, and it may have huge influence on final LCA numbers. Transporting the by-products requires mainly equipment such as trucks and energy, usually diesel. Indirect emissions causing environmental impacts are embodied in both, while direct emissions are a result of diesel burning in engines. Recognizing the importance of transportation phase in the evaluated case study, a sensitivity analysis is performed by ranging the distance of transporting the fiberglass waste until the concrete block company, assessing the influence of such environmental impact into the total generated impact by concrete blocks produced. The goal of this sensitivity analysis is to assess the maximum distance in which the fiberglass waste can be transported to achieve, at least, similar performance for the LCA impact categories as for traditional concrete blocks without using fiberglass waste. For calculation purposes, the coefficient of 1,223 $kgCO_{2\text{-eq.}}$/ton km from Agostinho et al. (2019) is considered, however, since authors have accounted for the trucks, diesel, road implementation and its maintenance without applying any allocation approach (not only trucks use the road 100% of time), we have assumed 50% of this value at this moment, but aware that efforts are needed to obtain more accurate values. Important to emphasize that transportation simulation is performed exclusively for climate change indicator due to data availability.

2.4. Approach for results discussions

To allow a broader understanding of results and accomplishing the initial objectives of this study, the obtained results are discussed in two different ways: (a) The LCA results for traditional and alternative concrete blocks production are presented to identify those most impacting items on total LCA impacts, as well to allow a direct comparison between both concrete block production systems; (b) Include the transportation step of fiberglass waste to the concrete blocks company, initially ranging the transportation distance in 10km, 50km and 100km as a way to assess the maximum allowed distance that would result in similar LCA impacts for the traditional concrete blocks production.

3. Results and Discussions

3.1. Life cycle assessment for traditional and alternative concrete blocks production

Fig. 2 shows the energy diagram of concrete blocks production from both, traditional and the alternative way using fiberglass waste. The larger figure at the bottom represents the traditional way in producing concrete blocks, which demands external resources from the economy such as gravel, rock dust, water (from municipal treatment plants), cement, electricity and labor. All these resources requires payment, which is symbolized by the interaction among them with the services external source, as well the by the monetary flows in dashed lines. The unique external natural energy source is the solar radiation, used for the drying internal process. Internal processes include, in order, mixing the raw materials in specific equipment powered by electricity, and then the resulting material is modelled, dried under solar radiation, and send to the market for use in building constructions. Concrete blocks production are guided by Brazilian standards related to size and mechanical properties. Wastes generated during blocks production in the molding and/or drying processes are cycled back to the mixer process after milled, resulting in zero solid waste generation. Direct labor is used in all processes.

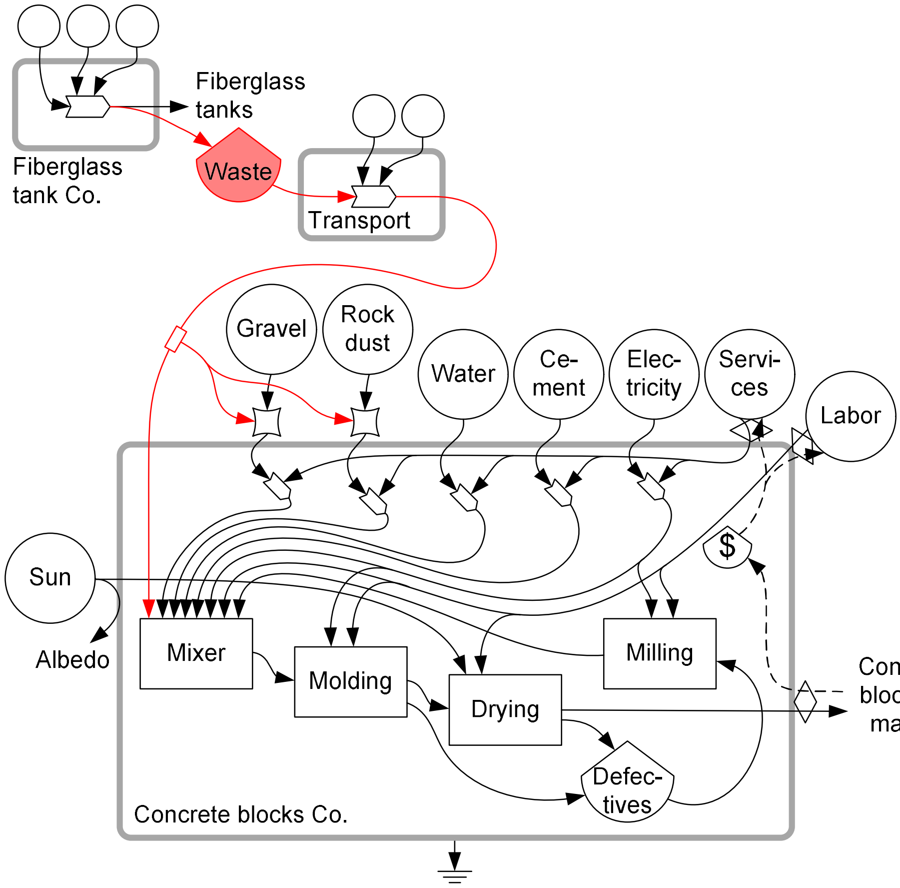

Fig. 2. Energy diagram of fiberglass tank production. Lines and symbols in red indicates fiberglass waste flow to concrete blocks production. Symbols from Odum (1996). Legend: Circles means external energy sources, internal rectangles means internal processes, largest external rectangle indicates system boundaries, tank symbol means storage, continuous line means flows of energy and/or matter while dashed lines means monetary flows, and wide arrow means interaction of flows.

The alternative concrete blocks production includes, besides the traditional blocks production from the bottom of Fig. 2, the two subsystems located in the top. Initially, there is the fiberglass tank Co. that produce tank for the market and generates fiberglass residues as by-product. Residues comes mainly from two different internal process, including spray up (where small-sized fiberglass is mixed with resin and pulverized onto the mold), and filament winding (where long fiberglass mixed with resin is rolled-up onto the mold); residues contains fiberglass in different sizes mixed with resin. This residue is characterized as an inert material that is currently diverted to specific landfills for its proper management according to Brazilian laws. Instead of landfilling the fiberglass waste, it is transported until the concrete blocks company and considered as raw material for concrete production, partially replacing gravel and rock dust inputs. According to Asokan et al. (2010), fiberglass waste can replace up to 15% of gravel + dust rock materials without compromise the structural functions of concrete blocks; this percentage is assumed in this work for LCA calculations. Red lines connecting the main concrete production system of Fig. 2 with the

two subsystems indicates the pathway of fiberglass from its generation until its use in the concrete blocks production. Important to note that using fiberglass waste reduces the demand for gravel and rock dust (as represented by the switch symbol), as well zeroing out the amount of fiberglass that would go to landfills. These characteristics are strongly related to circular economy, cleaner production and industrial ecology concepts.
As hypothesis, it is expected that using the fiberglass waste in the concrete blocks production would result in environmental benefits, but before confirming such hypothesis, it is important to apply the LCA on the studied case. Table 1 shows the inventory step for the concrete blocks production plant, including the main inputs of materials and energy as previously identified in Fig 2. Blocks production includes very simple processes that demand as materials the steel for machineries (divided by their life spam), gravel, rock dust, water and cement, and electricity from national grid as energy source. In mass units, gravel and rock dust are the most demanded materials with 9.14E05 kg/yr each, followed by cement 1.52E05 kg/yr and water 1.16E05 kg/yr. The studied concrete block plant produces ~1,980 ton of blocks per year (2022 baseline), considered a small plant; the region considered in this study has twelve similar small concrete blocks companies. Table 1 also shows the LCI impact coefficients for each item and impact category, as detailed in Appendix A. Interesting to note that steel and cement have the highest coefficient values comparatively with all other items, meaning that even using a small amount of them would result in larger impacts.

Table 1. Inventory for the concrete blocks company. Primary data for 2022 yr base obtained *in situ*.

Item	Input or Output	Amount	Unit /yr	LCI coefficients [a]		
				$kgCO_{2\text{-eq.}}$ /Unit	$Kg_{oil\text{-eq.}}$ /Unit	m^2 /Unit
Steel (machinery)	Input	1.36E03	kg	2.1101	0.57523	0.00048187
Gravel	Input	9.14E05	kg	0.0049416	0.0014288	3.2396E-06
Rock dust [b]	Input	9.14E05	kg	0.0049416	0.0014288	3.2396E-06
Water	Input	1.16E05	kg	0.00019934	5.4349E-05	1.2242E-07
Cement	Input	1.52E05	kg	0.82814	0.089315	6.8232E-05
Electricity	Input	1.21E04	kWh	0.064956	0.0012364	0.00011074
Concrete blocks	Output	1.98E06	kg	n.a.	n.a.	n.a.

[a] Appendix A.; [b] Due to lack of available data, LCI coefficients for rock dust were assumed as equal to gravel.; n.a. = non-applicable because concrete blocks is a system output rather than an input.

Table 2 shows the LCA impact categories for both, the traditional and alternative concrete blocks production. Initially, it can be observed that although in the third position for input material in mass units (Table 1), the cement is the most contributor for all three LCA impact categories, achieving 90.8% for climate change (GWP), 79.9% in fossil depletion (FFP), and 56.6% in natural land transformation (LOP). This highlights the importance in using methods such as LCA to quantify environmental burdens instead of considering exclusively the absolute amount in mass units of materials or direct emitted gases. Important to highlight that concrete blocks production has none direct emissions (none internal combustion or fermentation processes), but it has indirect emissions as accounted for by the LCA method. Exclusively for LOP category, gravel and rock dust appears as some importance on total, achieving 16.1% each.

From an overall performance, Table 2 shows that traditional and alternative concrete blocks have the same performance for GWP (achieving ~69 $kgCO_{2\text{-eq.}}$/ton block) and FFP categories (~8 $kg_{oil\text{-eq.}}$/ton block). Larger difference is observed by the LOP category, but it can also be considered as similar (~0.009 m^2/ton block) due to existing data inaccuracies. These results indicates that replacing 15% in mass of gravel and dust rock by fiberglass waste has insignificant advantage for concrete blocks production from an LCA perspective. On the other hand, when accounting the avoided emissions of fiberglass transportation and landfill operation that are no longer needed, results indicates advantages for the alternative concrete blocks, achieving 7.91 $kg_{oil\text{-eq.}}$/ton block (6.7% reduction from traditional concrete block), and 55.63 $kgCO_{2\text{-eq.}}$/ton block (20% reduction). Although these numbers still needs efforts to improve their accuracy (from the original coefficients provided by Sulis et al., 2021), the partial obtained results are optimistic.

Table 2. Life cycle assessment impact categories for traditional and alternative (using fiberglass waste) concrete blocks production.

Item	GWP - Climate change (100yrs)		FFP - Fossil depletion		LOP - Natural land transformation	
	$kgCO_{2\text{-eq.}}/ton_{block}$	%	$kg_{oil\text{-eq.}}/ton_{block}$	%	m^2/ton_{block}	%
Steel (machinery)	1.45	2.07	0.40	4.60	3.31E-04	3.58
Gravel	2.28	3.26	0.66	7.69	1.50E-03	16.18
Rock dust [b]	2.28	3.26	0.66	7.69	1.50E-03	16.18
Water	0.01	0.02	0.00	0.04	7.17E-06	0.08
Cement	63.57	90.83	6.86	79.90	5.24E-03	56.67
Electricity	0.40	0.57	0.01	0.09	6.77E-04	7.32
Total for traditional concrete block [a]	69.99	-	8.58	-	9.24E-03	-
Total for alternative concrete block [b]	69.65	-	8.48	-	9.02E-03	-
Total for alternative concrete block with avoided emissions [c]	55.63		7.91		n.a.	n.a.

[a] Results from data presented in Table 1. [b] Calculated by replacing 7.5% (4.27E-01 ton_{gravel}/ton_{block}) of gravel and 7.5% (4.27E-01 $ton_{rock\text{-}dust}/ton_{block}$) of rock dust by fiberglass waste, based on Asokan et al. (2010). [c] Calculated considering the avoided emissions of fiberglass transportation to landfill, and the landfilling operations: fossil depletion 6.92E-02 $ton_{fiberglass}/ton_{block}$ 8.31 $kg_{oil\text{-eq.}}/ton_{fiberglass}$ = 0.58 $kg_{oil\text{-eq.}}/ton_{block}$, global warming 6.92E-02 $ton_{fiberglass}/ton_{block}$ 202.52 $kgCO_{2\text{-eq.}}/ton_{fiberglass}$ = 14.02 $kgCO_{2\text{-eq.}}/ton_{block}$. n.a. = not available

From a simulation exercise by changing the fraction of fiberglass usage, Fig. 3 indicates an expected linear decrease for the two LCA categories. For climate change, Figure 3 shows that replacing 20% of the current gravel & rock amount would achieve more than 50% reduction on environmental burdens for this LCA category, and that a ~38% substitution achieves the 'zero emissions' for this category. Different behavior is observed for the fossil depletion category, because to achieve a 50-% reduction in its value would demand about 50% of fiberglass waste usage, and a 'zero emissions' is achieved only after ~95% of fiber glass. Natural land transformation LCA impact category in not included at this time due to lack of LCI coefficients.

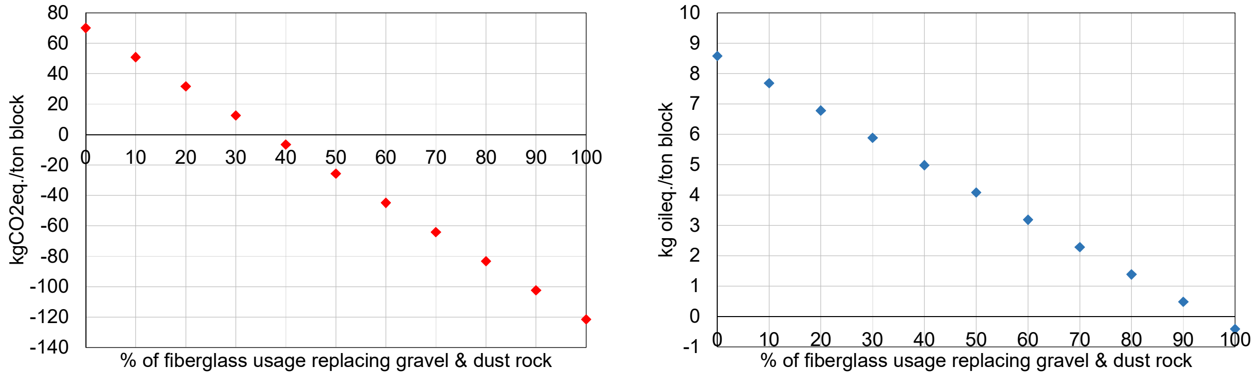

Fig. 3. Results for LCA impact categories simulation by changing the percentage of fiberglass waste usage for concrete blocks production. Avoided emissions are included. Natural land transformation category is not included due to lack of LCI coefficient its avoided emissions.

3.2. Including transportation step in the alternative concrete block's LCA performance: a sensitivity analysis

Fig. 4 shows the behavior for climate change LCA impact category by considering different distance in transporting fiberglass waste to concrete blocks production. It becomes clear that transport phase is of paramount importance for the evaluated system, since very few distances such as 5 km results in 267 $kgCO_{2\text{-eq.}}/ton_{block}$, a value about 4.8 times higher than when transportation is excluded from calculations. As argued before, the LCI coefficient for transportation considered in the calculations must be deeper verified, thus conclusions on this regard would be premature. However, as also identified by Uherek et al. (2010), transportation phase show to have an important role in the environmental burdens for systems operating under industrial ecology concepts using abiotic by-products of one industry as raw materials for other industries.

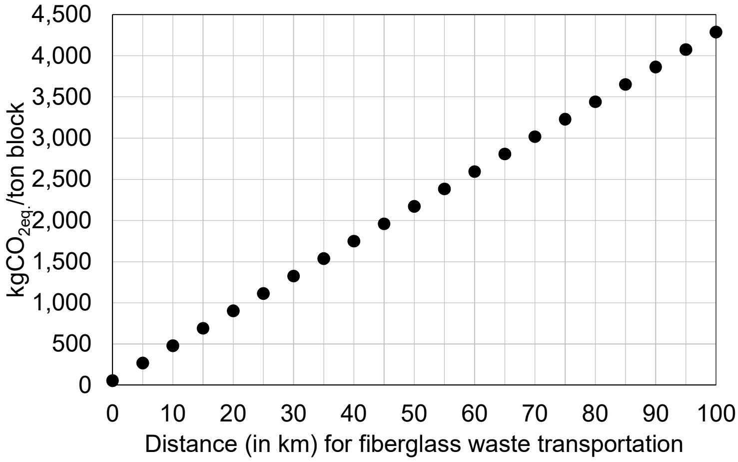

Fig. 4. Simulation for climate change for different distances of fiberglass transport from fiberglass tank Company until the concrete block Company.

3.3. Limitations of this study

The avoided emissions were considered by using the coefficients provided by Sulis et al. (2021) that evaluated organic waste generation, its transport until landfill, and all landfilling operation as spatial boundaries. However, the distance for transportation and the kind of landfill are two issues to be better evaluated. The distance considered by Sulis et al (2021) is a very particular case, with 25,2 km, which can be different to the fiberglass transportation to concrete blocks company that operate very close each other, in clusters. Another aspect is related to the landfill studied by Sulis et al (2021), which is a traditional landfill focused on solid urban waste treatment, but the fiberglass waste must be managed by a different landfill to treat inert wastes according to the Brazilian rules. This could lead to higher or lower environmental burdens.

The 1,223 $kgCO_{2\text{-eq.}}$/km ton considered climate change LCI coefficient for transport from Agostinho et al. (2019) needs to be verified since it was calculated considering a much larger spatial scale than needed for this present study. Although we have assuming 50% of its value, still amendments are needed for a more accurate value.

Other limitation is related to the capacity of regional companies in generation fiberglass waste and the capacity of the concrete blocks companies in absorbing it. Although our primary results are per ton of concrete blocks produced, the regional capacities were disregarded at this moment but it must be considered in the next steps.

4. Conclusions

Considering the methods applied and existing limitations, the following conclusions can be raised:

(a) The alternative concrete blocks production by using fiberglass waste as raw material has the same performance for all three LCA impact categories evaluated than the traditional concrete blocks production: ~69 kgCO2-eq./ton block for climate change, ~8 kgoil-eq./ton block for fossil depletion, and ~0.009 m2/ton block for natural land transformation.

(b) When accounting the avoided emissions, the alternative concrete blocks production shows better performance for climate change and fossil depletion than tradition concrete blocks, achieving 20% and 6.7% reduction respectively.

(c) The percentage of gravel & rock dust substitution for fiberglass waste shows higher representativeness for climate change LCA impact category than for fossil depletion, since

20% of fiberglass waste usage achieves 50% reduction on kgCO2-eq./ton block, while the same reduction for fossil depletion is achieved only after replacing 50% of raw materials by fiberglass.

(d) Transporting the fiberglass waste to the concrete blocks production appears to be the most important driver for LCA impact categories, but future efforts will be developed in obtaining more accurate numbers to support solid conclusions.

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Appendix A. Impact categories coefficients obtained from Ecoinvent database

Table A.1. Impact category coefficients for the items embodied into the concrete blocks companies. LCI coefficients from Ecoinvent database, version 3.8 (2021), allocation at the point of substitution, Recipe midpoint (Hierarchist) LCI method. Climate change (100yrs), fossil depletion and natural land transformation.

Item and Unit	Description	Climate change	Fossil depletion	Natural land transformation
		$kgCO_{2\text{-eq.}}$ /Unit	$Kg_{\text{oil-eq.}}$ /Unit	m^2 /Unit
Steel (kg)	Metal working, average for steel product manufacturing, RoW	2.1101	0.57523	0.0004819
Gravel (kg)	Gravel production, crushed, BR	0.0049416	0.001429	3.24E-06
Rock Dust (kg)	[a]	0.0049416	0.001429	3.24E-06
Water (kg)	Tap water production, conventional treatment, BR	0.0001993	5.43E-05	1.22E-07
Cement (kg)	Cement production, Portland, BR	0.82814	0.089315	6.82E-05
Electricity (kWh)	electricity production, hydro, reservoir, tropical region, BR-Southern grid	0.064956	0.001236	0.0001107

[a] Assumed as equal to 'gravel' due to lack of data.

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Power Distribution Maintenance Operations and Carbon-Neutral Operation

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Abstract

Reducing greenhouse gas emissions is a fundamental objective of modern society as we strive to create a more sustainable future. One area that garners significant attention regarding emissions is the power system, particularly in countries heavily reliant on fossil fuel combustion for energy generation. While studies on carbon-neutral power systems primarily focus on proposing changes in electricity generation, it is crucial to recognize that other elements within the power system also contribute to atmospheric pollution. Failures in the electrical system, especially in the distribution of electric power, are frequent occurrences during system operation, necessitating maintenance crews to identify and rectify the affected parts. This article aims to evaluate various scenarios to estimate the environmental impact of maintenance processes following failures in distribution systems, specifically in terms of polluting gas emissions. While the impact of individual failures and maintenance events may appear modest, a substantial impact on polluting gas emissions becomes evident when considering a broader timeframe and scaling it to encompass the entire electrical system.

Keywords: Electric Power Distribution, Greenhouse Gases, Electric Failure Location, Transportation Routes, Maintenance Crews

1. Introduction

Europe's Climate Target Plan sets ambitious goals to combat climate change, aiming to reduce greenhouse gas emissions by at least 55% compared to 1990 (Commission). Furthermore, the long-term objective for 2050 is to achieve climate neutrality. According to the United Nations (UN), the energy sector accounts for three-quarters of global greenhouse gas emissions (Forum). Although Europe has made progress in reducing emissions, with a 32% decrease in polluting gases compared to 1990 indices, challenges persist due to political and social instabilities observed in recent years. These elements may impede decarbonization efforts and delay the shift to a sustainable future.

Electricity is a fundamental resource for modern society due to the dependence of industrial, commercial, and urban activities on this resource. Therefore, availability in the amount demanded and in quality parameters that meet the needs of final consumers is of fundamental importance. The electric power system consists of generation, transmission, and distribution subsystems, each with its own particularities and characteristics. For each system, several options can be taken to optimize the amount of energy generated, reduce losses in the transport of electricity, and evaluate the expenses related to raw materials, both regarding pollution and being renewable sources. For generation, the resource used as a source for electricity production is the main variation. There is a current trend towards using renewable sources, such as photovoltaic generation and wind turbines, in the energy matrix of each country, given their ability to reduce greenhouse gas emissions and pollution in general (Crippa et al., 2019). The discussion for the transmission sector usually focuses on energy line losses and transporting energy via alternating or direct current (Kalair et al., 2016). In both the generation and transmission systems, the challenge of reducing greenhouse gas emissions is studied in terms of planning (Junne et al., 2021) and operation (Liu et al., 2019).

The power distribution sector delivers electricity from the transmission system to end-users, ensuring reliable and efficient supply at lower voltages. However, despite the critical role of the power distribution sector in the overall electricity supply chain, there needs to be more extensive discussions and evaluations regarding the emission of polluting gases, specifically within this sector. While studies on carbon-neutral power systems often propose changes in electricity generation and transmission, the emissions associated with the power distribution sector remain relatively unexplored. This knowledge gap is significant considering the frequent failures and maintenance activities within the distribution system (Gomez-Exposito et al., 2018), which can potentially contribute to polluting gas emissions. Therefore, there is a need for comprehensive investigations and analyses to assess the environmental impact of the power distribution sector and identify strategies to mitigate emissions in this essential component of the electrical power system.

One of the critical challenges within the distribution sector is the efficient management of maintenance activities to address disruptive events and power outages (Fogliatto et al., 2022). These events often require the deployment of maintenance teams to identify and resolve issues, displacing personnel and vehicles. Numerous factors can significantly influence the amount of polluting gases emitted during maintenance operations in the distribution sector. These factors include the selection of optimal routes for maintenance crews, considering road conditions and traffic congestion, as well as the types of vehicles used and the choice of fuel. By carefully analysing and optimising these factors, it becomes possible to identify the best combination that minimises the emission of polluting gases. A proper method to evaluate the environmental impact of maintenance activities in the power distribution sector is crucial for building a more sustainable future. By adopting strategies that prioritise the reduction of greenhouse gas emissions during maintenance operations, the overall environmental footprint of the power distribution system can be minimised. This contributes to mitigating climate change and enhances the electrical infrastructure's sustainability and resilience.

The power distribution sector experiences numerous failures annually, and each city has its unique power distribution system (Gomez-Exposito et al., 2018). This highlights the criticality of scalability, especially when considering a countrywide perspective, where carbon emissions become evident. To address this challenge, assessing the various options for transporting maintenance teams within distribution systems and identifying the most environmentally friendly combination is essential. While failures in the electrical system are inevitable, striking a balance between sustainability and meeting the current travel time standards for teams is crucial. However, on a larger scale, it is anticipated that significant reductions in polluting gas emissions can be achieved when finding the optimal solution.

The optimisation of transportation methods for maintenance teams offers an opportunity to minimise greenhouse gas emissions. By considering the specific needs of each distribution system and striving for sustainability, it is possible to reduce the overall environmental impact. Although challenges may arise regarding meeting travel time requirements, prioritising long-term objectives and adopting sustainable practices can lead to substantial improvements. By embracing these measures on a broader scale, the power distribution sector can significantly reduce carbon emissions, contributing to a greener and more sustainable future.

Furthermore, we delve into the challenges associated with transportation for distribution system maintenance teams, particularly in the last mile (Suguna et al., 2021). The last mile refers to the final leg of the delivery process. It is pivotal in optimizing efficiency and reducing carbon emissions. By investigating innovative solutions and optimizing routes and vehicles used for maintenance activities, we seek to contribute to reducing carbon emissions associated with last-mile transportation within the power distribution sector. Our comprehensive approach underscores the significance of sustainable practices and resilient operations, ultimately fostering an environmentally friendly and efficient power distribution network.

Additionally, it is important to highlight that the method applied in this study can be extended to address the last-mile problem in various other contexts. The last-mile challenge is wider than the power distribution sector. Still, it extends to other industries, such as healthcare (Suguna et al., 2021), e-commerce (Viu-Roig & Alvarez-Palau, 2020), and food delivery (Puram et al., 2022). By leveraging the insights and techniques developed in this research, stakeholders in different sectors can adapt and apply them to their domains to optimize last-mile operations and mitigate carbon emissions. This interdisciplinary approach encourages knowledge transfer and collaboration across industries, leading to a broader and more impactful application of sustainable last-mile solutions. Thus, the findings and methods presented here hold the potential to drive innovation and facilitate sustainable practices beyond the power distribution sector.

This research aims to assess the emission of polluting gases in the context of the last-mile problem in power distribution systems. Specifically, it focuses on evaluating the amount of polluting gases emitted during the transportation of maintenance teams to restore service in distribution systems. The study considers various factors that can influence this problem, including the failure rate of the system and the road conditions, which impact the average speed of the vehicles. The research takes a comprehensive method to accomplish this goal. It incorporates an entire road network and generates a synthetic distribution system based on real data, enabling a realistic representation of the problem. A multilevel model is employed to accurately capture the system's failures and the routing algorithm used by the maintenance crews to restore out-of-service areas.

This work's key contribution is quantifying carbon dioxide (CO_2) emissions based on the routes taken by the maintenance crews and their corresponding road speeds. By analysing the emissions associated with different routes and considering the interplay between system failures and crew routing, insights can be gained into the environmental impact of the last-mile problem in power distribution systems. The findings of this research will provide valuable information for decision-makers in the power distribution sector, enabling them to make informed choices that can reduce greenhouse gas emissions and promote sustainable practices. Additionally, the method developed in this study has the potential to be applied to other sectors facing the last-mile problem, contributing to a broader understanding and addressing the environmental challenges associated with last-mile logistics.

2. Problem Description

In order to accomplish this goal, a thorough approach is used in the research after a failure event and protective device action to estimate the outage area (Fogliatto et al., 2022). Then, operators further reduce the outage area by operating remotely controlled switches and dispatch repair crews to patrol the area along the power system to find failure evidence and ensure safety before reestablishing service (Bahmanyar et al., 2017). Different from a previous study (de Souza Sant'Anna Fogliatto et al., 2022), in the fault location stage, the manual reconfiguration was fixed into the topological sort of the feeder in the out-of-service area. The patrolling strategy was also addressed by inspecting the entire outage area before restoring the customers, a common empirical approach.

Essentially, the multilevel approach establishes a connection between the failures in the distribution system and the work of maintenance teams to restore out-of-service regions (de Souza Sant'Anna Fogliatto et al., 2022) properly. The failure scenarios were created using the models proposed by Fogliatto et al. (2022b) and Fogliatto et al. (2022a). The parameters of a Weibull distribution were modified from the values presented in previous works to create different scenarios where failures can be less or more intense, resulting in five distinct scenarios.

Aiming to estimate the carbon footprint of the maintenance crews in a power distribution system during the patrol and restoration stages can be challenging. First, the traffic speed data provided by Uber Movement data to big cities such as São Paulo is permeated by a high rate of missing data that covaries with time (Chen et al., 2022) and space. Second, the power distribution system was unavailable for São Paulo due to its proprietary and security nature. Finally, proposing a power distribution system for such complexity involves strong network and statistical tools.

3. Material and Methods

This section will present a summary of the data and models used and how they were used. The creation of an artificial electrical network, fault modelling based on real data from distribution systems, and an analysis of the speed of the roads given the atmospheric and traffic conditions stand out. Considering each of these parts as a layer, the union of all of them demonstrates the contribution of the work through a multilayer model.

3.1 Creating a Synthetic Power Distribution Network

Creating a synthetic distribution system (DS) is essential to analyzing its influence on other critical infrastructures, such as road infrastructure, especially when the data related to the DS is private due to its proprietary nature. This work is simulated under the city of São Paulo, Brazil, whose georeferenced data, available in OpenStreetMaps (OpenStreetMap contributors, 2017), gives information about the road network in the form of a directed graph, where edges represent the streets, and the nodes constitute the intersection between each lane. Additionally, the individual location of each substation is available. Each substation is manually assigned to the closest node of the road network in terms of geographical distance. The data is processed and manipulated using the Python language with the OSMnx package (Boeing, 2017).

3.2 Speed Model and CO_2 Emission

The road network is represented by a directed weighted graph $G = \{V, E, w\}$, in which the set of nodes V contains georeferenced points, and the edges set $E \subseteq V \times V$ are the roads connecting those points. The edges' weights w are the lengths of the roads. To create a systematic probabilistic analysis to estimate the traffic speed, the road network must be transformed into a line graph, the intersection graph of the edges of G (Harary, 1969). The line graph of G will be denoted by $L(G) = \{E,\{\{e, f\} : \forall_e , f \in E: e \neq f, e \cap f \neq \varnothing \}\}$. In this sense, $L(G)$ is a Markov Random Field, a probabilistic graphical model that encodes a joint probability distribution or the conditional independence structures of a set of random variables (Hern ández-Lemus, 2021), which are, in this case, the traffic speed. Being $\mathcal{N}_{L(G)}[e]$ and $\mathcal{N}_{L(G)}(e)$, respectively, the closed and open neighbourhoods of e in the graph $L(G)$ and assuming the local Markov property $X_e \perp X_{E\setminus\mathcal{N}L(G)[e]} \mid X_{\mathcal{N}L(G)(e)}$, the traffic speed can be estimated by a local latent spatiotemporal Bayesian model in (1).

In the observation model in (1a), the measured speeds S^* are independent and normally distributed with a latent process S as mean and a measurement error $\boldsymbol{\tau}$. Next, (1b) describes the latent process from a multivariate normal distribution with parameters mean μ and covariance matrix Σ. In this case, the latent speed in each time slice for edge e covary with its neighbour's latent processes and depends on their past values through the autoregressive structure, with parameters ϕ in (1c). Additionally, the average speed for each edge in each time slice is a function of a general average speed α, an intercept for each edge α_N in the neighbourhood and intercepts for units of time α_D and α_H, for days of the week and hour, respectively. To ease encoding prior assumptions on the covariance matrix, (1d) decomposes the covariance into scale parameters σ and the correlation matrix Ω (Lewandowski et al., 2009). The prior distributions are in (1c) - (1h). After fitting the model to speed in Uber Movement data, a direct application of the model is estimating the CO_2 footprint based on the latent speed posterior distribution by applying the emission functions as in (Barth and Boriboonsomsin, 2008).

$$S^*_{ft} \sim normal(S_{ft} , \boldsymbol{\tau}_{ft}) \;\; \forall f \in \mathcal{N}_{L(G)}[e] \qquad (1a)$$

$$S_t \sim multivariate\ normal\ (\mu_t , \Sigma) \qquad (1b)$$

$$\mu_t = \alpha + \alpha_N + \alpha_{Dt} + \alpha_{Ht} + \sum\phi_k S_{t-k} + \beta X_t \qquad (1c)$$

$$\Sigma = diag\ (\sigma)\ \Omega\ diag(\sigma) \qquad (1d)$$

$$\alpha_H ,\ \alpha_N ,\ \alpha_D \sim normal(0,1) \qquad (1e)$$

$\alpha, \phi, \beta \sim normal(0,1)$ (1f)

$\sigma \sim exponential(1)$ (1g)

$\Omega \sim LKJ\ corr(4)$ (1h)

4. Results and Discussion

This section will present the results for the synthetic distribution network and the local speed model. In addition, the CO_2 emission rates were estimated based on the crews' speed for each failure rate scenario.

4.1 Synthetic Network

Previous literature works have dealt with the problem of creating artificial networks. Mainly, the work done by (Schweitzer et al., 2017) uses a real dataset to fit several properties of a Distribution System in the form of random variables, which are used in our work. The following variables were mainly used: Fraction of Load Nodes, Hop Distance, and Load Deviation From Uniform.

However, some characteristics needed to be included in the mentioned study and were essential to correctly modelling the carbon-neutral approach proposed in our work, such as allocating each switch's position in the DS (normally open and normally closed). With this in mind, a mixture Poisson model is also used to fit the hop distance between switches and feeders, using the data from the South Region of Brazil, as described in Section 3.

The hop distance from switches to feeders was determined for each bus in the Brazilian DS to verify our theory that a mixed model should be used. A histogram was created, as shown in Fig. 1. While there is a peak frequency at around 800, frequencies around 200 and 400 also appear at a considerable ratio, which seems to indicate that a single distribution is not enough to model the variable's behaviour, thus serving as a motivation to model the maximum hop distance from feeders as a Mixture Poisson Model. The Python Pymc3 library (Salvatier et al., 2016) was used to fit it properly, and the final parameters' values are shown in Table 1.

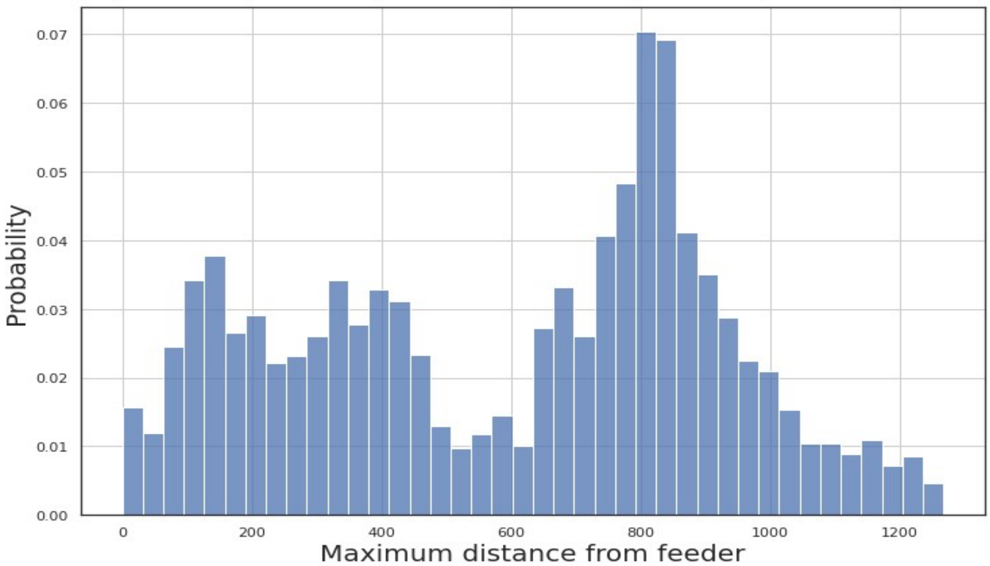

Fig. 1 Histogram for the maximum hop distance from feeders in km, using the South Region of Brazil dataset. This data is used to properly allocate switches in the Synthetic Network proposed in this work, which is used later on to properly simulate CO_2 emission in the crew's displacement in the Power Distribution System.

Tab. 1 Means (μ), Standard deviations (σ), and their Highest Density Intervals (HDI) for the Mixture Poisson used to model the hop distance from switches to feeders. The data of Distribution Systems located in the South Region of Brazil were used to fit the model.

Parameter	μ	**σ**	**HDI** (3%)	**HDI** (97%)
λ_1	685.60	72.95	651.15	825.54
λ_2	56.05	99.78	0.73	250.64
w_0	0.78	0.06	0.62	0.83
w_1	0.22	0.06	0.17	0.38

4.2 CO_2 Emission

The speed model from Section 3.2 was applied to estimate the route speeds for each time slice in a Bayesian fashion. Fig. 2 shows an example of the posterior distribution of the traffic speed in a neighbourhood of a random edge of the road network. The posterior distribution of the latent process was applied to the emission model in (Barth & Boriboonsomsin, 2008), resulting in Fig. 3, which shows the CO_2 emission distributions for five failure rate levels. Faults were simulated at each level, and two crews were dispatched to patrol and restore the faulted area using a simplified version of De Souza Sant'Anna Fogliatto et al. (2022), as described in Section 2.

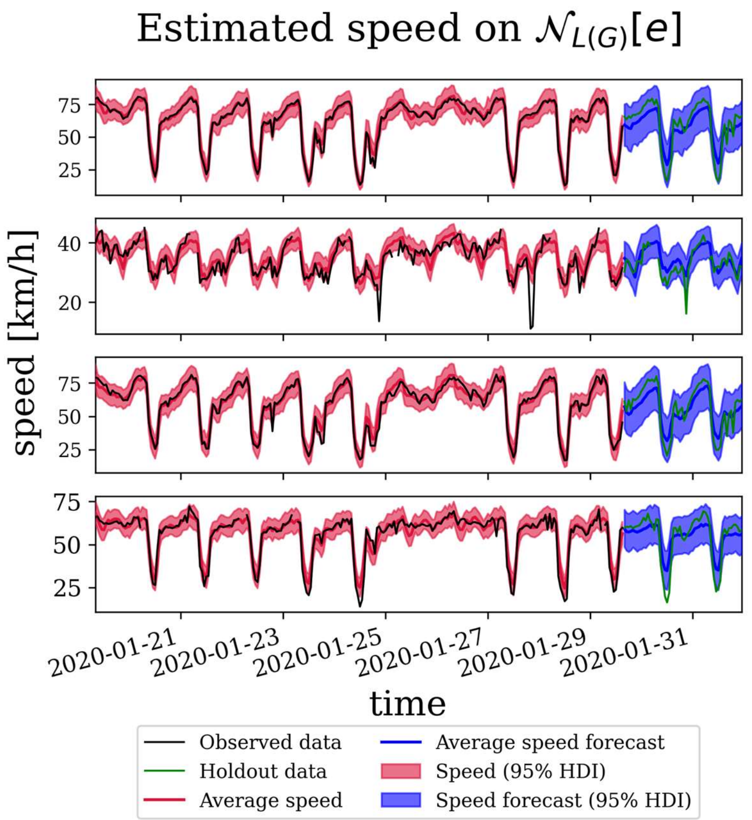

Fig. 2 Posterior distribution mean and HDI of the latent process for traffic speed in a closed neighborhood of a random edge e in São Paulo's road network G. In addition to missing data imputation, the latent process can be used to forecast, as depicted on the right, and compared to the holdout data.

As can be seen, the CO_2 emission rate increases with the failure rate (represented by the number of failures per year). With more failures, the crews will travel a greater distance, thus emitting

more CO_2. Additionally, the probability of multiple failures, leading to a more significant portion of the distribution system being out of service and consequently to a multipoint route being taken by the crews, will once again culminate in a higher intensity of CO_2 emission.
Each failure rate value represents a scenario with its probability distribution, as indicated in Fig. 3. The zoomed figure on the right shows a kernel density estimation of all points simulated with that particular failure rate, called the standard scenario. This variation is caused by the possibility of fault locations due to the time to repair being taken as a random variable and traffic speed variations, as detailed in Fogliatto et al. (2022b). Additionally, the routes taken by crews vary with the road speed and the weather conditions, as detailed in Subsection 3.2. With this in mind, the result presented is a culmination of a multilevel approach, which was adapted to properly simulate the CO_2 emission in the distribution system crews' operation.

The standard scenario, without any extreme weather variables, uses the model presented in Fogliatto et al. (2022b). In this sense, the proposed method could take the initial CO_2 emission model for vehicles, shown in Subsection 3.2, and scale it to the power distribution sector's point of view. A vehicle with an average speed of 60 km/h (the average road speed in the city where the original road network is located) has an emission factor of roughly 0.245 g/km of CO_2. While this individual value is small, two factors must be taken into account: the number of annual failures in a typical distribution system (going up to thousands, as shown in the results presented here); and the crew's routing problem, which led to an average distance of 20km taken by each crew to locate and reach the fault. This dynamic culminates in the final values shown in Fig. 3: an emission rate of 60 tons per year in the average scenario.

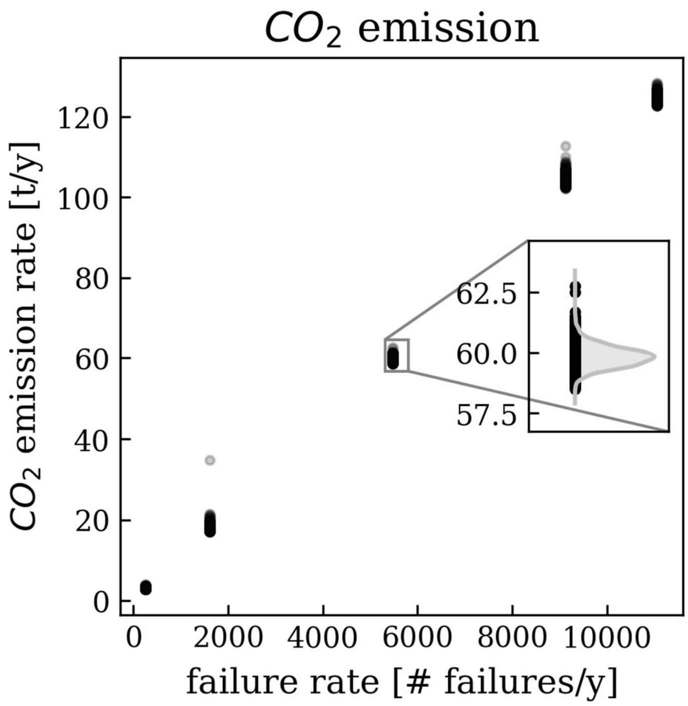

Fig. 3 CO_2 emission distributions for five failure rate levels. The crews' route speeds were locally estimated using the Bayesian model. Finally, the speed posterior distribution was applied to the emission model in Barth and Boriboonsomsin (2008). The result shows a proportional relationship between failure rate and CO_2 emissions due to maintenance crews' operations. The zoom shows a kernel density estimate for the posterior distribution samples in the standard scenario.

5. Conclusions

The goal of the current study was to examine the carbon footprint of staff relocation in Power Distribution Systems while considering severe weather, the state of the road system, and the system's dependability (measured in terms of failure rate). A CO_2 Emission Model was mainly used to correlate road speed with CO_2 emission, coupled with a crew's routing algorithm to calculate total CO_2 emission in tons of *CO2* per year. It is essential to highlight that while the emission per individual failure looks small (between 8 and 11 kg of CO_2, on average), we must consider the scalability of the problem. On the one hand, the results are simulated for only 2 crews, while in real cases, the number of crews working simultaneously is higher; on the other hand, a typical Distribution System can have thousands of failures in an annual time window, culminating in up to 120 tons of CO_2 in an extreme scenario, as shown in the results presented here. Regarding environmental compensation, an average tree in Europe absorbs around 10kg of CO_2 in one year. Thus, considering the method presented here, two crews patrolling the city of São Paulo for one year, in the average scenario, could emit as much CO_2 as roughly 5 hectares of trees would absorb in one year.
The model used in this work is the first step towards carbon-neutral Power Distribution Systems, at least from a crew's patrolling perspective. Previous work tends to focus on CO_2 emissions in the generation sector. While the generation sector's analysis must continue, a carbon-neutral approach in the distribution sector must also be applied to adequately address its impact, especially from a decentralised point of view, where each urban area has its network and crews. In this case, each part contributes a small portion of CO_2 emission, and the combined effect of repeated behaviour of large groups will be significant.
Regarding future work, the method applied to calculate CO_2 emissions can be used as the objective function of any optimisation problem (single or multi-objective), bringing a carbon-neutral point of view into the decision-making of distribution operators. Additionally, the CO_2 emissions can be compared between vehicles and fuels, aiming for a more sustainable choice. Finally, while the generation and distribution sectors of the electrical power system have their particularities and scalability issues, they both contribute to the CO_2 emission problem. They can be coupled in a single optimisation problem toward a carbon-neutral approach.

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Photovoltaic Solar Panels End-Of-Life: A Comparative LCA For a Gate-To-Grade Approach

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Abstract

The use of non-renewable energies has exponentially accelerated pollution in the environment through the emission of greenhouse gases and the scarcity of natural resources. The use of photovoltaic solar energy has increasingly consolidated itself as an alternative for reducing the impacts of using fossil fuels. However, the widespread use of this technology generates a future problem, which is what is it possible to do with the Photovoltaic Solar Panel (PSP) waste post-use? Studies indicate that in 2050 there will be more than 70 million tons of PSP waste in circulation. In this sense, this study aimed to comparatively evaluate the potential environmental impact of 2 scenarios of the destination of Photovoltaic Solar Panels through the technique of Life Cycle Assessment. The analyzed scenarios were: Scenario 1 – disposal of PSP to landfill; Scenario 2 – allocation of PSP divided between landfill (5%), incineration (11%), and recycling (84%), considering the potential for material use of PSP presented in scientific studies. The approach adopted for recycling in Scenario 2 was the environmental bonus for the recycling actions carried out. The results show that the environmental impact reduced between 12 and 51%, and two impact categories obtained negative impacts, being them -409% for Marine ecotoxicity, and -529% for Terrestrial acidification. Thus, it is possible to note that including actions such as recycling could be an interesting alternative for reducing environmental impacts in PSP waste management.

Keywords: *Photovoltaic Solar Panel; LCA; end-of-life*

1. INTRODUCTION

The use of electricity produced by Photovoltaic Solar Panels (PSP) has been growing over the years. The large consumption of electricity has influenced the demand for alternative energy sources, such as solar energy (PRADO, 2018). In the first half of 2019, the exponential growth in the use of PSP has made it expand the variety of models, resulting in different applications. In 2022, the territory added 9.3 GW of solar photovoltaic energy according to the National Electricity Agency (ANEEL, 2022), surpassing the record of the year 2021, representing more than 80% between two periods. This increased operational capacity to more than 23 GW, 6.6 GW from distributed generation (GD), and 2.7 GW from GC (centralized generation) (ABSOLAR, 2023).

This sector in Brazil stood out from the approval of Resolution 482 of 2012 of the Brazilian Electricity Agency (ANEEL), attracting a market that was previously little explored. Photovoltaic solar energy has numerous benefits, but it is not possible to say that there are no impacts generated by the life cycle of solar modules (BRASIL, 2012).

When it comes to the post-use environmental impacts of Photovoltaic Solar Panels, little has been said about them on the environment and human health. Many materials are disposed of improperly, such as ruthenium, indium, tellurium, and gallium, and they are extremely rare and fundamental chemical components for photovoltaic modules. According to Farrell et al. (2020), most end-of-life PSPs are sent to landfills, which is not a good environmentally acceptable alternative and is not sustainable in the long term.

From Finger (2019), the inadequate disposal of PSP can bring harmful effects on the environment and human health, as it contains hazardous metals such as cadmium and lead, even in small amounts. Thus, the scarcity of public policies and planning related to the disposal of photovoltaic solar panels represents a problem for the coming decades (PEDROSO et al., 2023).

In the vision of Dias (2015), the PSP end-of-life to be disposed of represents a WEEE (Waste Electrical Electronic Equipment), given that the WEEE owns a great possibility of contaminating the soil with toxic materials. These modules may release cadmium, selenium, and lead, which are harmful to the environment (DIAS, 2015). Lead, for example, has a high potential for accumulation in both the environment and the human body and this is related to diseases of the neurological system, cardiovascular and osteoporosis, according to the amount of exposure of the individual. On biodiversity, lead affects the growth and reproduction of plants and animals, and it affects the neurological system of vertebrate animals (SCOLLA, 2020).

PSPs have a limited lifespan of between 25 to 30 years, and the main factors responsible for their end-of-life are the decomposition of encapsulant (EVA) due to high sun exposure, defects in photovoltaic cells, and internal materials (DIAS, 2015).

When dealing with environmental factors, the life cycle assessment (LCA) conducts the study of environmental impacts throughout the life cycle of the product, from the cradle to the grave. LCA is a technique that allows the assessment of environmental aspects and impacts caused by a product or service, as well as identifies the polluting points for water, soil, and air (CLAUDINO AND TALAMINI, 2013).

Thus, this study aimed to comparatively evaluate the potential environmental impact of 2 scenarios of PSP destinations using LCA.

2. METHODOLOGY

The methodological steps used in this research were organized considering ISO 14040 for the development of Life Cycle Assessment studies (ISO, 2006). ISO 14040 is a recognized international standard, which establishes guidelines and principles for carrying out the life cycle assessment of products, services, and systems. This establishes a structured and consistent approach to the comprehensive analysis of environmental impacts throughout the life cycle of a product, from the extraction of raw materials to final disposal (ISO, 2006).

The main phases for the development of an LCA study are Goal and Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation (Figure 1).

In this sense, sections 3.1 to 3.3 were structured to describe the phases of the PSP LCA study of LCA, considering 2 different end-of-life scenarios. The idea has been to understand how the PSP end-of-life can impact its environmental performance.

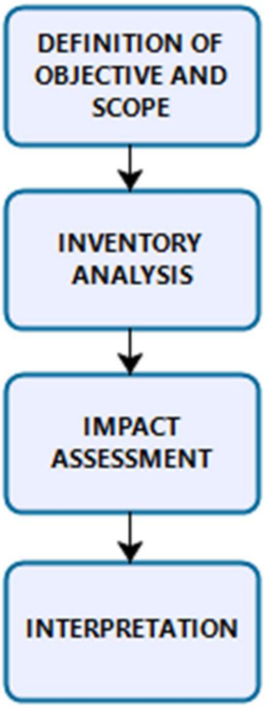


Fig. 1. ISO 14040 Step Flow for Life Cycle Assessment (ISO, 2006).

3.1. Goal and Scope Definition

The goal of this study was to perform a Life Cycle Assessment (LCA) to identify, quantify and compare the environmental impacts of photovoltaic solar panels, considering two distinct scenarios: Scenario 1 – PSP final disposal to landfill; Scenario 2 – PSP waste management based on landfill (5%), incineration (11%), and recycling (84%), according to Figure 2. Other elements of the goal and scope definition are presented in Table 1.

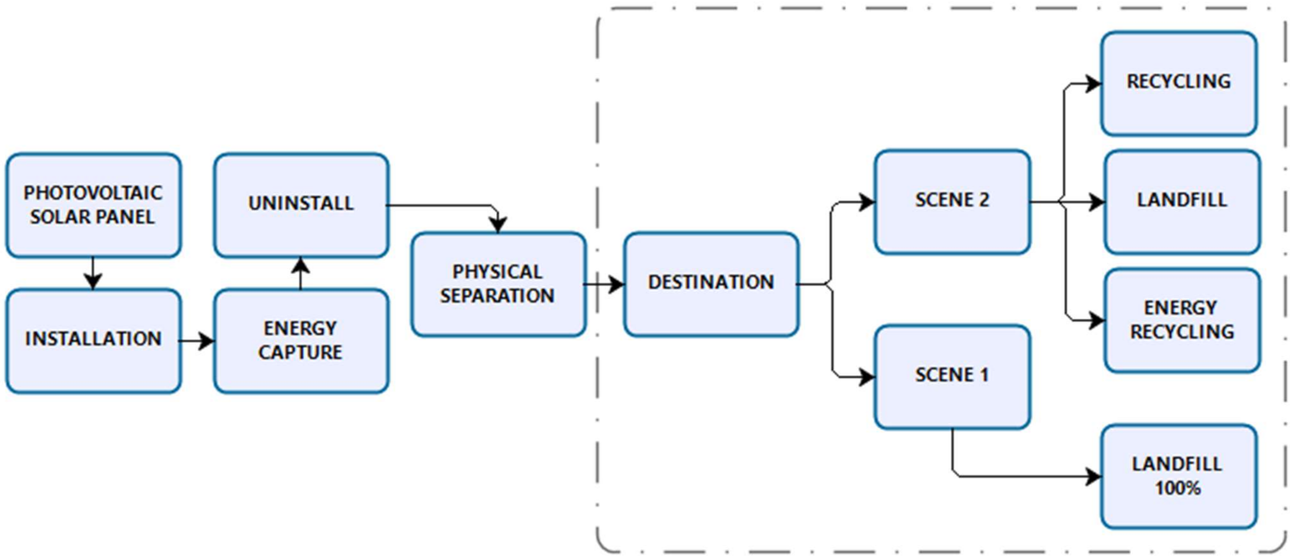


Fig. 2. Life Cycle of the Photovoltaic Solar Panel.

Item		Definition in this study
GOAL	Intended application	Analyze the potential environmental impact of two different PSP end-of-life scenarios.
	Target audience	The academic community, industries, and society.
	Reason	Identify the PSP scenario with the least environmental impact.
SCOPE	Function	Produce electricity
	Functional unit	Produce 10,946,322 kWh of electricity over 25 years
	Reference flow	1 PSP for end-of-life
	Product system	Final destination in 2 scenarios, excluding the manufacturing and use stages. Thus, Scenario 1 – PSP final disposal to landfill; Scenario 2 – PSP waste management based on landfill (5%), incineration (11%), and recycling (84%).
	System boundary	Gate-to-grave (from post-use to final disposal).
	LCIA methodology	ReCiPe 2016 Midpoint (H) v1.06
	Software	OpenLCA

Tab. 1. LCA goal and scope definitions.

For modeling the Life Cycle Assessment, OpenLCA has been used, which is software for calculating the environmental impact of products and modeling the life cycle. The software models and evaluates the product throughout its lifecycle, from resource extraction to disposal.

3.2. Life Cycle Inventory (LCI)

The life cycle inventory data of the PSP has derived from the study developed by MACENO; PILZ OLIVEIRA, (2020), and it is presented in Table 2. This study aimed to evaluate the circularity of a first-generation crystalline silicon photovoltaic solar panel, using circular economy tools, and to calculate the environmental performance, using LCA. Table 2 presents materials, quantity, and destination for Scenario 2. It is worth mentioning that for Scenario 1 the PSP has been sent 100% to the landfill.

Material	Quantity in the product (kg)	Destination (% and type)	Quantity in the destination (kg)
Solar glass	16.3894	95% R 5% L	15.5699 0.8194
Aluminium	2.2763	100% R	2.2763
Acetate of vinyl (EVA)	1.4476	100% I	1.4476
Polyvinyl fluoride (Tedlar or PVF)	0.7956	100% I	0.7956
Silicone (sealant)	0.2564	100% I	0.2564
Silicon	0.6630	81% R 19% L	0.5370 0.1259
Lead	0.0155	100% L	0.0155
Copper	0.1260	89% R 11% L	0.1121 0.0138
Tin	0.0265	100% L	0.0265
Silver	0.0013	40% R	0.0005

	60% L	0.0007

Tab. 2. PSP LCI for Scenario 2. Note: R: Recycling; L: Landfill; I: Incineration.

3.3 Life Cycle Impact Assessment (LCIA)

In the evaluation of potential environmental impacts, it was used the ReCiPe 2016 Midpoint (H) LCIA method, because it is one of the most used LCIA methods in LCA studies (MACENO; PILZ; OLIVEIRA, 2020).

The impact categories analyzed were Fine particulate matter formation, Fossil resource scarcity, Freshwater ecotoxicity, Freshwater eutrophication, Global warming, Human carcinogenic toxicity, Human non-carcinogenic toxicity, Ionizing radiation, Land use, Marine ecotoxicity, Marine eutrophication, Mineral resource scarcity, Ozone formation-Human health, Ozone formation-Terrestrial ecosystems, Stratospheric ozone depletion, Terrestrial acidification, Terrestrial ecotoxicity, and Water consumption.

4. RESULTS AND DISCUSSIONS

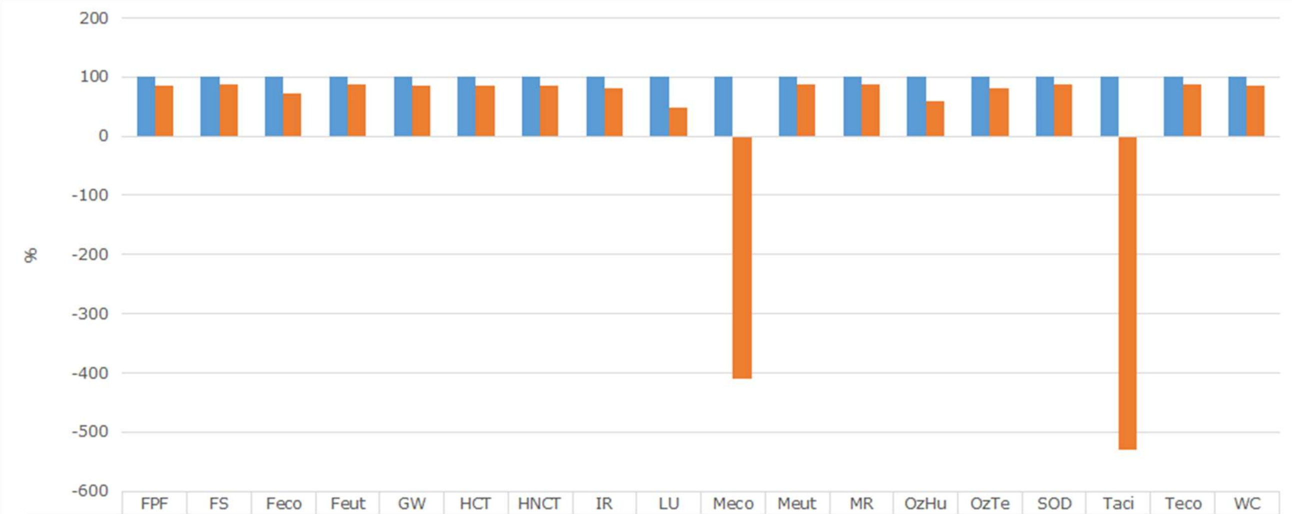
The results obtained for the simulation in each Scenario using ReCiPe 2016 Midpoint (H) are presented in Table 3 (results of the impact categories with physical units).

ID	Impact category	Unit	Landfill	Recycling
1	Fine particulate matter formation	kg PM2.5 eq	4.9722E-05	4.2699E-05
2	Fossil resource scarcity	kg oil eq	4.2000E-04	3.7000E-04
3	Freshwater ecotoxicity	kg 1.4-DCB	8.2362E-09	5.9881E-09
4	Freshwater eutrophication	kg P eq	9.6960E-02	8.4710E-02
5	Global warming	kg CO2 eq	7.8940E-02	6.6780E-02
6	Human carcinogenic toxicity	kg 1.4-DCB	8.5600E-03	7.3300E-03
7	Human non-carcinogenic toxicity	kg 1.4-DCB	9.1262E-05	7.8290E-05
8	Ionizing radiation	kBq Co-60 eq	6.3448E-05	5.1761E-05
9	Land use	m2a crop eq	2.5000E-04	1.2000E-04
10	Marine ecotoxicity	kg 1.4-DCB	5.0800E-03	-2.0780E-02
11	Marine eutrophication	kg N eq	6.8820E-07	5.9524E-07
12	Mineral resource scarcity	kg Cu eq	6.5000E-04	5.7000E-04
13	Ozone formation. Human health	kg NOx eq	7.8000E-04	4.6000E-04
14	Ozone formation. Terrestrial ecosystems	kg NOx eq	6.0921E-05	4.9776E-05
15	Stratospheric ozone depletion	kg CFC11 eq	1.2055E-05	1.0532E-05
16	Terrestrial acidification	kg SO2 eq	3.4300E-03	-1.8160E-02
17	Terrestrial ecotoxicity	kg 1.4-DCB	6.1862E-05	5.3961E-05
18	Water consumption	m3	3.3090E-02	2.8300E-02

Tab. 3. Impact categories results for each Scenario analyzed.

Furthermore, an internal normalization was performed with the maximum value method. Figure 3 shows the results of this normalization (results of the impact categories in %).

According to Table 2 and Figure 3, the results obtained represent a reduction of 12 to 52% in the potential environmental impact when using recycling, incineration, and landfill for PSP waste management, except for Marine ecotoxicity and Terrestrial acidification. The impact categories that have the greatest reduction in environmental impacts are Land use, Ozone Formation-Human health, and Freshwater ecotoxicity, with 52, 41, and 27%, respectively.



	FPF	FS	Feco	Feut	GW	HCT	HNCT	IR	LU	Meco	Meut	MR	OzHu	OzTe	SOD	Taci	Teco	WC
Landfill	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Recycling	86	88	73	87	85	86	86	82	48	-409	86	88	59	82	87	-529	87	86

Fig. 3. Results of the internal normalization for impact categories. Note: FPF=Fine particulate matter formation; FS=Fossil resource scarcity; FEco=Freshwater ecotoxicity; FEut=Freshwater eutrophication; GW=Global warming; HCT=Human carcinogenic toxicity; HNCT=Human non-carcinogenic toxicity; IR=Ionizing radiation; LU=Land use; Meco=Marine ecotoxicity; MEut=Marine eutrophication; MR=Mineral resource scarcity; OzHu=Ozone formation-Human health; OzTe=Ozone formation- Terrestrial ecosystems; SOD=Stratospheric ozone depletion; Taci=Terrestrial acidification; TEco=Terrestrial ecotoxicity; and WC=Water consumption.

Furthermore, according to Allegrini et al. (2015), the impact categories that generate negative results in the life cycle impact assessment are translated as benefits to the environment. In this study, the Marine ecotoxicity and Terrestrial acidification categories were considered as an avoided impact on the environment. As a global analysis, the greatest impacts are caused by Scenario 1, with 100% destination for landfill, while the smallest environmental impacts are caused in Scenario 2, which considers a divided destination between landfill, recycling, and incineration, confirming the results obtained in the study by Lunardi et al. (2018) which demonstrates that the recovery of materials from solar modules results in lower environmental impacts.

5. CONCLUSION

It is possible to observe according to the results obtained in this study that recycling generates a benefit to the environment, in the PSP case. Considering that the use of PSP is growing on a large scale around the world, there must be a long-term concern with the proper management of this waste, prioritizing circular economy actions.

However, it is worth noting that this study was developed considering two theoretical scenarios for the allocation of PSP, according to findings in the literature, and with the management capacity of each component material of the PSP. Then, studies considering real scenarios with data collection in loco are important to provide greater certainty in the results of potential environmental impact.

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Power Dynamics of Sustainable Business Networks in a Circular Economy – A Governance Perspective from Africa

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Abstract

The attainment of a Circular Economy requires multi-stakeholder partnerships. Sustainable Business Networks have played a catalytic role in promoting a Circular Economy. However, power dynamics and governance issues have a potential to affect their success. This research aims to assess the existing governance structures and power issues within the sustainable business networks. It assesses the effectiveness of these leadership regimes in promoting a circular economy and for the continuity of the network. Nine (9) Case studies were drawn from 3 African countries (Zimbabwe, South Africa and Kenya). A questionnaire was sent to each of the networks. Key informant interviews were carried out with both Network Representatives and also with network members in the form of corporate firms. Document review of constitutions, network documents, project reports and evaluation reports was undertaken in order to identify patterns related to governance, leadership and power. The results indicated that Sustainable Business Networks vary in power dynamics. In some networks, the coordination of the network activities is by nomination or voluntary assumption of office. In some cases, the power dynamics were determined by electoral processes based on the constitutional provisions. For regional networks, members aligned to regional blocs had the ability of aligning to certain candidates to lead the network based on regional alignment. In the context of Africa, networks are becoming more formalised and registered in order to access financing and attain good corporate governance. The legal status varies from not-for profit, private and public institutions and consultancy model. Succession issues in Sustainable Business Networks also had an effect on the success of Circular Economy activities. A common governance denominator of all networks evaluated is the existence of an institution that coordinates network activities such as a Secretariat, Executive Committee, Council or Board. The separation between management and governance of networks was lacking in some of the networks. We conclude that the governance structure of the Sustainable Business Network has an influence on the success of circular economy activities and also the separation of management and governance could unlock financing.

Keywords: Sustainable Business Networks, Circular Economy, Governance, Leadership

1. INTRODUCTION

In order to attain a Circular Economy (CE), drastic shifts in the patterns of consumption and production are required (Ellen MacAthur Foundation, 2012) (Ghisellini, Cialani, & Ulgiati, 2016). Organisations can operate idiosyncratically, using their own internal capacity and resources but their capabilities are limited without tacit knowledge (Hart, 1995). Individual organisations are restricted in their ability to implement circular economy innovations, without external knowledge platforms to benchmark performance. Collaboration amongst organisations has been widely proven as a pathway to facilitate accelerated CE transition. Sustainable Business Networks are a forms of collaboration where organisations can share innovation, technology, awareness and knowledge in the domain of a circular economy.
However, the success or failure of these Sustainable Business Networks is determined by their governance regimes and also their power dynamics. The need for able leadership, coordination and vision formulation is a key determinant with regards to whether or not a network attains high

level impact (Yin, Yan, & Zhang, 2022) (UNIDO, 2011). In the context of Africa, Sustainable Business Networks are under-researched. Where they exist, networks are mainly governed by those who founded them and there is no clear pathway to guide transition of power from different governance regimes. Due to the familiarity amongst regional peers, some networks can be oriented to select governance structures oriented to specific regional blocs and geographical proximities. As a result of differences in the leadership focus and priorities, geographical and societal differences amongst network actors can be a key divisive factor amongst network actors. The understanding of dichotomous relationships between public governance and network governance is a key enabler of leapfrogging towards a CE transition (Cramer, 2022). Barriers also exist, which have a bearing on CE network success (Bacudio, et al., 2016) (Hina, Chauhan, Kaur, Kraus, & Dhir, 2022).

Collaboration has been widely researched in many country contexts as a key enabler of CE (Jager & Piscisceli, 2021) (Leising, Quist, & Bocken, 2018) (Madanhire & Mupaso, 2018) (Mahuni & Bonga, 2016) (Mbohwa & Rwakatiwana, 2010) (Samitthiwetcharong, Kulivanijaya, Suwanteep, & Chavaparit, 2023) (UNIDO, 2011) (Suchek & Franco, 2023) (Veleva & Bodkin, 2018) (Berlin, Feldman, & Nuur, 2022). Empirical research confirms that inter-organizational collaboration is a useful tool for transferring knowledge from one organisation to another. The collaboration could be in the form of clusters (Yin, Yan, & Zhang, 2022). On the other hand, if improperly managed, inter-organisational collaboration can also result in intra and inter-firm conflict and disagreements (Kito, Moriya, & Yamanoi, 2021).

Some of the disagreements related to Sustainable Business Networks are related to the governance structure, framework and governance priorities that the organisations involved in network relationships are confronted with. Collaboration and conflict are often regarded as common paradoxes faced by networks promoting and facilitating a CE transition. The ability to reduce and limit unprogressive conflict within networks is a key determinant of success of Circular Economy Networks (Kito, Moriya, & Yamanoi, 2021) (Xu, Wu, & Gu, 2023). In their diverse forms, networks ensure institutional isomorphism, where organisations gradually become similar due normative, mimetic and coercive pressures (Di Maggio & Powell, 1983).

In the context of human development, sustainable development theories have come to the fore since Brundtland Commission coined the concept of Sustainable Development in 1987. Over the years, further elucidation of sustainability concepts such as Sustainable Consumption and Production, Industrial Ecology, Eco-Efficiency, Resource Efficient and Cleaner (RECP) proliferated. The coming of the Circular Economy to the fore of the discussion, presents the few chances of the human species to correct the anomalies of decades of anthropogenic pollution that is human induced. Without a CE transition, humanity may be on the brink of a place of no return. Although the transition to CE state is aspired by society, there are key enablers of success, in the form of external organisations and networks, which have a catalytic role of promoting novel concepts into practical solutions at organisational level. Participation in such networks also pushes organisation to conform to the international standards of circular economy and environmental stewardship.

Over the past three decades, literature has focused much on elucidating the conceptualization of these CE concepts whose evolution has been illustrated by (Ghisellini, Cialani, & Ulgiati, 2016). Limited research exists on the network and collaboration dynamics in pursuit of CE. As a result, a number of associations, networks and groupings of institutions have been formed without evaluation of their impact. Some of these institutions have survived, whilst some of them have collapsed. One of the key causes of collapse of Sustainable Business Networks has been as a result of poor governance and even lack of governance structures to steer the network forward. Knowledge gaps still exist as to what could be the ideal governance model for Sustainable Business Networks. Furthermore, knowledge about CE collaboration in Africa is not well developed.

There are common challenges that affect sustainable business networks including lack of good leadership, financing (Kierans & Chen, 2022), lack of strategy and failure to manage success from different time periods. The lack of strategic planning of CE activities by the network leadership may result in the network suffering from a leadership vacuum and lack of coherence in CE activities. Different cultures amongst the organisations and individuals leading the networks makes it difficult to attain the best collaborative outcomes due to the complex nature of dealing with different organisations.

This research paper aims to assess the governance forms of Sustainable Business Networks from three Africa countries (Zimbabwe, South Africa and Kenya) in order to identify power dynamics associated with the collaborative institutions. The research paper answers the following research questions

i. What is the role of Sustainable Business Networks in promoting a Circular Economy in selected African countries (Zimbabwe, South Africa and Kenya)?
ii. How are the sustainable business networks contributing to the attainment of a Circular Economy?
iii. How are Sustainable Business Networks governed and what power relations exists amongst the network actors
iv. What governance challenges exist in Sustainable Business Networks in selected Africa countries?
v. To what extent do governance practices affect the attainment of a Circular Economy and effectiveness of the Sustainable Business Networks.

2. METHODOLOGY

The research was based on Nine (9) Case studies which were drawn from 3 African countries (Zimbabwe, South Africa and Kenya). Case Study research aims to elucidate depth rather than breadth of the research discourse (Yin R. , 2003). A questionnaire was sent to each of the networks in order to access data about the activities, governance systems of the network. Key informant interviews were carried out with 9 network representatives and also with network members in the form of corporate firms who received a questionnaire. The key informant Interviews were held in a hybrid format, whereby some of them where done physically, whilst some of them were undertaken via video call. Interviews for respondents based in Zimbabwe were undertaken physically, whilst those of respondents from South Africa and Kenya were undertaken virtually due to geographical dispersion. Document review of constitutions, network documents, project reports and evaluation reports was undertaken in order to identify patterns related to governance, leadership and power. Data was analysed using qualitative and quantitative methods. In order to ensure that there was reliability and validity of the data that was gathered, a number of strategies were used. Triangulation of sources as well as triangulation of data was implemented in order to cross check the reliability of the information and also to prevent and detect any forms of biases. The selection of case studies followed an organized protocol based on a set criteria. The criteria for selecting case studies included, willingness to participate, location in Africa, focus on Circular Economy Network.

3. RESULTS

3.1 Governance practices of the networks

The results show that networks are at varying levels of organisational development and governance. The power of the network is mainly vested in the hands of the Board, Council or Executive Committee. Some networks also appointed a formal Executive Director who has the powers for managing the network on a day to day basis. The Executive Director would in most cases report to a Chairman of the network. There was a high establishment of strategic plans for 7 out of the networks which were selected as case studies out of the 9 cross country case studies. However, the effectiveness of the strategic plans has not been empirically assessed.

Table 1. Governance Models of Sustainable Business Networks

Case Identity	Strategy	Executive Director/President/Chairman	Existence of a Board/Council/Executive Committee	Legal Status	Selection of Governance Body
Case Study A	Yes	Yes	Ongoing development	Not for Profit (Formally registered)	Nomination
Case Study B	Yes	Yes	Yes	Not for Profit (Formally registered)	Nomination
Case Study C	No	Yes	Yes	Not-for Profit (Formally registered)	Electoral
Case Study D	Yes	Yes	Yes	Not-for Profit (Formally registered)	Electoral
Case Study E	Yes	Yes	Yes	Not-for Profit (Formally registered)	Nomination
Case Study F	No	Yes	No	Not for profit	Electoral
Case Study G	Yes	Yes	Yes	Not for profit	Electoral
Case Study H	Yes	Yes	Yes	Quasi-government	Electoral
Case Study I	Yes	Yes	Yes	Not-for profit	Electoral

The results show that 7 out of the 9 selected case studies have formal strategic documents to guide network activities. Implementing and developing a strategy ensures that there is a formal approach to CE activities in a way that can be measured and tracked. The lack of a strategic plan in some of the Sustainable Business Networks may be resulting in ad-hoc CE activities and lack of sustained impact.

All the 9 case studies of networks had a focal point of leadership in the form of a President, Chairman or Executive Director. This was essential as a point of guiding CE activities and officiating networking events. Most often, the person appointed in the office of the Chairman, President or Executive Director, as also the one responsible for liaison with key stakeholders in CE discourse such as those involved in CE financing. The office was also primarily focused on heading the Secretariat and driving membership growth and development. 7 out of the 9 network case studies assessed has an established Board of Directors to provide guidance to the network. This was considered as an essential move to separate management and governance of the network in line with corporate governance requirements. One network did not have a Board of Directors and most duties were entirely managed by the Secretariat. The need to separate responsibilities in networks is an essential component for attaining sustainable development

With respect to the election of the governance body there was a binary division amongst the networks. A group of 6 case studies selected governance bodies and office bearers using electoral processes. Various positions would be at stake for members to partake in them. Rules and institutional requirements would be stipulated in order for prospective candidates to elucidate their candidature. In this domain, this is where the power dynamics emerged. From the interview responses, distance was a major hindrance to full participation in network activities including electoral process.

In addition, there was also a tendency to vote on regional lines especially for regional and continental networks on CE. Voting on regional lines was considered as a clear positioning for network benefits such as funding, favours and higher chances of accessing consultancy roles. The consideration of merit in selecting office bearers was still needing improvement in some of the sustainable business networks. Whether or not, regional alliances work, it is still to be empirically proven in the context of sustainable development. In one of the case studies voting on regional lines and in general electoral processes of accessing network governance, created divisions between stakeholders in different parts of the Africa continent.

3.2 Unclear Role of Founder Members
The role of founder members was reported as a paradox. On one hand, founder members made a key contribution in terms of creating institutional memory and ensuring that every member is well oriented and focused to values of the association. In few instances founder members helped to induct new leadership. However, some of the founder members were refusing to let go the Circular Economy networks that they helped to establish and often encountered a *founder's syndromne*. Clear rules were essential in both existing and future networks to ensure that the founder members would not be disruptive to new activities of CE, for instance, the evolution of Sustainable Consumption and Production requires a drastic shift towards Circular Economy in line with current discourse. Founder members found themselves with nostalgic feelings of how they used to run the Sustainable Business Network, when new leadership and diverse new members were pre-occupied with the current discourse. Aligning the requirements of both founder members and new members of networks is essential to prevent conflict within networks.

3.3 Challenges of governing Sustainable Business Networks - Differences in priorities

Due to the different levels of priorities, governing networks was cited as a major challenge. Network members have differing views on how they should tackle Circular Economy issues. This applies to appropriate technologies, processes, develop circular products and services. Furthermore, varying contexts and contrasting industrial sectors makes it difficult for network governance to converge on common interest of network members. Due to the fact that the members of a sustainable business network are at different levels of development, it is common to see some members advocating for more advanced concepts whereas others are still at a n inception stage of circular economy knowledge. Harmonizing such priorities proved to be a major governance challenge. In addition, there are smaller network members who are members of circular economy networks and may be pre-occupied with survival and economic growth whereas other members may be pre-occupied with getting in tandem with other network members in terms of their CE standards.

3.4 Challenges of governing Sustainable Business Networks - Geographical constraints
Some networks cited geographical differences as a key governance challenge as they could not meet with members regularly to articulate policies of the sustainable business network. However, this challenge was insignificant in some networks as they entirely management network activities virtually. With the advent of technology, it was possible to undertake Board Meetings virtually as well as other networking activities that required the indulgence of governance structures of the network. To some networks, the physical engagement of governance level stakeholders and membership in general the physical engagement is considered as having a higher impact on the foothold and effective implementation of network activities.

3.5 Challenges of governing Sustainable Business Networks - Battles of Power
The research noted that in some networks such as Case Study D, there were some power struggles to lead the network. This pattern was also prevalent in Case Study H, Case Study C, Case Study G and Case Study I. In electoral processes there was an element of rivalry amongst network members in order to ensure that the candidate who was desired by different members was elected. At times electoral processes further divided networks. Battles between regional blocks such as different parts of Africa were evident in the Case Study D. The line of reasoning of aligning with certain network candidates was positioning for Circular Economy projects, access to funding and just egoistic tendencies of regional presence in leadership of international networks.

3.6 Challenges of governing Sustainable Business Networks - Leadership styles
The key informant interviews cited cases of differences in leadership styles amongst networks members. This because a challenge when one network members was elected or nominated into the governance structure of a network. It was observed that organisations have different corporate culture regimes and different leadership styles amongst them. As a result, interactions

of such organisations is filled with great complexities. Some of these complexities were experienced in all case studies.

3.7 Effect of formalization and legal status on CE activities

Networks can operate formally or informally. Most of the case studies were registered as not-for profit organisations. The legal status was preferred as it allowed for some of the network organisations to be tax exempt and also to be better able to access funding. Case Study A had a hybrid model as it was still able to combine not-for profit model and consultancy model. This is considered as a means of ensuring sustainability of the sustainable business network. Formalization of the network enabled a more organized a planned approach to meetings including hose that included Board Members and senior representatives of the association. The research also noted that it was possible to formulate sustainable business networks which depicted quasi-government characteristics. In this regard, it was possible to observe some governmental influence traits and involvement of public sector stakeholders. Future research should assess the impact of multi-stakeholder involvement in CE networks with a specific focus on government stakeholders and private sector stakeholders respectively.

3.8 Power relations amongst the members and governance bodies

An assessment of the 9 Case Studies showed that there was a vertical and a horizontal relationship within the sustainable business network. The vertical network as between the governance body such as a secretariat, board of directors, executive committee or otherwise as appropriate. Due to the voluntary nature of Sustainable Business Networks, there was no strict power centralization and members did not feel suppressed by the governance body. This was due to the fact that there were, no entry or exit barriers and there were no dire consequences that could be execute by the governance bodies. In a few cases governance bodies could enforce membership subscriptions or suspend membership where subscriptions have not been paid. Although the networks had charters where there were specifications of sustainability conduct, very few if any cases have been documented to demonstrate any action taken against members who violate the founding values of the sustainable business network. Lack of evidence for this situation clearly demonstrates that networks may have well documented governance systems, rules and norms of practice towards CE, but the implementation of such measures may still be low as the network Secretariats may not wield adequate power to be able to execute decisions. Due to the act that enterprises are also members of other organisations, it is also possible to explain this scenario of mild governance requirements as being driven by the desire of not frustrating members, who may end up leaving the association and paying their subscriptions elsewhere. The main challenge for the network governance bodies is how to maintain governance integrity, whilst also retaining network membership.

3 DISCUSSION

Although most of the sustainable business network have established governance systems, the effectiveness of the governance system is still unknown. Strategic planning is common in Sustainable Business Networks in Zimbabwe, South Africa and Kenya, However the independent evaluation and tracking of the strategic plans is still lagging behind. All networks apart from 1, have established a point of leadership through president, Chairman or Executive Director. The roles differ from network to network, but revolve along the lines of coordinating network activities. There is evidence of separation of management and governance through establishment of the Board of Directors, Councils or Executive Committees. Meeting of the governance institutions varied from time to time and also the leverage of enforcing decisions and following up on subscriptions was a key determinant of success. Most networks, favoured the legal status of not-for profit and most of them are legally registered. From our analysis, this legal status was selected due to the need attract financing and also to access tax exempt benefits in different national jurisdiction. Selection processes vary from election and appointment by nomination. Due to varying contexts, it was possible to facilitate network power transfer using either electoral or appointment means. Electoral processes for sustainable business networks were deemed transparent but on the other hand were regarded as divisive to the network growth and attaining a circular economy.

4 CONCLUSION

We conclude that networks have a role to promote, transfer and build capacity on the Circular Economy in Africa. We also conclude that the governance structure of the Sustainable Business Network has an influence on the success of circular economy activities and also the separation of management and governance could unlock financing. The level and extent to which the governance factors affect the sustainable business networks depends on the contextual factors existing in the jurisdiction under consideration. Rival-filled power dynamics in CE networks may have an impact on network participation.

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Recovery of Rare Earth Elements from NdFeB Waste Magnets

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Abstract

The increasing volumes of waste electrical and electronic equipment (WEEE), reported in developed countries, will soon be a major concern facing local municipalities. This waste contains a critical raw material group of rare earth elements (REEs), among other components. With the surge in electrical and electronic equipment use in recent years, responsible management of these associated solid wastes is developing. However, it is yet to be addressed practically in South Africa.

Hydrometallurgical processing by acid dissolution of waste permanent magnet (WPM) powders is used to recover REEs and their compounds from neodymium-iron-boron (NdFeB) magnets. These magnets were removed from discarded hard disk drives. The chemical treatment processes are predominantly based on inorganic acids such as hydrochloric, nitric, and sulphuric acids, which offer a good transition of the metals into salts dissolvable in the aqueous solutions. The first stage of operation in the extraction of REEs from waste (NdFeB) magnets includes the physical processes of demagnetization, crushing, and grinding to obtain WPM powders. In contrast, the chemical process is initiated by leaching the WPM powder with an acid. Then leachate is contacted with a selective organic extractant to recover demanded ions from the aqueous solution. The last step of the processing is precipitation, where ions create insoluble metalorganic complexes or REEs, which can be used in further manufacturing processes.

Experiments were performed with nitric acid to recover neodymium and iron from crushed NdFeB magnets. The results indicate that the best leaching conditions were obtained for experiments conducted using 100-150µm powder digested with 12.3M HNO3 at 60°C for 24 hours. HDEHP of 1M in n-dodecane showed the highest transfer of neodymium ions to the organic phase. The precipitation process utilizing the saturated aqueous oxalic acid solution showed a significant recovery of the Nd^{3+} ions from the organic phase. Recoveries above 95% were obtained for precipitant-to-extractant ratios 5:1 and 10:1.

Keywords: *neodymium magnets, rare earth recycling*

1. Introduction

Neodymium-iron-boron (NdFeB) magnets are mainly composed of iron, neodymium, and boron with additives in the form of other rare earth elements (REEs) such as praseodymium (Pr) and dysprosium (Dy) or other metals, i.e., cobalt (Co). The final composition of the permanent magnet is defined by the future application (Tunsu, 2018). To prevent corrosion of the permanent magnets, common additives are nickel, used for coating the manufactured product or adding 1-2% of cobalt to the alloy (Gruber et al., 2020; Lee et al., 2017). The Curie temperature is an important parameter of the permanent magnets which is a critical temperature of transition between ferromagnetic and paramagnetic properties of the material (Fabian et al., 2013). According to Sarfo (2019), market demand for neodymium, dysprosium, yttrium, europium, and terbium is nearing the quantities obtained from geological deposits. Thus, the collection and recycling of NdFeB magnets and other WEEE are critical to meet the sustainable growth goals of this industry sector (Chu, 2010).
Some key applications of neodymium magnets include wind turbines, electric cars, hard disk drives (HDDs) and military equipment (Xie et al., 2014). One of the promising sources of waste magnets that can be used in the recycling process is hard disk drives (HDDs). Each HDD contains between 1 and 30 g of neodymium magnets with an Nd and Dy content of approximately 31% and 4-7%, respectively (Erust et al., 2021).

The implementation of commercial processes for waste electrical and electronic equipment recycling, especially REEs recycling, is limited. (Binnemans et al., 2021). Commercially available processes mostly focus on recovering scrap magnets from the waste electrical and electronic equipment (WEEE) and repurposing them using the magnet-to-magnet (M2M) approach.

Recycling NdFeB magnets is necessary to increase the available amounts of REEs, which can delay the depletion of the known deposits (Reisdörfer et al., 2019) and address unsustainable mining practices. The three possible approaches to REE recycling include magnet-to-magnet (M2M), pyrometallurgical and hydrometallurgical methods. The magnet-to-magnet approach refers to the production of new magnets from spent magnets. The waste magnets are refurbished and prepared for sintering by adding approximately 3% fresh permanent magnet alloy. Greater than 90% of REEs are recovered with less than 5% freshly mined rare earth metals (Jin et al., 2016). The most important disadvantage of this approach is the decrease in the final product quality, mostly due to the inconsistency in the composition of the final product. Several applications report using these magnets in electrical engines, wind turbine generators or magnetic separators (Nlebedim et al., 2018). The pyrometallurgical approach primarily processes freshly mined ores with high concentrations of REEs (Tunsu, 2018). The main disadvantages of this approach are high energy consumption used to reach the required temperatures, low selectivity of the process, and high levels of pollution in the form of emissions of gas and solid particles into the air (Tunsu, 2018).

Hydrometallurgy is one approach to recovering rare earth elements from WEEE (Gruber et al., 2020), with leaching being a well-established technique in converting metals into ions of soluble salts via chemical reactions (Behera et al., 2016; Lee et al., 2013). REEs react with sulfuric acid, nitric acid, and hydrochloric acid to form hydrogen gas and cations in salts containing sulfate, nitrate, and chloride anions, respectively. The low energy consumption, reduced gas emissions and adaptability to varied materials by adjustment of the reagents to achieve lower environmental impact (Reisdörfer et al., 2019). However, the amount of acidic waste generated in liquid form poses a significant drawback to this approach (Gruber et al., 2020). NdFeB magnets are demagnetized and comminuted to small diameter particles in hydrometallurgical processes, preferably in leaching processes. Then waste permanent magnet (WPM) powder is digested with acid to obtain mixtures containing ions of metals present in the alloy used to manufacture magnets. This approach is based on the use of inorganic acids such as hydrochloric, nitric, and sulfuric acid, which, according to the literature, allow for high leaching recoveries (Erust et al., 2021; Lee et al., 2013; Ni'am et al., 2019). Leaching is affected by WPM powder modification, type of acid, particle size, concentration of acid, solid-to-liquid ratio, stirring speed, the temperature of the solution, and contact time with leachate (Ni'am et al., 2019). Lee et al. (2013) conducted batch experiments to establish optimal leaching conditions for Nd recovery from permanent magnets. The authors concluded from the large list of parameters investigated that for WPM powder of particle size less than 297 μm, optimal leaching conditions were obtained using 3M H2SO4 and HCl over 15 minutes using a solid/liquid ratio of 0.02. Ni'am et al. (2019) reported that optimal WPM leaching conditions were obtained by utilizing 5 M HCl at a temperature of 368 K for 24 h using 0.02 solid-liquid ratio, 800 rpm stirring speed, and 0.250 mm particle size of the WPM powder.

Reisdörfer et al. (2019) characterized roasted and unroasted NdFeB magnet powders sourced from HDDs. Roasting is performed at high temperatures to convert the elements in the sample into oxides. This enhances the selectivity of Nd in the leaching procedure. Unroasted NdFeB powders contained 32.36% of Nd and 58.5% of Fe. Lee et al. (2013) reported similar values, with 31.27% of Nd, 59.62% of Fe, and 1.26% of B. It must be noted that the Nd percentages of 25.19% and 32.36%, with and without roasting, respectively, were considerably higher than the amounts typically found in mineral ores. Nd extraction from bastnasite is approximately 18.5 wt%, while percentages in the 15-20% range are extracted from monazite.

Leaching, extraction and precipitation experiments were conducted in this study using HNO_3, bis(2-ethylhexyl) phosphate (HDEHP), oxalic acid and WPM powder from HDDs. The effect of particle size, nitric acid concentration, temperature and contact time were reported for the leaching experiments. The concentration of HDEHP and the time of the extraction process are reported for the extraction experiments. Oxalic acid was utilized as a precipitant to selectively recover REEs from the organic phases collected during the extraction measurements. The sample analyses were performed using Inductively Coupled Plasma – Optical Emission Spectrometry (ICP-OES) to determine concentrations of ions in samples.

2. Methodology

The experimental work consisted of four processes: pretreatment of the waste magnet powder leaching, extraction and precipitation. Table 1 presents a list of the chemicals used in this work. Waste magnet powders were obtained by dismantling hard disk drives (HDDs) supplied by the University of KwaZulu-Natal.

2.1 Pretreatment of waste magnet powders

HDDs were dismantled manually to remove the NdFeB magnets by removing the aluminum casings. NdFeB magnets of varying sizes and compositions were isolated and stored for subsequent waste processing. All other components were dispatched for waste treatment. To remove the magnetic properties of the magnets, these were heated above Curie temperature in a Scientific 909 model laboratory furnace at 400℃. Once the temperature of the furnace stabilized

Table 1. List of chemicals used during this study.

Chemical compound	CAS Number	Molecular Mass, g/mol	Supplier	Purity
Bis(2-ethylhexyl)	298-07-7	322.4	DLD	0.999
n-Dodecane	11-40-3	170.33	Sigma Aldrich	0.995
Nitric acid	7697-37-2	63.01	Honeywell	0.650
Sodium hydroxide	1310-73-2	39.99	Sigma Aldrich	0.98
Phenolphthalein	77-09-8	318.32	Sigma Aldrich	0.9995

At the set point, the magnets placed in a ceramic crucible were carefully inserted into the furnace and heated for 30 minutes, left to cool for 30 minutes. The magnets were then comminuted using a roller mill. Several repetitions were performed until magnet powder fines were obtained. The magnet fines were screened using a series of laboratory test sieves of varying apertures (100 µm, 150 µm, 200 µm, 300 µm, 355 µm, 425 µm, 500 µm, and 600 µm). This allowed the particle size distribution after comminution to be determined with the agitation of the sieve trays set for 30 minutes by an electrical shaker. The final masses of each tray were then weighed using a mass balance, and the contents of each tray were stored in labelled airtight bags for further waste processing.

2.2 Leaching

All leaching experiments were performed on a batch scale, with a solid-to-liquid ratio (S:L) of 1:50 being utilized, as Erust et al. (2019) recommended. Magnetic stirrer plates with integrated heating elements were employed. Borosilicate glass beakers were filled with nitric acid solution (6.7M and 12.3M). Each beaker was placed on a heated magnetic stirrer plate, with a stirrer rate set at 333 rpm. After the temperature had stabilized at the desired setpoint (45°C or 60°C), magnet powder (100-150 µm and ≥600 µm grain size) was weighed and added to each beaker. After the leaching period had elapsed, the run was terminated, and samples were collected immediately. A 45 µm micro-filter plunger syringe was used to draw out a 1ml sample, diluted with a factor of 100 to prepare for ICP-OES analysis. Sampling was performed in triplicate, and each experiment was conducted in triplicate. The remaining solution was filtered and stored in an airtight container for further waste processing.

2.3 Liquid-liquid equilibria

Two sets of experiments were performed to measure the distribution of the metals between aqueous and organic phases. In the first setup, 10 ml glass cells were used. In the second setup, a 100 ml extraction cell was utilized. This approach was used to determine the scalability of the process. The water bath temperature was kept at 25°C throughout the experiments. The leached solutions from the previous experiments were utilized as the aqueous phase. The organic phase (1M and 0.5M HDEHP in n-dodecane) was prepared by combining predetermined volumes of HDEHP and n-dodecane. The glass cells were each loaded with the aqueous and organic phases in a 1:1 volume ratio. The contents of the cells were stirred for 12h. After agitation, the mixtures within the glass cells were left to separate for 12h in isothermal conditions to prevent any equilibrium disturbance. Approximately 5 ml of the aqueous phase was withdrawn from each cell without disturbing the equilibrium. The withdrawn samples of the aqueous phase were diluted with a factor of 100 for the ICP-OES analysis. The organic phase concentrations of REE were determined following the ICP-OES analysis and were calculated based on the mass conservation law. The REE concentrations of the aqueous feed prior to extraction and the equilibrium concentration of the REE of the aqueous phase in the cell after extraction and settling were used to perform mass balance calculations.

2.4 Precipitation

Various acid concentrations and organic: acid (O:A) ratios were used to precipitate REEs. A 100mL was used during this process. Calculations were performed using mass balance. The organic phase was drawn to the vial. The desired volume of a saturated mixture of oxalic acid was added, and the contents of the vial were stirred vigorously for 10 minutes. The vial was left at ambient temperature to settle for 48 hours to allow precipitation. The contents of the vials were filtered, washed, and dried. Solids were then dissolved in concentrated sulphuric acid and diluted with a factor of 100 for ICP-OES analysis.

2.5 Safety

Each experiment was conducted using personal safety equipment. The remaining acidic solutions were collected and stored in properly marked containers under the fume cupboard for the chemical recycling company to neutralize. The remaining HDEHP was also collected and stored for future experiments regarding multi-stage extraction and recycling of the extractant.

3. Results and discussion

3.1 Demagnetization

The high magnetism of NdFeB magnets causes strong coercive forces, making them nearly impossible to separate. It is advised to have the proper padding or material on hand for optimal storage. Demagnetization made handling the NdFeB magnets and their subsequent comminution stage more convenient. Lee et al. (2013) reported that total demagnetization occurs at 350°C after 15 minutes. In contrast, Reisdörfer et al. (2019) used a temperature and duration of 350°C and 30 minutes, respectively. As a result, 400°C and 30 minutes were used to ensure complete demagnetization.

3.2 Comminution

The size distribution of crushed magnets is presented in Table 2. The mass fraction of crushed magnets consistently decreased with decreasing sieve sizes. This indicates that the comminution process should be improved in future work. In practical operations, further crushing would demand increased equipment to screen samples, thereby increasing the capital costs of the process and the workforce required. The desired particle sizes were 100 – 150 μm and 600 μm. A particle size range of 600 μm was used to determine if additional crushing or grinding is required. In practical operations, further crushing would demand increased equipment to screen down samples, thereby increasing the capital costs of the process and the workforce required.

Additionally, an efficient crushing procedure is necessary to fast-track the leaching process. Behera et al. (2016) and Sahin et al. (2017) reported that optimal particle sizes were 46-75 μm and 63-90 μm, respectively. The mass distribution of the particles of different sizes is shown in Table 2. The standard uncertainties for mass measurements were 0.03 g.

Table 2. Sieve analysis of the waste permanent magnet powder after comminution.

Sieve Size (μm)	**Mass retained (g)**	**Mass fraction**	**Cumulative Mass Passes (g)**	**Total Percent Passed (%)**
600	339.3	0.554	273.0	44.59
500	40.88	0.067	232.2	37.91
425	37.24	0.061	195.0	31.83
355	32.69	0.053	162.2	26.49
300	30.39	0.050	131.8	21.53
200	57.50	0.094	74.34	12.14
150	28.79	0.047	45.55	7.439
100	33.86	0.055	11.69	1.910
Pan	11.69	0.019	0	0
Total	612.3	1	612.3	100

3.3 Leaching

The parameters investigated in the experiments were the leaching period, the concentration of acid, particle size of magnetic fines and temperature. The contact time between acid and WPM powder is crucial in leaching. Four different leaching periods were tested to investigate the effect of leaching time on leaching efficiency, namely 30, 60, 240 and 1440 min. The results are presented in Table 3, which shows that the leaching period significantly affected leaching performance based on the variation of metal ion concentrations. The concentration of both Fe^{3+} and Nd^{3+} ions was observed to have increased logarithmically as the leaching period was increased. It is noted that the reaction rate was visually observed to have been higher upon introducing the magnet fines to the acid solution. This results in the leaching rate being significantly higher for the shorter leaching periods and reduced for the increased leaching periods. Based on the results, the 24-hour leaching period consistently produced the best and optimal leaching performance.

The size of the particle being subjected to leaching also affects the leaching performance. The concentration of both Nd and Fe ions was higher for the 100–150 micron particle size than the ≥600-micron particle size. This was observed across all leaching periods. This result is due to the larger contact surface area facilitating the leaching reaction for smaller particles. Due to the abovementioned, the 100–150-micron particle size was deemed optimal for the process. The concentration of acid used for leaching directly impacted the leaching performance. Two different concentrations of nitric acid were utilized to investigate the effect of concentration on leaching performance, namely 6.7M and 12.3M. The concentration of both Fe and Nd ions was higher when utilizing 12.3M nitric acid as a leaching agent, compared to 6.7M nitric acid. This was observed for all leaching conditions. Due to this result, 12.3M nitric acid was deemed optimal. The temperature of the leaching reaction directly impacts the process performance. Two temperatures were utilized in the leaching experiments to investigate the effect of temperature, namely 45℃ and 60℃. The concentration of both Nd and Fe ions was higher for the 60℃ leaching experiments than the 45℃ leaching experiments. This was evident for all leaching conditions. It was therefore concluded that 60℃ is the optimal temperature for leaching REEs. This result was due to the higher temperature providing access activation energy to facilitate the chemical reaction.

Table 3. Concentrations (ppm) of Nd^{3+} and Fe^{3+} ions obtained after leaching at a given nitric acid concentration (M), temperature (°C), time (h) and particle size (μm).

			Particle size			
			100-150 μm		≥600 μm	
$[HNO_3]$/M	T/°C	Time/h	$[Nd^{3+}]$/ppm	$[Fe^{3+}]$/ppm	$[Nd^{3+}]$/ppm	$[Fe^{3+}]$/ppm
6.7	45	0.5	13400	17815	6950	14533
		1	14100	19483	7852	15573
		6	15200	21850	8765	16578
		24	15800	23117	11408	22106
	60	0.5	14277	19225	8165	16147
		1	14792	21817	9025	19883
		6	16268	24183	10023	20800
		24	17172	26450	14257	23217
12.3	45	0.5	15012	21397	9888	16990
		1	16192	24117	10983	20817
		6	17210	30729	12183	22017
		24	18003	37367	16767	24783
	60	0.5	15758	26950	12763	21133
		1	16738	29417	13002	23933
		6	18044	34333	14462	24450
		24	18763	39233	19133	26450

3.4 Liquid-liquid equilibria

The extraction measurements involved an organic phase of HDEHP in an n-dodecane solution, and an aqueous phase of REEs leached in a nitric acid solution. The concentrations of the aqueous and organic phases were varied to investigate their effect on extraction performance. Two aqueous phase concentrations were deployed, 0.5M and 1M of HDEHP in n-dodecane. The REE concentrations in the organic phase varied based on the leaching conditions that they were subjected to. The extraction measurements were performed on a laboratory vial scale (10 ml) and a pilot-plant scale (100 ml). This was performed to investigate the scalability of the REE extraction method proposed.

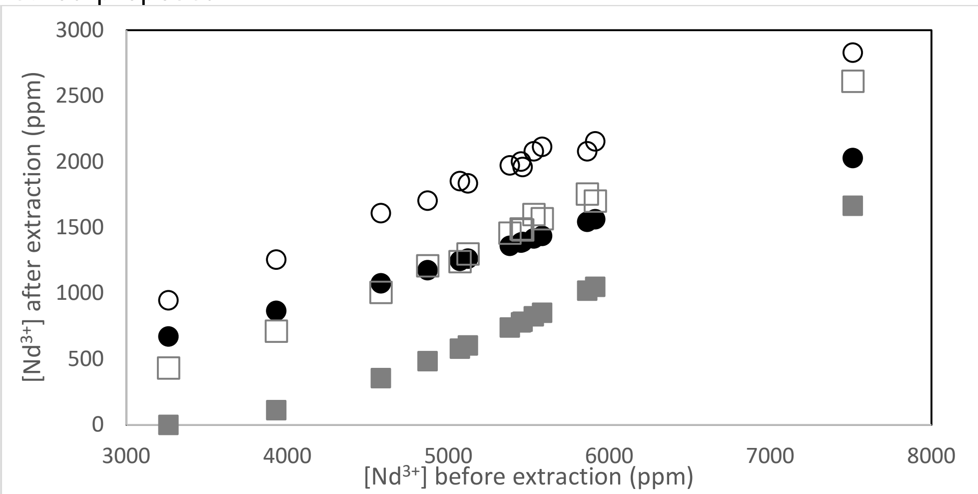

Figure 1: Nd^{3+} ions concentration before extraction vs Nd^{3+} ions concentration after extraction experiments; ● – 0.5M HDEHP in n-dodecane in 10 ml cell, ■ – 1M HDEHP in n-dodecane in 10 ml cell, ○ - 0.5M HDEHP in n-dodecane in 100 ml cell, □ – 1M HDEHP in n-dodecane in 100 ml cell

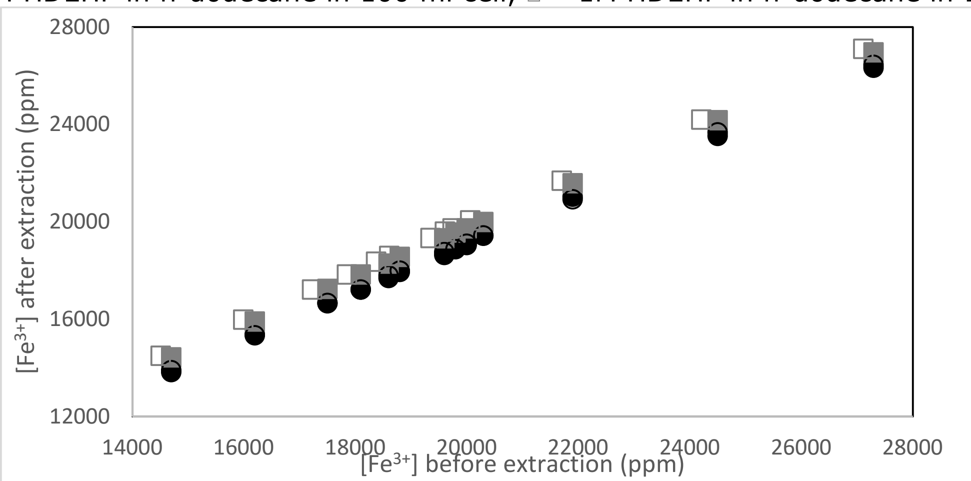

Figure 2: Fe^{3+} ions concentration before extraction vs Fe^{3+} ions concentration after extraction experiments; ● – 0.5M HDEHP in n-dodecane in 10 ml cell, ■ – 1M HDEHP in n-dodecane in 10 ml cell, ○ - 0.5M HDEHP in n-dodecane in 100 ml cell, □ – 1M HDEHP in n-dodecane in 100 ml cell

Figs. 1 and 2 show that the concentration of Nd^{3+} in the aqueous phase had significantly decreased, signifying that the Nd^{3+} ions were transferred into the organic phase. A 1M HDEHP solution was significantly more efficient during experiments in both scales. However, the results of small-scale experiments show a higher efficiency of the extraction in comparison with the larger-scale results. This might be caused by the inefficient stirring in the larger equilibrium cell. For Fe^{3+} ions, however, the decrease in concentration was barely noticeable throughout the experiments. This is due to the nature of the organic phase deployed, being selective towards REE ions.

3.5 Precipitation

Precipitation measurements were performed using conditions reported by (Binnemans et al., 2013). Table 4 presents the precipitant compositions and overall neodymium recovery. The volume ratio of saturated oxalic acid to the organic phase was crucial for the recovery of the neodymium in the precipitation process. The 1:1 volume ratio shows the lowest recovery of the Nd^{3+} ions, with approximately 71% recovery. Ratios of 5:1 and 10:1 show the best recovery rates exceeding 95% and 97%of recovery, respectively.

Table 4. Concentrations (ppm) of Nd^{3+} and Fe^{3+} ions obtained before and after precipitation processes at a given HDEHP concentration (M) and various oxalic acid (OA) to organic phase (OP) volume ratios.

[HDEHP] /M	OA:OP ratio	[Nd^{3+}] in the extract	[Nd^{3+}] in solids	[Fe^{3+}] in the extract	[Fe^{3+}] in solids	Recovery of Nd^{3+}/%
0.5	1:1	3499	2492	917.2	566.3	71.18 ± 0.10
	2:1	3264	2965	839.8	681.4	90.86 ± 0.23
	5:1	3114	2975	830.0	707.3	95.54 ± 0.12
	10:1	3703	3569	815.0	696.4	96.37 ± 0.13
1	1:1	3971	2796	211.2	140.7	70.43 ± 0.11
	2:1	3801	3443	241.8	203.2	90.59 ± 0.34
	5:1	3625	3457	205.5	178.9	95.39 ± 0.22
	10:1	4107	3993	223.3	203.5	97.22 ± 0.09

3.6 Limitations of this study

Experiments performed on a small scale (10ml) and larger scale (100ml) showed that the process can be upscaled. A pilot-scale operation is recommended for further tests to assess the scaleup potential. Regarding the process feasibility, additional studies must be undertaken to choose the optimal precipitant-to-extractant ratio. Waste management strategies must be implemented for a sustainable approach.

4. Conclusions and recommendations

A hydrometallurgical process involving leaching using extraction and precipitation to recover neodymium from waste permanent magnet powders successfully yielded recoveries greater than 95% neodymium. The set of optimal conditions for each subprocess was established. Optimal leaching conditions were obtained using 100-150μm powder digested with 12.3M HNO_3 at 60°C for 24 hours. HDEHP was proven a good extractant due to its selectivity towards neodymium ions. The precipitation process with saturated oxalic acid solution showed a significant recovery of the Nd^{3+} ions from the organic phase, with recoveries of above 95% for the precipitant-to-extractant ratios above 5:1. Oxalic acid salts can be relatively easily thermally decomposed to the REE oxides, which can then be used in the manufacturing process of new magnets.

The trends shown by the data for the 10 and 100 ml cells are similar, indicating that upscaling of the process is possible. The insufficient mixing in the large cell can explain the discrepancy between both data sets.

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Simulating The Driving and Charging of Electric Minibus Taxis: A Case Study for Stellenbosch

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Abstract

The Global North is increasing the drive for the electrification of the mobility industry. In sub-Saharan Africa, however, the adoption is yet to pick up steam due to various other challenges in the region. The viability of converting the paratransit fleet (which consists mostly of minibus taxis) to electric vehicles (EVs) with current combustion-based operations is investigated by making use of simulation software, and EV-Fleet-Sim. This developed software simulates the driving and charging of operationally tracked taxis in the Stellenbosch area. A charging algorithm, as well as a simple battery model, was included in the simulation to provide a more accurate representation of the scenario. Most of the taxis were found to still complete their required trips with the specified battery size of 70 kWh. However, new methods would need to be found, such as including a mixed fleet with some petrol or diesel taxis, to assure a 100% trip completion rate. The grid impact per vehicle was found with an expected maximum load appearing between the hours of 08h00 and 10h00 of 22 kW per vehicle, which corresponds to the time after the morning peak traffic of getting people to work. Furthermore, a minimum number of chargers can be implemented which will not affect the trip completion rate of the taxis. This was found to be for 4 chargers per 17 taxis. Future work is left to the testing of various parameters to find optimal solutions as well as including home charging and failed trip classification.

Keywords: minibus taxi, electric mobility, grid impact, charging

1. Introduction

The drive for scaled electric mobility in the Global North has increased exponentially in the past decade. However, in sub-Saharan Africa, this adoption has been slow due to the many other challenges the region faces, such as a severely restricted electricity supply. This paper evaluates the viability of converting the paratransit industry (consisting mostly of minibus taxis) to electric vehicles by investigating whether the demand of the taxis can be met with an electric version of it. This is done by simulating the driving and charging of the taxis over a period of a month. Furthermore, this paper aims to investigate the impact that these vehicles will have on the grid, for the case scenario of charging at a centralised taxi rank.

Sub-Saharan Africa's so-called "paratransit" industry differs substantially from the developed countries' paratransit industry in both the vehicle type and operations. In developed countries, it is defined as a point-to-point, demand-responsive and flexible transport. However, in sub-Saharan Africa, this word refers to the mode of mobility for the majority and has subsequently been termed as an informal public transport system (Askari et al., 2021; Behrens et al., 2017; Horni et al., 2016; Ndibatya et al., 2014). Its operation can be characterised as one falling between a private passenger transport system and a conventional public transport system in terms of its scheduling, cost, routes, and quality of service (Horni et al., 2016; Ndibatya et al., 2014). As a result, many depend on this industry for their livelihood (Behrens et al., 2015), and the social and economic development of a country heavily depends on the existing transport sector (Khalid et al., 2019).

The minibus taxis make up most of the vehicles in the paratransit industry, with South Africa having approximately 250 000 taxis (SA Taxi, 2023). These minibus taxis are currently powered by internal combustion engines (ICE) which contribute towards the emission of greenhouse gasses

(GHG) as well as a general decline in air quality within cities (Collett & Hirmer, 2021). The minibus taxi contribution towards the decline in air quality within a city is further aided by the minibus taxis being old (often older than 20 years) and thus fuel inefficient (Amegah & Agyei-Mensah, 2017; Dalal et al., 2011).

The World Health Organisation has linked the exposure to ambient air pollution to the increase in cardiopulmonary and cardiovascular diseases and have thus classified exposure as a major threat to human health (Amegah & Agyei-Mensah, 2017; Khalid et al., 2021). Three of the seventeen United Nations Sustainable Development Goals are clean energy, sustainable cities, and climate action (goals one, eleven and thirteen respectively) (Zinkernagel et al., 2018). Thus, the development of low-carbon transport in cities is crucial to the global agenda, with the electrification of vehicles promoted as the low-carbon transport strategy to slow down climate change and reduce carbon emissions (Khalid et al., 2019).

The transition from ICE vehicles to electric vehicles (EVs) is gaining traction in developing countries (C. J. Abraham et al., 2021; Berckmans et al., 2017; Münzel et al., 2019), with many of the global manufactures planning to stop production of ICE vehicles as early as 2030 (Booysen et al., 2022; Niese et al., 2022). Sub-Saharan Africa has already seen a few isolated cases of electric mobility with the focus on the micro-mobility (tricycles and motorcycles) industry, as well as a small minority investigating buses and cars (C. J. Abraham et al., 2021). Many have called for a total overhaul of the minibus taxi industry (to something akin to that in Europe) as part of this global shift, but it is well entrenched within society. It is unlikely to be phased out as the preferred mode of transport due to its existing dominance in the market as well as its agility in the informal townships (Collett & Hirmer, 2021). The electrification of the paratransit industry is therefore a necessity, but the question still remains regarding the impact that such vehicles will have on an already energy scarce and fragile grid system (Buresh et al., 2020).

1.1 Contributions

This paper aims to quantify the impact that the charging of electric minibus taxis will have on the local infrastructure, or the localised grid. Furthermore, the paper establishes to what extent the electric minibus taxis will be able to complete the trips based off current operations, thereby meeting the demand of passengers, given the limiting nature of the battery size, slow charging and number of chargers. These impacts are assessed using custom software using tracking data of real vehicles driving within the city of Stellenbosch, South Africa.

2. Literature Review

The electrical grid in South Africa is run by the government-owned entity, Eskom, which has an installed capacity of 48 GW. However, the available capacity frequently reduces to 24 GW due to regular breakdowns and maintenance programs. This has resulted in rolling regional blackouts, colloquially known as "loadshedding", being a regular occurrence in the country. (Buresh et al., 2020) The localised grid of Stellenbosch is in question for this paper, which experiences many of the challenges of the national grid.

2.1 Grid Impact of EV Charging

The utility grid, and more specifically the distribution grid, can be negatively affected when private EVs charge either at public charging stations or at home in an unscheduled manner (Dang, 2018; Sundström & Binding, 2012). The same logic can then be applied to the electrification of the minibus taxis. The development of EV charging structures with minimal impact on the existing grid is therefore required for sustainable integration (Khalid et al., 2019). This is further substantiated by Abraham et al., 2021, who states that a substantial burden can be placed on the local electrical grid if a large enough fleet is charging.

Three different charging strategies are currently utilised in industry: charging ports, battery swap stations and fast charging stations (FCS) (Liu, 2012). It has been stated by Giliomee & Booysen

(2023) that the battery swapping method is not a viable solution to the electric taxi fleet, as it would place strain on the OEMs to produce this technology when sufficient other technologies already exist. The charging power for EVs in charging ports and FCSs can be categorised into various classes and power levels (Wang et al., 2021a). The first class is known as slow charging (Wang et al., 2021b), which consists of AC charging at Level 1, ranging from 1.4 to 2.2 kW (Khalid et al., 2019; Meyer & Wang, 2018a; Rajendran et al., 2021a). The second class is known as accelerated charging (Rajendran et al., 2021b), which consists of AC charging at Level 2 and ranges from 19.2 to 22 kW (Khalid et al., 2019; Meyer & Wang, 2018a; Rajendran et al., 2021a). However, AC Level 2 can also range between 4 and 8 kW (YILMAZ & Krein, 2013), depending on the vehicle type. The final class is known as fast charging (Wang et al., 2021b), which consists of DC charging at Level 3, which can range anywhere from 50 to 350 kW (Meyer & Wang, 2018b; Rajendran et al., 2021b; Wang et al., 2021b). DC charging stations require an external power converter while AC charging requires an on-board power converter (Rajendran et al., 2021b; Wang et al., 2021b).

3. Methodology

This section describes the details and functionalities of the software developed to determine the grid impact and completion rates of the electric taxis. Furthermore, the type of input required for the simulation program and EV-Fleet-Sim (the program responsible for simulating the driving of the electric vehicle) is also described. A high-level overview of the simulation setup is shown in Fig. 2. Each of these components are broken down and discussed in further subsections.

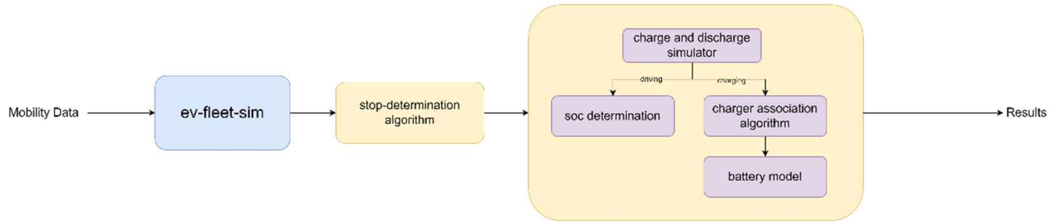


Fig. 2. High-Level Overview of software and EV-Fleet-Sim

3.1EV-Fleet-Sim

EV-Fleet-Sim is a software developed by Abraham et al. (2021) which takes in the mobility data of tracked vehicles, in this case minibus taxis, and calculates the energy requirements of an electric version of the vehicle by using a developed EV-model, and routing simulator. The mobility data used in this study was provided by GoMetro. Seventeen taxis were tracked for a month within the Stellenbosch area. An example of the mobility data provided can be seen in Fig. 3, which shows a heat map of where a taxi drove in the Stellenbosch area. The "hotspots" show how often the taxi was in a specific location in the month. Additionally, one of the outputs of EV-Fleet-Sim is the energy consumed from the EV battery during driving [in Wh/s], which is used in Eq. (1).

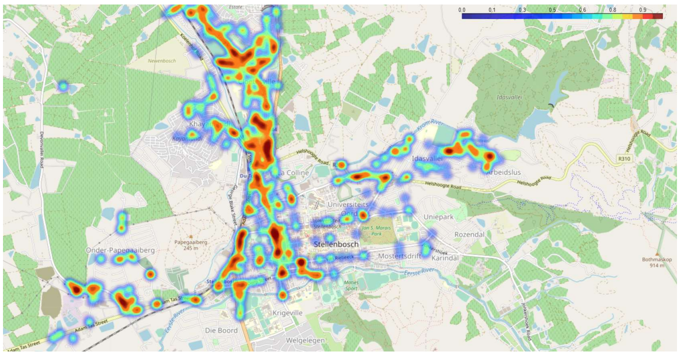
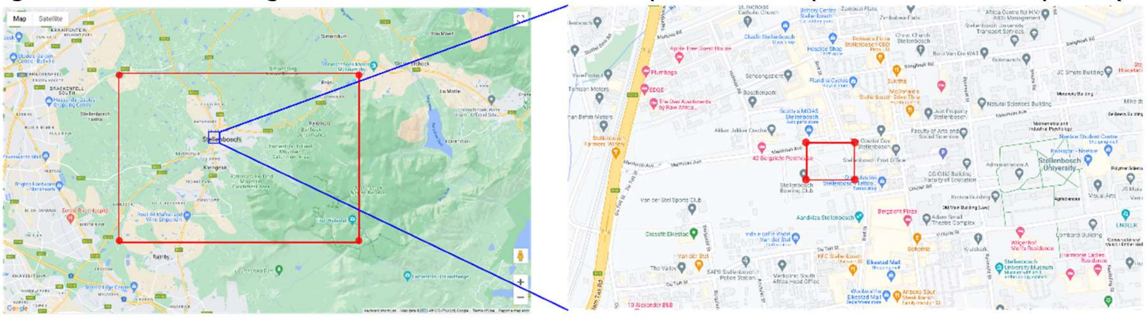


Fig. 3. Example of mobility data

The tracked taxis travelled in and around Stellenbosch. The set boundary can be seen in Fig. 4(a). If a vehicle is found to travel outside this boundary, it is not considered within the data and the vehicle is seen as "not driving" on that day. Furthermore, on weekends, the taxis make long distance trips to the Eastern Cape, and so weekends are also excluded from the dataset. A solution for long distance travelling of electric minibus taxis is presented by Giliomee & Booysen (2023).



(a) (b)

Fig. 4. (a) Stellenbosch Boundary (b) Stellenbosch Taxi Rank - Charging Location

3.2 Stop-determination Algorithm

The data was setup and run according to the steps in the documentation of EV-Fleet-Sim (C. Abraham, 2022). However, even though EV-Fleet-Sim was able to provide the energy requirements for the EV battery, it was unable to determine if the vehicle was stopped and available to charge. Thus, a stop-determination algorithm was developed for this.

The vehicle is considered to be "stopped" based on two conditions: speed within 10 km/h and the new GPS location being within a 25 metre radius of the first stop location. The first stop location is determined by the vehicle speed being below 1 km/h. The algorithm evaluates if the vehicle has stopped and if the vehicle remains stopped based on the conditions stated previously. Once these stop locations are determined, the vehicle must be stopped for a minimum of 20 minutes in order to be considered "Available to Charge". These values are used in subsequent sections.

3.3 Taxi-State Model

The output of EV-Fleet-Sim has datapoints for every second for each day, ranging from 00h00 to 23h59, for a normal day. This data exists as daily information grouped to each vehicle. However, the simulation software requires the day to start at 04h00 and simulate until 03h59 of the next day, instead of the normal day. This more accurately resembles the activity and motion of the taxis, as they start their operations at approximately 04h00 in the morning. Thus, the data must be transformed from the original times to these new times. The simulation software also takes in the data as vehicle information, grouped to each day, and requires further formatting.

The stopping data created in the previous section was used to determine if the vehicle has stopped at the specified charging location or if the vehicle has merely stopped at a traffic light or is in traffic. The charging location was taken as the Stellenbosch Taxi Rank in the centre of town and can be seen in Fig. 4(b). This presents the two states the taxi can be in: driving or charging. Even though the taxi may be stopped in traffic, it is still considered to be "driving". The state-of-charge (SOC) of the vehicle's battery can then be calculated according to Eq. (1) for the driving state, where *i* represents the current time index, *e* is the energy consumed by the vehicle in *Wh* and *B* is the battery capacity of the vehicle in *Wh*. The SOC for the taxi for the case of charging is described in further sections.

$$SOC[i] = SOC[i-1] - \frac{e[i]}{B} \quad (1)$$

3.4 Charger Association Algorithm

A charging algorithm was developed and incorporated into the simulation software to perform the association of available chargers during charging. If the vehicle needs to charge and is available to charge (based on the condition that it is within the bounds of the taxi rank and stopped for more than 20 minutes), and a charger is available, the algorithm assigns the vehicle to that charger. The algorithm can also handle a few conditions and edge cases when simulating. If there are not enough chargers available for the number of vehicles that need to be charged, the algorithm checks if there is a vehicle on charge that has an SOC greater than 80%. It then selects the vehicle with the highest SOC and de-assigns it from the charger and replaces it with a vehicle with a low SOC. If all the vehicles have an SOC greater than 80%, the algorithm keeps the vehicles on charge until they have reached 100% before assigning a new to charger to a vehicle with an SOC greater than 80%.

3.5 Battery Model

The slower charging of the battery as the SOC approaches 100% can be accounted for with the inclusion of a simple battery model within the simulation software. A Constant Power Constant Voltage (CP/CV) charging profile was assumed. The implemented battery model can then be used to determine if the battery of the EV is in Constant Power or Constant Voltage mode. The battery model parameters are highlighted in Table 5, with the calculations and charging mode determination based on the work presented by Qian et al. (2023). The only modification to the equations presented in their work is given by Eq. (2), where V_{OC} is the open circuit voltage, which has been modified from their Eq. 5. Furthermore, the calculation of the SOC during charging is given by Eq. (3), where *g* is the charging power based on the calculations presented by Qian et al. (2023). For the purposes of this simulation, a grid charging power of 22 kW was chosen due to it being able to charge vehicles sufficiently without having the impact that DC chargers would have on the grid. Furthermore, a charging efficiency of 88% (Qian et al., 2023) was incorporated to account for the inefficiencies of real chargers.

$$V_{oc}[i] = a_v(SOC[i] \times E_{nom}) + b_v \quad (2)$$

$$SOC[i] = SOC[i-1] + \frac{g[i]}{B} \quad \textbf{(3)}$$

Table 5: Battery Model Parameters

Parameters	Description	Values	Parameters	Description	Values
V_{nom}	Nominal cell voltage	3.7 V	M_p	Number of cells in parallel	78
V_{max}	Maximum cell voltage	4.15 V	M_s	Number of cells in series	110
R	Cell impedance	148 mΩ	a_v	Model coefficient per cell	67.92 mV/Wh
Q_{nom}	Nominal cell capacity	2.2 Ah	b_v	Model coefficient per cell	3.592 V
E_{nom}	Nominal cell energy	8.14 Wh			

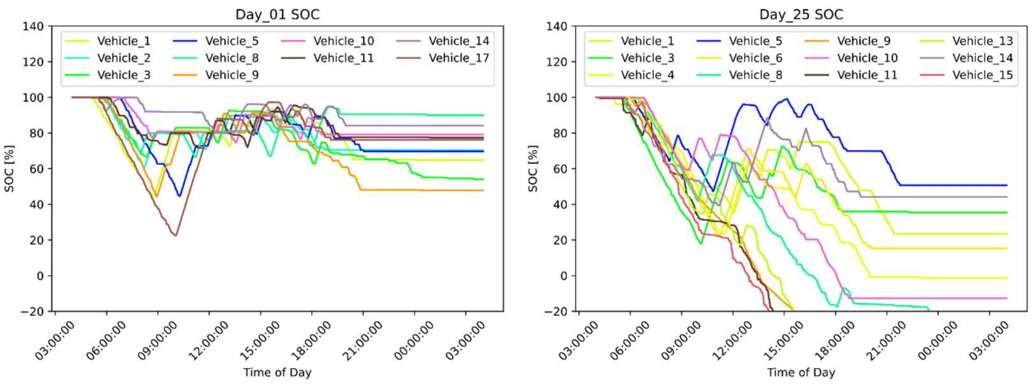
4. Results

This section describes the results obtained from the simulation software. The first section describes the ability of the electric minibus taxis to drive and meet the demand of the passengers, and is followed by the second section, which describes the grid impact with current approaches. The vehicles were simulated for each day of a month. Each vehicle started at 100% SOC at the beginning of each day, and "loadshedding" times were not incorporated in the simulation.

Fig. 5 demonstrates two example days of the month, with Fig. 5(a) being an example of a good day and Fig. 5(b) being an example of a bad day. It is important to note that the vehicles were allowed to "travel" past 0% SOC, as it was assumed that a larger battery capacity would be needed in this case. This was done to test if the vehicle would be able to regain its expended energy if a larger battery capacity was used, without having to re-simulate at different battery capacities. This can be seen in Fig. 5(b). Furthermore, the Charging Allocation Algorithm can be seen in operation in Fig. 5(a), where a total of 2 chargers were used at the taxi rank.

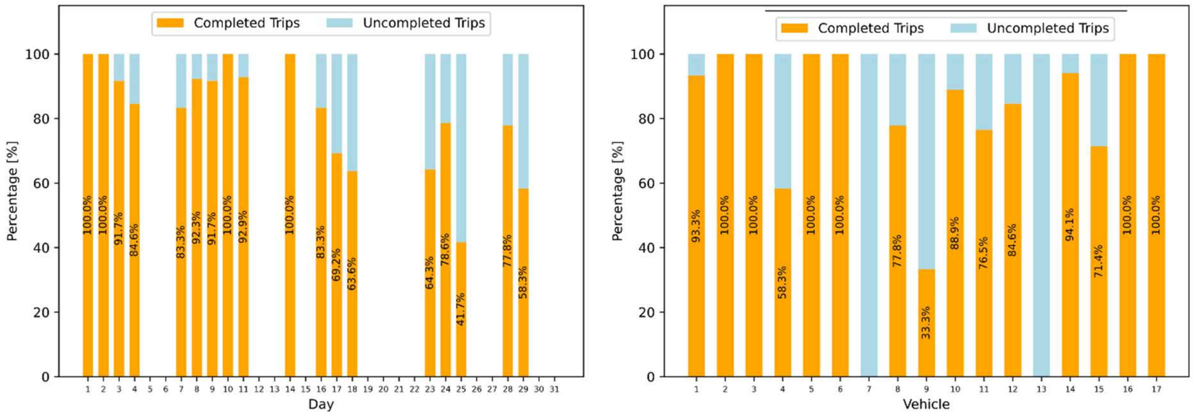
4.1 Trip Completion Rate

Fig. 6 shows the vehicle trip completion rates for the month as well as the trip completion rates for each vehicle. A vehicle is considered to have a successful trip if the SOC remains above 0% for the whole day. Fig. 6(a) answers the question of: "how many vehicles, of those driving on each day, had successful trips?". Furthermore, the weekends were excluded from this figure, as well as days where the vehicles did not drive. Fig. 6(b) answers the question of: "how many days, when the vehicle was driving, were successful trips?".



(a) (b)

Fig. 5. Example Days of Simulation for SOC (a) Good vehicle-day with charger association (b) Bad vehicle-day with energy expenditure



(a) (b)

Fig. 6. Completion Rates: (a) Daily completion rates (b) Vehicle completion rates

As can be seen from Fig. 6, most of the vehicles were able to complete the necessary trips in a day based on the current demand of trips, with a given usable battery capacity of 70 kWh. The battery capacity is based on current on-the-market electric taxis (*Higer H5C EV*, 2020). However, there are certain trips that the vehicle makes which EVs would be unable to match. Further investigation into what specific routes and distances to classify these failed trips is left for future work. It can also be seen in Fig. 5(b) that there are not enough charging opportunities in the day for the vehicle to regain its expended energy, and so bigger batteries may not be the solution. Possible solutions could include increasing charging opportunities by introducing home charging and/or incorporating some petrol or diesel vehicles to the electric fleet.

4.2 Grid Impact

Fig. 7 shows the maximum power for each day for differing number of chargers, where N denotes the number of chargers. As the number of chargers decreases, a limit is reached in the maximum power required from the grid while charging, as can be seen for the case of 4 chargers and lower. It was found that 4 chargers for 17 vehicles was the minimum number of chargers which could be implemented without affecting the trip completion rates of the taxis.

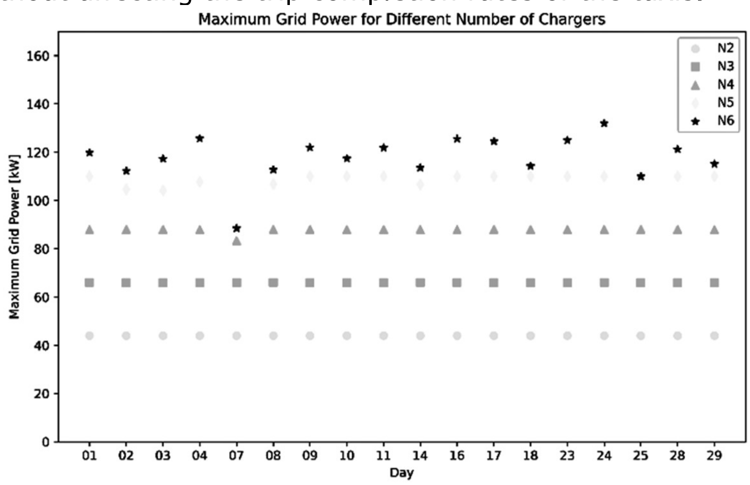


Fig. 7. Maximum Power per Day for Different Number of Chargers

In the case of 6 chargers, the maximum power on the grid is achieved on day 24. As a result, the maximum and minimum power on the grid was taken for the case where the number of chargers being utilised is 6. The minimum and maximum power was determined by finding the average of the power drawn from the grid in an hour over all the days. The maximum and minimum values of these averages would then correspond to the specific day and hour that experienced the minimum and maximum power. These values were then used to build the maximum and minimum power per vehicle that could be drawn from the grid, with the result displayed in Fig. 8. The average power per vehicle is also displayed and given by the blue line.

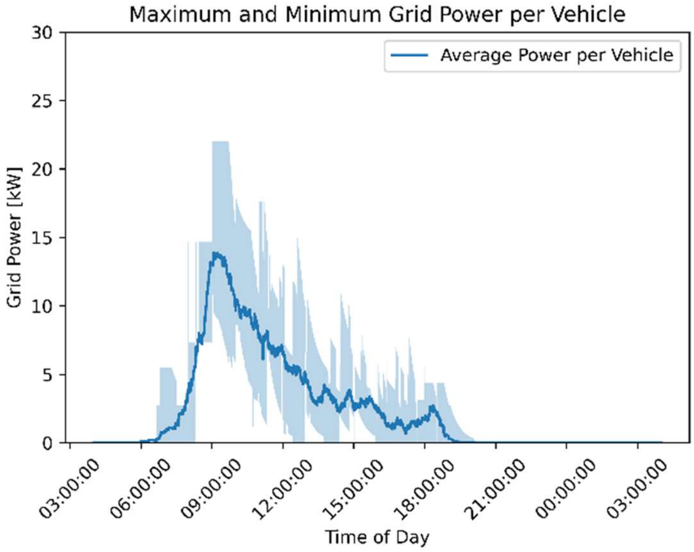


Fig. 8. Maximum and Minimum Power on the Grid for charging at the depot (taxi rank) only

As can be seen in Fig. 8, the peak power for charging occurs between the hours of 08h00 and 12h00 which corresponds to the time after which the minibus taxis have driven the population to their work. Furthermore, given a certain number of operational electrical taxis, the grid power required for charging will fall somewhere between a multiple of the shaded region, and never exceed a maximum of 22 kW per vehicle.

5. Conclusion

A novel tool was developed to simulate the driving and charging of electric minibus taxis within Stellenbosch. This tool was incorporated with an existing and already developed model known as EV-Fleet-Sim. A simplified battery model was also added to the simulation to better simulate charging.

The simulation was run to determine the impact that these electric vehicles would have on the grid, and the ability of the vehicles to complete their trips. It was found that the electric taxis would be able to meet the demand given a 70 kWh usable battery capacity. However, this was not for all the cases and a further investigation is required to determine what these conditions are.

Furthermore, the impact on the grid was determined with the highest peak being experienced with 6 chargers being implemented. This resulted in a maximum power of 22 kW drawn from the grid per vehicle. It was also found that one can implement a minimum number of chargers without affecting the trip completion rate of the taxis. This was found to be 4 chargers for 17 taxis. Future work is left to investigating home charging, changing variable values to find optimal solutions and classifying successful trip completion vehicles.

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Stakeholder Management and Engagement in Sustainability Reports

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Abstract

The issue of corporate sustainability is increasingly becoming important in society as companies develop their strategies aimed at sustainable development and meeting stakeholder requirements. The classic sustainability of TBL, Economic, Environmental and Social) can be represented in company sustainability reports. Regulations and Standards such as AA1000SES (Stakeholder Engagement Standard) and GRI (Global Reporting Initiative) consecutively provide guidelines for stakeholder engagement and elaboration of sustainability reports. The main objective of this analysis is to: assess the extent of stakeholder involvement in company reporting and highlight the central role of stakeholders as catalysts for sustainability. A literature review was carried out to obtain information on sustainability reporting practices, such as reporting standards. Next, sustainability reports from companies from different sectors of the market were selected and analyzed using ATLAS.ti. The analysis highlighted the importance of stakeholders in preparing the report and different forms of inclusion and engagement of stakeholders in preparing SR (sustainability reports). As a result, different forms used to engage stakeholders were identified. It was also seen that the stakeholder management approach differs within the same and different business sectors.

Keywords: Sustainability Report, GRI Standards, Stakeholders, AA1000SES, Materiality.

1. Introduction

Sustainability is a term increasingly used in society, since the concern about how to take care of the environment, and seeking its preservation is progressively increasing. Sustainability focused on the industrial area works on the economic, social, and environmental aspects. The three perspectives are also called the pillars of sustainability (Elkington, 2001).

In the corporate world, sustainable development is analyzed based on the company's progress in three major pillars: economic, social, and environmental. Therefore, all of the corporation's actions must be aimed at being more efficient. "A sustainable company is one that generates profit for shareholders while protecting the environment and improving the quality of life of the people with whom it interacts." (Savitz, 2007).

The stakeholders favor the institutions that practice sustainability, not only with measures but with results presented in reports. Therefore, stakeholders have interaction and interest in finding out the evolution of corporate sustainability in the company. In 1984, Freeman defined that a company can consider its Stakeholders to be any individual or group that influences or generates impact about the objectives and goals of an organization (Fremman, 1984, Stakeholder Management: Framework and Philosophy, quoted by Jadoon et al., 2020). As mentioned by Paula and Gil-Lafuente (2018), stakeholder engagement plays a crucial role in corporate sustainability.

Analyzing several reports collected, Dallabona understood that Companies that include stakeholders in composing the sustainability report have more complete reporting content, including meeting the GRI principles. The quality of the report and the inclusion of stakeholders are fundamental to creating a sustainability report (Dallabona et al, 2023).

The purpose of this paper is to analyze the interaction between stakeholders and the sustainable performance of organizations through Sustainability Reports (SR), aiming to show evidence of how stakeholders influence sustainable aspects and, consequently, the performance measurement and reporting of corporate sustainability. For the organization and analysis of the data, a qualitative approach through content analysis was used. Specifically, the ATLAS. ti software operationalized documents, reports, regulations, standards, and guidelines such as AA1000, IIRC, SASB, and GRI. Of these frameworks mentioned, this study will focus on sustainability reports that use the GRI as a basis. And also in the way of managing stakeholders suggested by AA1000SES. In other words, within the reports, it will be observed how companies are including stakeholders to report their sustainability practices. With these documents, it was possible to verify how stakeholders influence the sustainable reporting of companies, ensuring the quality of the information in the reports. It is hoped that this paper will facilitate the inclusion of stakeholders and analysis of sustainability reports in a faster, more inclusive, and effective way.

2. Research Design

The objective of this project is to monitor and verify the interaction between stakeholders by analyzing the sustainability reports of companies based on their desires for the company. With this study, it is expected to highlight the importance of stakeholders as drivers in sustainable practices in the corporate world.

A literature review was conducted to verify the available materials on the subject and to have a deeper and more detailed view of it. The literature review aims to study a specific subject through analysis, evaluation, and investigation of the subject. "It is a type of research focused on a well-defined issue, which aims to identify, select, evaluate and synthesize the relevant evidence available" (Galvão, 2014). After that, a content analysis was conducted to understand the meaning of the materials found, among them the reports, standards, and procedures. Content analysis allows an understanding of the essence of the research, pointing out patterns, and extracting results according to selected variables (Saldana, 2015; Bardin 2016).

3. Context

Sustainability indicators have been gaining great relevance in recent years, being a differential for many companies to get more investors and increase their power. According to Tinoco and Kraemer (2011), the disclosure of the results of the reports is of great importance to pass information to the external environment, making the public synthesize the actions that the organization has been doing.

The GRI rules were also studied because they define what sustainability reports need to have in environmental, social, and economic aspects called Triple Bottom Line. According to (Gasparino & Ribeiro, 2007) sustainability is only achieved with the alignment of these three pillars.

For the development of the research, it was also made the reading of the file: "AA1000 Accountability Principles" where it is explained the synthesis of the importance of sustainability in the company. The AA1000 was chosen because it shows how the management of stakeholder interaction and inclusion can be done in a company.

AA1000 Accountability was created to facilitate and guide the implementation of sustainability in the corporation based on principles. Based on this guideline, the company must analyze which processes are important to it, identify stakeholders' desires with regard to sustainability, develop strategies and goals to develop sustainability, and, finally, disclose through reports the information of the progress within the company. "AccountAbility is a global sustainability standards and consulting firm that works with companies, governments, and multilateral organizations to promote responsible business practices and improve long-term performance" (Accountability, 2018).

In addition, within AA1000, there are three other standards: AA1000APS for the accountability part, AA1000AS for ensuring standards within sustainability implementations, and AA1000SES, created in 2005 by over twenty companies in order to ensure that all stakeholders in the organization's sustainability development have their vision implemented in the practices on the agenda.

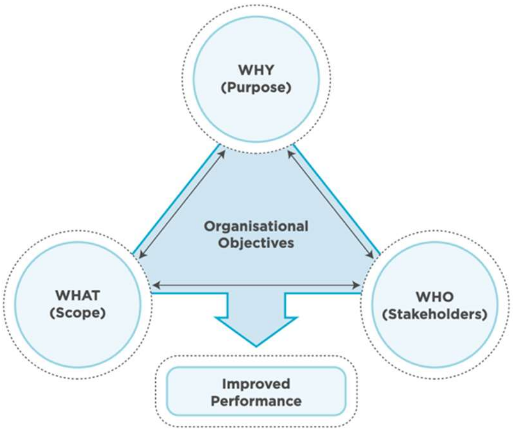

Fig. 1. AA1000 Stakeholder Engagement Standard (AA1000SES), 2015. Source AA1000SES.

According to AA1000SES (2015), the company must establish criteria to map and identify each stakeholder, these criteria are divided into:

Responsibility: Analyze which customer groups the company has responsibilities, whether financial (employees), legal (local government), or even in contracts (suppliers) or regulations (federal government); Influence: Which stakeholder groups have more power in the company's decisions; Proximity: The groups that the company has more daily contact with, such as employees, suppliers and customers; Dependence: Separation between parties that are more independent or dependent on the development of the organization; Representation: The social parties involved with the company, such as NGOs, local community, trade unions; Strategic interests: which groups the company has the strategy to have a closer and more trustful relationship with, such as consumers and suppliers.

With the AA1000SES standard, the principles and commitment to stakeholders are guaranteed, and the company shows the responsibility that the organization should have on sustainability decisions. The GRI, through its indicators and principles, requires the inclusion of stakeholders in the preparation of the SR. In this way, the principles set out in AA1000SES can be synchronized directly and indirectly with sustainability reports that use the GRI Standards.

4. Results

From the synthesis of what is corporate sustainability, the sustainability reports were analyzed by ATLAS.ti, a qualitative research software, where codes or general topics that should be found in the reports were selected. Nineteen sustainability reports from different companies were analyzed, seeking to diversify the market niches. The sectors of activity and the list of companies can be consulted in Appendix A.

After carrying out the initial coding process in ATLAS.ti, that is, reading the reports in advance and understanding the context of the material, some codes were defined. The codes used in ATLAS.ti to analyze the reports were: Stakeholder Management; and Inclusion of Stakeholders in the companies; - Types of stakeholders identified in the reports. These codes show the significance of the theme and are intended to answer the research objective through the coding and analysis stage.

To understand the structure, in vivo coding was initially carried out. In all, twenty-one "stakeholder management" codes, nine "inclusion of stakeholders in companies" codes, and eighteen "stakeholder types" codes were identified. With these forty-eight codes, we analyzed what they had in common: which stakeholders were highlighted more often, which words were written more often in each code, how each company deals with its stakeholders, and whether there is actually a sustainability development in each organization. From the data of the sustainability reports placed in ATLAS. ti, it was noticed that the stakeholders of all the companies are similar, having a pattern.

The stakeholders' contribution to the report was well worked out within the files; it can be analyzed that they contributed to the implementation of the facts in the reports, describing what the company has really been investing and developing in sustainability. The implementation of the stakeholders' view in the report was via the materiality process, where they were asked their opinion about the company's actions and whether they were positively affected by these developments.

In the environmental aspects, the subgroups shown were related to water treatment, waste, sewage, production impacts on the environment, emissions, recycling, and other issues related to the environment and its care, as there are SDGs (Sustainable Development Goals) made by the UN which establishes goals to be met by all countries by 2030, Some of these goals are directly related to the environment, so there is a need for development at this point that is very much demanded by the government, society, and stakeholders upon companies to develop in the environmental requirements since a sustainable company has a very strong point within the market in which it is inserted.

Each organization has a different stakeholder management, this management is linked to the mission, values, and vision of the company along with its strategy because each company has its goal in its business niche. Despite the diversity of the companies studied, the stakeholders remain virtually the same in all organizations and the management is taking actions so that they continue to have an interest in the company, generating value for it.

With the words most found in these codes it can be said that suppliers have the highest management, in addition, all stakeholders are concerned about the reputation of the company, so it is made a management for them. With this management, it is seen the direction that needs to be taken for the stakeholders, which services will be offered to them, and the importance of the company's performance. There is a code related to which stakeholders the company has, again suppliers have more weight in the surveys, along with customers because they determine the reputation that the company passes to society.

4.1 Application

The main results obtained in the analysis of the sustainability reports of the companies in Appendix A will be presented.

Apple conducts multiple global round tables on environmental topics with key stakeholders, as seen in Figure 2, aiming to not only understand issues and regulations for each region but also share information and understand where to enhance transparency (Apple, 2022)

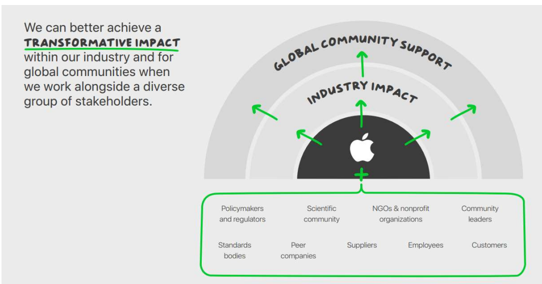

Fig. 2. Apple's stakeholders. Source: Apple, 2022

Amazon stakeholders that were consulted in order to determine material topics for their reporting are internal decision-makers, employees, partner organizations, nongovernmental organizations, and academics, aiming to capture inputs and perspectives, inspired by reporting frameworks such as the GRI. They were also included in multistakeholder initiatives regarding supply chain and human rights. The Apex's standard procedures and guidelines were used to conduct this work. (Amazon, 2022). The Coca-Cola company interviewed more than 30 stakeholders, internal and external, and ran a global survey that had 90 global responses, to align the priority topics and business-relevant issues. The stakeholders consulted were investors and financial institutions, NGOs, bottling partners, trade and industry associations, business peers, customers, and suppliers (The Coca-Cola Company, 2022).

Petrobras selects stakeholders to be engaged through prioritization, analyzing relevance, impact, and existing relationships. Their classification can be seen in Figure 3.

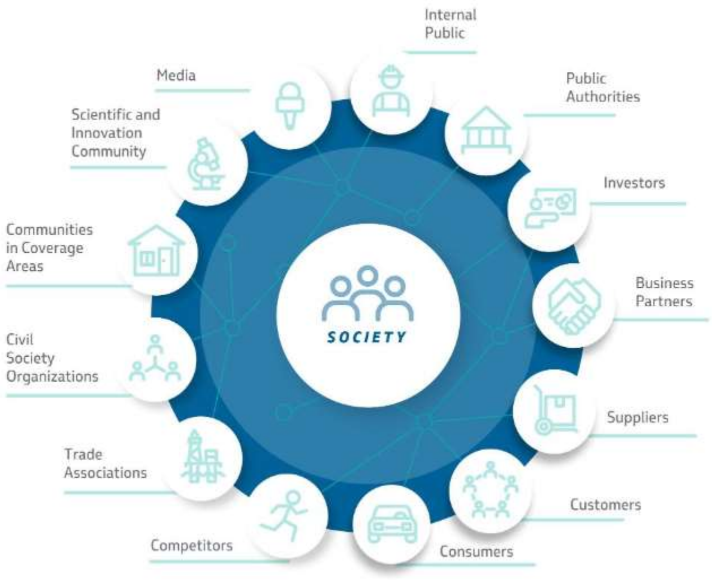

Fig. 3. Petrobras' stakeholder classification. Source: Petrobras, 2022

The ones that analyzed material topics and helped define their significance through interviews, documents, and a survey were customers, consumers/society, suppliers, communities in the coverage area, investors, media, public authorities, and the internal public. The GRI Standards are used as guidelines for the report (Petrobras, 2022).

Mercedes-Benz Group assessed the importance of topics through a desk analysis and an international online survey involving stakeholders such as employees, private and business customers, interested consumers, suppliers and business partners, investors, politicians and government officials, scientists, and representatives of government administrations and non-governmental organizations (NGOs). They also conducted 20 additional interviews with internal and external experts from stakeholder groups. The GRI Standards are used as guidelines for the report (Mercedes-Benz Group, 2022). Nestlé worked with a third party to identify the material topics, conducting desk research and interviews with 55 stakeholders, internal and external, and the process was overseen by the ESG and sustainability council. The stakeholders included suppliers, investors, customers, non-governmental organizations, business associations, executive board members, functional heads, and market heads. The GRI Standards are used as guidelines for the report, as well as the Sustainability Accounting Standards Board (SASB) Standard for the Processed Foods sector and World Economic Forum Stakeholder Capitalism metrics (Nestlé, 2022).

Electrolux has systematic contact with major stakeholder groups, and besides including them in the materiality analysis, they also maintain specific engagement plans with each kind of stakeholder. Consumers are involved in surveys to understand perceptions on sustainability, customers and investors are engaged constantly to share learnings and discuss sustainability, employees go through surveys and confidential interviews, and suppliers work along during responsible sourcing and quality auditing so the company can understand the most important topics to them. The GRI Standards are used as guidelines for the report (Electrolux, 2022). Fujifilm doesn't go deep into the stakeholder's participation in materiality analysis, mentioning only that there was attention to stakeholders' demands in relation to business areas that are linked or likely to be linked to the group. Regarding communication, the group ensures that information disclosure is appropriate, and the business activities are aligned with stakeholders' demands. The group can be seen in Figure 4. The GRI Standards are used as guidelines for the report, as well as SASB and ISO 26000 (Fujifilm, 2022).

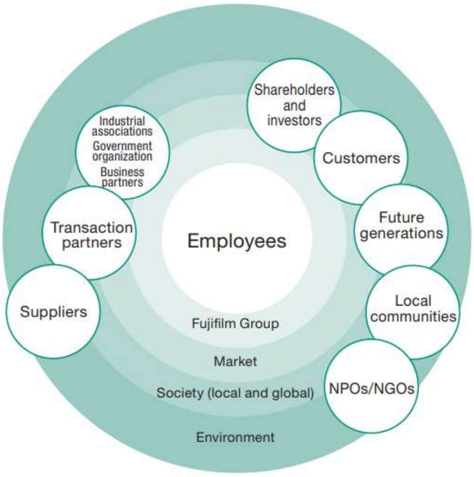

Fig. 4. Fujifilm stakeholders. Source: Fujifilm, 2022.

H&M scores and prioritizes topics to understand their importance to stakeholders (internal and external) based on how often they raise them, and their level of economic, environmental, and social impact. The stakeholders include customers, colleagues, supply chain workers and representatives, communities, business partners, experts, innovators, challengers, investors, and policymakers. The GRI Standards are used as guidelines for the report, as well as UNGP Reporting frameworks (H&M Group, 2022).

General Motors undertook a four-step process aligned with the GRI materiality principle, to understand stakeholders' perspectives did a survey with employees, interviewed both internal and external stakeholders, and maintained a regular engagement, through Ceres, a nonprofit organization whose aim is to transform the economy and build a sustainable future (General Motors, 2022) The DataFlex company has several stakeholders, including customers, employees, and suppliers, and take a comprehensive approach to include these stakeholders in their sustainability reporting and management process.

This is done through two major publication forms: the annual publication of a Sustainability Report and the open communication "Sustainability Stories" on its website, used to share relevant information about its sustainability initiatives and to keep stakeholders informed about the company's actions. In addition, they also manage their stakeholders through employee engagement programs, the promotion of community volunteering, and the introduction of social audits at its key supplier facilities. Furthermore, in 2022 the company became a B Corp, in other words, they gained the BIA certification (used to measure and evaluate a company's social and environmental performance, governance, and overall impact on society).

VP Capital (2022) states in its progress report that its main stakeholders are their shareholders, employees, companies in which it invests, and other family offices. The company is fully aligned with ESG practices, has B Corp Certification, and adopted its bylaws to consider, as a requirement, the interests of all stakeholders, and not just shareholders, when making decisions. In terms of Materiality, the group states that it takes into account two perspectives, financial materiality and impact materiality. They also ensure transparency and communication with their stakeholders by publishing annual progress reports, participating in different types of social networks, and participating in discussion panels and round tables. On this last subject, they stated in their report that by being transparent and sharing their knowledge, they are receiving "more investment consultations for impact companies and are more frequently in contact with parties working on sustainability".

Forbo (2022) mentions that their Stakeholder groups include Employees, Customers, Suppliers, Policy Makers, Environmental NGOs, Unions, communities, and Industry and Trade Associations. To keep these groups informed, and engaged and manage their materiality, the company has some approaches, such as regular meetings, surveys and audits, customer feedback mechanisms and satisfaction surveys, representation on committees, and other regular contact regarding environmental and safety compliance, open days at their production plants, involvement with charities, local sponsorship activities, and other regular contacts.

The company also mentions a materiality assessment that considers the three pillars of environmental, social, and governance (ESG) classification, involving its stakeholders. Furthermore, the company states that it not only evaluates financial materiality but also materiality related to impact, how its actions affect different areas and factors, and how those can impact the company´s operations. Forbo also uses a matrix as a tool for assessing the importance of different aspects of sustainability, especially aspects linked to ESG practices, in the view of its stakeholders, as follows:

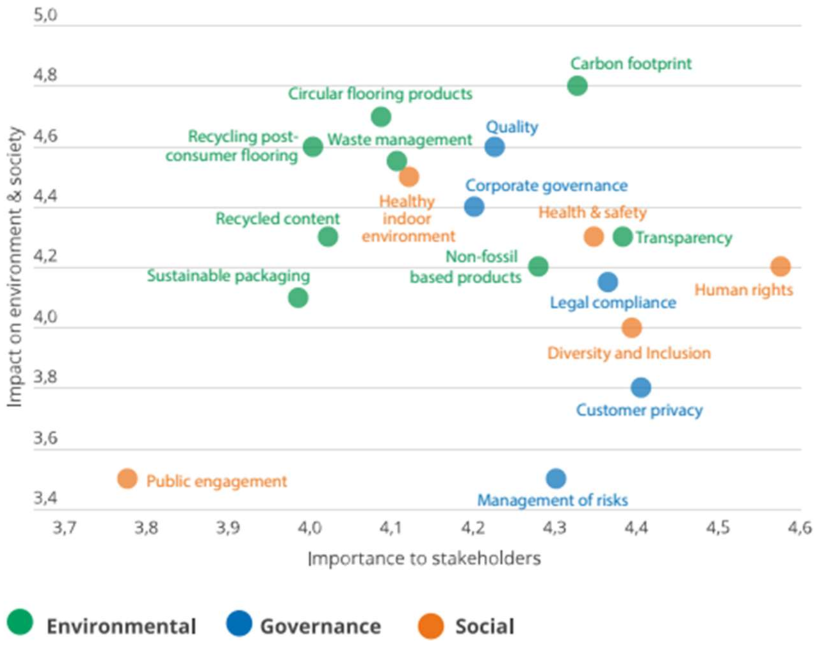

Fig 5: Materiality Matrix- Forbo. Source: Forbo, 2022

HP (2022) identifies and engages a wide range of stakeholders, such as employees, investors, suppliers, customers, peer companies, public policymakers, industry bodies, NGOs, and sector experts; based on criteria such as expertise, willingness to collaborate reputation, location, sphere of influence, and ability to scale and accelerate progress.
To be transparent and communicate with them, they use several communication channels, such as executive leadership updates, posts on their website, articles in online magazines, social media

posts, corporate statements, and participation in public events. The company carries out materiality assessments related to ESG aspects to identify the most relevant sustainability topics for its business and also values strategic partnerships to determine the content of its sustainability reports, considering feedback from external stakeholders, for example. In 2021 the enterprise involved multiple stakeholders to create a materiality matrix, for further analysis on important topics.

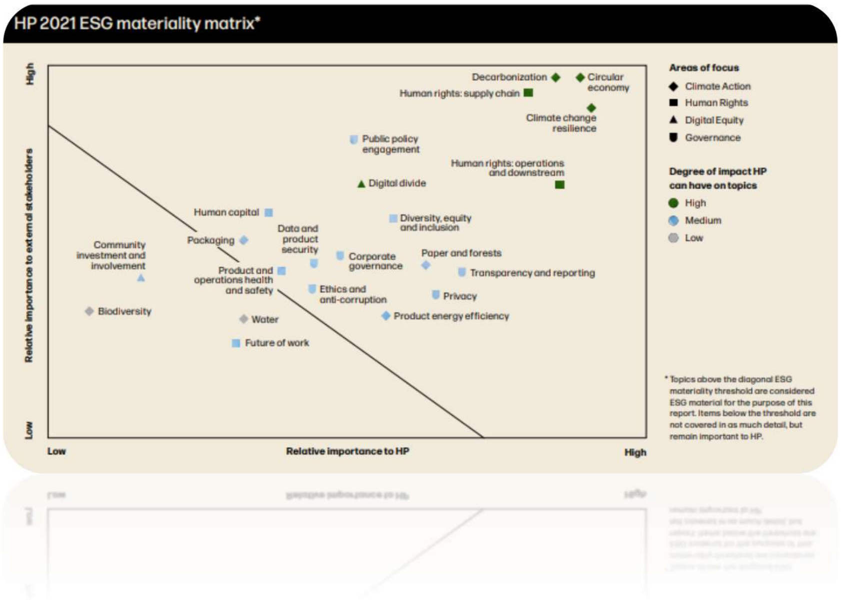

Fig 6: 2021 HP´s Materiality Matrix. Source: HP, 2022

Microsoft states that its stakeholder groups encompass employees, customers, partners, shareholders, suppliers, and communities. Considering the importance of transparency and communication, the company publishes its Environmental Sustainability report annually to provide information about its strategy, performance, progress against goals, and key challenges. The company also strives to disclose its environmental data, such as greenhouse gas emissions and offers a consolidated view of its corporate social responsibility initiatives through the "Reports Hub" on its website. For their reports, they follow international environmental reporting standards, such as the Greenhouse Gas Protocol (GHG Protocol) and the Global Reporting Standards of the Global Reporting Initiative (GRI). In terms of materiality, Microsoft directly interconnects with ESG aspects (2022)

In the section of its report "How SHV Energy creates value", the company SHV mentions its stakeholder groups, as well as its communication channels with each group. Among them can be listed: Employees (Meetings, Newsletters, Polls and questionnaires, Speak Up, Sustainability, Reports, Councils, Yammer (social networking platform), Videos), Customers (Conference calls, Newsletters, Social media, and campaigns, Calls, and meetings), Suppliers (Audits, Contracts, Direct correspondence, Supplier Code of Conduct), Regulators/government authorities (Collaboration initiatives, Conferences, Direct correspondence, Meetings, Calls), Local communities (Meetings, Social media and campaigns), NGOs (Collaboration initiatives, Conferences), SHV Holdings family (Meetings). As previously seen in other companies mentioned in this dissertation, SHV also uses a materiality matrix to define important topics, for the company. To gather information to define the company's materiality, SHV carried out some actions such as media and benchmark analysis, and also the creation of an online survey with different stakeholder groups. Figure 7 shows the process.

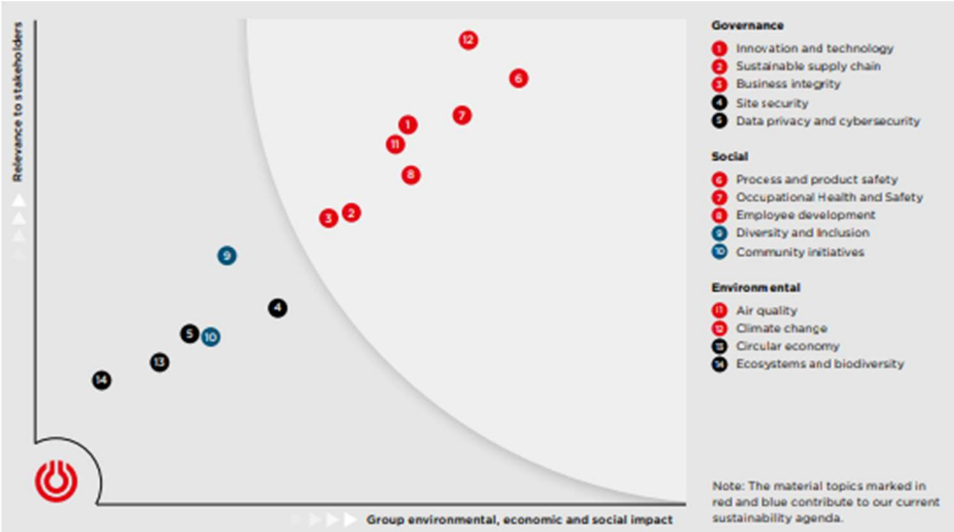

Fig 7: 2020 SHV´s Materiality Matrix. Source: SHV, 2022

The Telecom company Vodafone's (2022) main stakeholders are the following groups: employees, customers, partners, suppliers, and the government. For the company, material topics are those that, according to its stakeholders, have the most significant impact on society, considering both the community and people as well as the environment. For gathering answers regarding materiality, Vodafone carried out a range of activities, including surveys, one-on-one interviews, employee satisfaction surveys, review of reporting guidelines, reputation surveys, business risk analyses, trend analysis, and market developments, among others. These material topics identified from this process form the basis of their Integrated Annual Report.

A.S.R's stakeholders are employees, customers, advisors, civil society organizations; government, tax authorities and regulators, trade unions, media, investors, suppliers, academics, peers, and business partners. The definition of materiality for the company is divided between social material topics and environmental material topics, and originates from consultation with its main stakeholders, in addition to the existing definitions of materiality in respected reporting models such as the Global Reporting Initiative (GRI) and Integrated Reporting Council (IIRC). Heineken engages with a diverse group of stakeholders, such as NGOs, academic experts, customers, investors, government representatives, and industry peers. The company conducts a materiality assessment process to identify and prioritize its most material issues. To this end, Heineken believes it is extremely important to consider some points: I: have a significant current or potential impact on their business or vice versa; II: be of significant interest to its stakeholders; and III -be an issue over which they have a reasonable degree of control where it comes to their impacts. In other words, they comply with the GRI standard when preparing the report. Again, another company uses a materiality matrix, based on most material sustainability issues based on their impact on our business and interest to stakeholders. In addition, the company also uses ESG guidelines when it comes to defining material issues: a) Get insights; b) engage with stakeholders; c) analyze and define; and d) validate. In other words, like a continuous PDCA cycle.

5. Conclusion

Corporate sustainability has been strongly developed by companies in recent years, which is a very positive point for society as a whole since the interest of companies in investing in sustainability is related to the stakeholders' desire to make society more concerned about environmental, social, and economic issues. It was possible to verify the development of sustainability in companies, because, through the codes, it was seen how the stakeholders are working within companies, what their real participation is in the design of reports, and, above all, who the stakeholders are. With the reading of the reports and the help of the software, it was possible to identify the common actions of the companies, and what they have been developing in terms of sustainability according to the GRI. Given that all fifteen reports had met all the requirements of the GRI, it can be said that the companies are developing.

The sustainability reports analyzed belong to different companies, from the most varied sectors. However, even with technological and management differences, it is possible to understand and highlight that there is a certain standard that has been followed by most companies. Materiality has been placed together with the interests of stakeholders, and not just taking into account what the company considers important. It is also noteworthy that, unlike what was happening in the past, material topics are no longer focused solely on gains and financial performance. The double, or multiple, materiality was mentioned several times in the analysis of the reports and shows how companies understand that different approaches to materiality such as performance, satisfaction, society, governance, and environment, among others; can result, even indirectly, in positive financial results for organizations. Also interesting are the materiality matrices, cited several times. As companies increasingly tend to plot them, in order to better analyze their material issues. In the case of companies from different segments, clearly, the material issues important for one will not be the same for the other, however, it is possible to observe that the modus operandi for setting up such matrices is very similar, and in many cases practically the same. Another point that became clear is how, both for stakeholder management and for material topics, the guidelines found in ESG practices and GRI reports have become increasingly common. This analysis concludes that stakeholders influence reporting through the prioritization of material topics, and as mentioned by Stocker (2021), companies have been selecting a wide range of stakeholders, both internal and external, making sure that all topics have been covered.

This work understood how stakeholders are inserted in sustainability reports, having a strategic role in the preparation, through the standard, and also serving as a source of consultation. That is, besides contributing information, the stakeholders are managed according to each company. The organizations showed different ways of managing their stakeholders and, more than that, they have different actors in each company.

Appendix A

NAME	INDUSTRY	REPORT YEAR
Amazon	E-commerce	2022
Apple	Technology	2022
ASR Nederland N.V.	Financials	2022
Coca-cola	Beverage	2022
DataFlex	Business Services	2022
Electrolux	Home appliances	2022
Forbo Flooring	Flooring	2022
Fujifilm	Image and communication	2022
General Motors	Automotive	2022
H&M Group	Textile	2022
Heineken	Food and Beverage	2022
HP	ICT	2022

Mercedes-Benz Group	Automotive	2022
Microsoft	ICT	2022
Nestlé	Food and Beverage	2022
Petrobras	Oil and Gas	2022
SHV Energy	Energy	2022
VodafoneZiggo	Telecom	2022
VP Capital	Financials	2022

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The Contribution of Industry 4.0 Technologies to the Sustainability of Civil Construction: A Literature Review

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Abstract

This article aims to analyze Industry 4.0 (I4.0) technologies, which can be used in civil construction to reduce the negative impact on the environment and society. For this, the scientific literature review method was used, through a search in the Scopus, Google Scholar and Scielo databases, using the keywords "Environment" or "Sustainability" and "Construction 4.0" or "Industry 4.0 technologies in construction". As a result, it was found that some technologies are important to reduce the aggression to the environment, such as the 3D printer that allows reducing the disposal of waste, BIM, which can reduce design errors that would result in rework and waste disposal, and the drones performing dangerous activities, in this case allowing greater safety for the worker.

Keywords: Sustainability; Construction; Technologies of Industry 4.0.

1. INTRODUCTION

With the arrival of the Fourth Industrial Revolution, better known as Industry 4.0 (I4.0), which holds several technologies, some such as Artificial Intelligence, Robotics, Internet of Things, Cloud Computing (CARVALHO et al., 2022). With Civil Construction it was no different, with the increase and adaptation of I4.0 technologies to this sector, new execution methods and more qualifications of labor will emerge. (LEKAN; CLINTON; OWOLABI, 2021).

Seeking to offer an alternative to align sustainable development goals with digital transformation, I4.0 is an option that is being inserted in manufacturing. "Smart factories" are considered highly efficient in the use of resources, quickly adapting to demand and economic scenarios, and can be implemented in Civil Construction (SIMÃO et al., 2019). I4.0 can support flexibility, efficiency and production through technologies that need further study and understanding of their connection to environmental sustainability challenges. In this way, contributions aimed at economic, ecological and social conquests are expected. (SOARES; GOHR, 2021)

This article aims to carry out a survey and a literature review on the contributions of Industry 4.0 enabling technologies used in Civil Construction, and the impacts on sustainability.

2. THEORETICAL FRAMEWORK

2.1 The Technologies of Industry 4.0

Civil construction has increasingly mirrored industry 4.0, adapting the use of technologies to its business model. (CAVALCANTI *et al.*, 2018). Such technologies are, as explained in Figure 1:

Fig.1 - Industry 4.0 enabling technologies

Source: (NETO, 2022)

Industry 4.0 can be described as a complex system, which includes many interactive agents that exhibit organized, non-ordinary behavior (CARVALHO *et al.*, 2022). It is a characterized system, which due to its technological advances is capable of uniform production and high performance. (CUENOT; QUENEDEY, 2016).

Artificial intelligence is a technology that, through combinations of algorithms and computing data, can intelligently learn and imitate human intelligence, making it possible to complete actions and decision-making. (CARVALHO *et al.*, 2022)

The Internet of Things (IoT) is a concept that takes into account the prevalence of a lot of technological equipment, being able to make digital connections of equipment, with transfer of technologies and information. Big Data and Cloud Computing are concepts in the pillar of Industry 4.0, Big Data can be a solution for storage and solutions for big data information, since Cloud Computing allows data to be shared by all devices of the project and with that can provide more agility in the civil construction process and offer better decision-making.

3. SUSTAINABILITY

It is believed that Industry 4.0 can produce positive results for better sustainability in the production process. In this interaction, several points can be examined, for example process safety, efficiency in resource consumption, and the development of more flexible and intelligent processes that deal with impacts at the level of sustainability. (KAYIKEI, 2018)

When civil construction uses the resources offered by industry 4.0, it helps to minimize environmental impacts, such as: better use and use of resources such as the water system, electrical system and waste disposal system (ROQUE; PIERRE, 2019). The water system can become more sustainable if decisions are taken during the construction project. For example, the use of a draining ecological floor and its layers of filters, which can receive rainwater, filter it and, through drains, take this water to a reservoir allows to reuse it for other purposes, saving drinking water for a more noble use.

Energy efficiency is another example that helps to minimize environmental impacts through the installation of solar panels for the production and storage of electrical energy.

And finally, the waste disposal system, in the constructive system, which uses recyclable waste, with the correct disposal certificate through tracking technology, indicating the disposal site and its recycling, would make the system less aggressive to the environment environment. According to Lara; Kempter; Penteado (2021, p.41) " Thus, the transition to a circular economy (CE) is seen as an alternative to reduce environmental impacts and contribute to economic growth, constituting a new system that promotes the valuation of materials throughout the life cycle and minimizes waste "

The examples above point out that the tendency of Civil Construction towards sustainability begins in its planning and design, where one should already think about sustainable means.

4. METHOD

The article presents a literature review on the technologies of Industry 4.0, Sustainability and the Applications of Technologies to Civil Construction, the article seeks to identify Sustainability with the increments of Technologies that address the relationship between the themes, Technologies of Industry 4.0 applied to Construction Sustainable Civil.

According to Koller; Couto; Hohendorff (2014, p.39), the best way to prepare a literature review is to research academic scientific articles already published, select articles related to the defined line of research, read the articles, and with that elaborate in a clear and succinct way the understandings obtained.

For the construction of this article, a search was made for scientific articles, books and periodicals, in the databases of Scopus, Google Scholar and Scielo, search made using the keywords "Environment" or " Sustainability " and "Construction 4.0" or " Industry 4.0 technologies in construction", with the presented results of 4,525 works, were refined through the selection of publications of articles from the years 2013 to 2023, and works of free access, with direction to the area of the subject, with this it was reached the result of 542 scientific articles, and with a reading of the abstracts of the selected articles, it was possible to extract only the articles that adhered to the objective of the research, which were read in full, and the critical analysis led to the narrative review presented in the results and discussions.

The results outline the final portfolio, and arguments related to this proposal for a literature review that are presented in this article.

5. RESULTS AND DISCUSSIONS

Human resources and natural resources, with the implementation of Industry 4.0 Technologies in civil construction, taking into account the major impacts, it should be noted the advantages of productivity, quality, efficiency without waste, the use of certified products and inputs, ecologically correct, thus achieving an improvement in sustainability (NETO, 2022).

According to Reis (2021), with the arrival of Industry 4.0, it was possible to automate production intelligently, being able to unite the real environment with the artificial one and with the proper use of Industry 4.0 technologies, it is possible to sustainably reduce consumption of energy, for Gregori et al. (2017) it is noticeable that industries that allow technologically and socially sustainable production methods improve social working conditions. As for NETO (2022, p. 36) "The adoption of Industry 4.0 components would have a great impact on the entire civil construction chain. In addition to the advantages generated by the increase in productivity, efficiency, quality and collaboration, the adoption of these components can increase safety and sustainability, improving the performance of the sector".

For Carvalho et al (2022, p. 8) "Industry 4.0 aims to increase the flexibility of the evolution of production processes in a more sustainable context". In addition to being integrated with sustainability and the environment, it is essential that all this technology can serve all classes of civil construction. The demand to deploy and implement must be a complex and costly process that can impact entrepreneurs in obtaining a tangible price for the majority of the population.

As for Ribeiro (2019, p. 50) "The monitoring and inspection of the work, previously done in person, is now done through devices attached to the drone and allows access to places of difficult access such as dams, bridges, buildings, towers, churches, among others. This methodology was applied in the pre-project phase of the site survey".

Therefore, among the advantages of deploying and implementing Industry 4.0 technologies in companies in the civil construction sector, it aims at changing to be less aggressive towards sustainability, reducing failures in the design phase of projects, in construction production, offering more quality, speed of execution and less waste of inputs, generating less disposal waste. The main contribution of this article is to analyze the benefits generated in the interoperability process in the management of technologies, and to obtain greater sustainability in civil construction.

Unmanned equipment for observation and manipulation of difficult-to-access places, being a useful tool for Civil Construction, for example: in a 30-meter-high building that has cracks on the outside on the top floor, instead of carrying out inspection in a traditional way that uses rappelling strategies involving the safety of the professional, you can use a Drone that is an Unmanned Aerial Vehicle (UAV), it is safer and offers greater agility for inspection, thus making response faster decisions (NERY, PIMENTA, BRAGA, 2021).

3D printers have the function of making solid objects quickly, through additive manufacturing with smaller particles, and with the elimination of customized production tools, the 3D printer has a cost reduction, avoids unnecessary waste collaborating with Environmental Sustainability , has greater production time agility, since the traditional construction process demands a lot of time, and production failures may occur during the construction process. Taking into account that the 3D Printer technology can be used, with the Civil Construction waste inputs, properly mixed with the appropriate aggregates, and thus avoiding the incorrect disposal of waste, obtaining an improvement in sustainable production. (PAIM, ALMEIDA, 2018)

The Autonomous or Robotized machines, through close commands interconnected to cables, or even through remote commands through data exchange between Cloud Computing, are used to perform human activities, where you can obtain the total security of the professional operator, achieve a faster production with more quality, avoiding waste with errors, or excess of materials. (ARAÚJO *et al.*, 2013).

Large buildings are increasingly using technology, due to the huge volume of data they can use in their cycle, Cloud Computing supports Big Data which in turn stores large volumes of data, with Computing in the Cloud, it is possible to remotely access the data of the civil construction project from any device that connects to the internet, in addition to offering greater security to the project information, it can make the process more agile and reduce the chances of error during execution of construction. (SIMÃO *et al.*, 2019).

The use of augmented reality BIM (*Building Information Modeling)* collaborates with the development of the project by the Architects, making it possible to mix physical and virtual environments, with the use of appropriate software, and associated Artificial Intelligence applications. The main attraction of using this technology is having the ability to project reality, without being in the physical environment of the building, making it safer, and providing convenience and comfort to the user, with this technology it is possible to have efficiency, speed in production and high agility in finding divergences and correcting them quickly (GABRIEL; AMARAL; CAMPOS, 2018).

Table 1 - Some of the Industry 4.0 technologies that can be implemented in Civil Construction

Technology	Utility in construction
Drone (NERY, PEPPER, BRAGA, 2021)	Known and called UAVs, (unmanned aerial vehicles). In civil construction, it can assist in collecting aerial images, helping with inspections in works, deliveries of inputs, it is an economical technology and can offer more security during the project process.
3D printers (PAIM, ALMEIDA, 2018)	In civil construction, it is a machine that can produce projects, three-dimensional models quickly with quality and without waste.

Autonomous or Robotized Machines (ARAÚJO *et al.*, 2013)	Autonomous machines and robots can be operated autonomously, without the need for a person inside the machine. Autonomous machines and robots can produce with previously programmed commands, without the need for manual guidance.
Cloud computing (NETO, 2022)	In civil construction, cloud computing helps to access any information, consult projects in real time, obtain the solution remotely from any device connected to the internet .
Augmented Reality (GABRIEL; AMARAL; CAMPOS, 2018)	Augmented reality technology can be coupled to the BIM concept and help a lot in the project, they propose a better view of what will be built, and even virtual tours of what is being built.
Artificial intelligence (GABRIEL; AMARAL; CAMPOS, 2018)	The artificial intelligence that mimics human intelligence, allows that through stored data, make decisions using patterns and algorithms, in civil construction artificial intelligence can help various phases of a construction process, from planning, as well as maintenance and project management.

6. FINAL CONSIDERATIONS

The fourth industrial revolution has become a reality. This concept is implemented in the production methods. When considering the benefits, global efforts are underway to implement these innovations through national action programs. Main technologies currently on the market, and under development: drones. 3D printing, autonomous machines, BIM concept and etc.

According to Ribeiro (2019), the BIM platform is a technology with great potential, widely accepted in the market and already being implemented. Drones offer labor savings, digitization and information gathering, mobility for inspections and field studies and are available at comparatively affordable prices. They can be applied from the field survey phase to post-work. It is noticed that technologies based on the fourth industrial revolution are constantly developing and adapting to needs.

For Barducco and Constâncio (2019) “the adoption of technologies to automate constructions, using augmented reality to design structures and visualize them before the start of execution, 3D printing to, among other functionalities, create models and shapes, facilitating and standardizing the execution stage and the use of software in general, which are increasingly complete, compiling in just one file all the information necessary for all those involved in the execution of the work”.

To improve aspects of sustainability, many companies in the civil construction segment have been using several sustainable alternatives in their projects, such as the construction of intelligent buildings that can control water and energy resources, avoiding unnecessary waste, implementing automation technologies that control air conditioning machines controlling the building's internal temperature and humidity, automation to identify natural sunlight and control the building's internal luminosity, dimming light fixtures and saving electricity, installing solar panels to capture and store electricity that can be used for self-efficiency and thus reducing environmental and economic impacts. Civil construction companies come in time in search of achieving sustainable certificates through the intelligent and technological means of the projects to be built, from the beginning to the delivery of the property. (JUNIOR, ROMANEL, 2013)

Thus, the aim of this article was to review the literature of edited studies on the contribution of Industry 4.0 technologies to Civil Construction and its integration with sustainability. After application of the search method and literature review. The in-depth analysis examined the triple perspective of sustainability, economic, social and environmental. Aiming that in the midst of commercial and financial competition, companies in the civil construction segment must adapt to technologies in order to offer more quality in delivery, reducing execution times and reducing disposable waste, avoiding impacts on the environment, and offering means and sustainable products, in the current scenario, the company that is not advanced in technologies, suitable to offer smart and technological properties and that are sustainable, will have less chances of participating and winning bids, even being placed outside the competitive market.

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The Evaluation of Centrifuged Water Treatment Plant Sludge Without Thermal Treatment as an Adsorbent for The Removal of Nutrients and Other Physicochemical Elements from Wastewater

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Abstract
Universalizing clean water supply is pivotal for SDG 6 – Clean Water and Sanitation, as it supports human health and activities. To provide potable water, treatment plants treat surface water, producing waste called WTP sludge (WTPS), containing organic and inorganic substances. Improper disposal can lead to environmental issues like heavy metal concentration increases and nutrient runoffs. Nevertheless, studies have explored beneficial WTPS uses, such as soil improvement, coagulant recovery, and turbidity removal, among others. Typically, these applications involve thermal treatment, which is costly. This research evaluated using centrifuged WTPS, without thermal treatment, to adsorb nutrients and physicochemical elements from wastewater. Such insights can promote sustainable WTS management, fostering a circular economy and reducing waste impact. The adsorbent was analyzed using equipment like SEM, TGA, and FTIR, assessing factors like pH, humidity, and organic matter. The wastewater was characterized by attributes like total coliforms, turbidity, and Chemical Oxygen Demand (COD). The study found WTPS had pH 7.0, conductivity of 465.5 μS cm-1, high moisture content, and organic matter content of 18.73%. Notably, the WTS contained silicon oxide and aluminium oxide, confirmed by the XRF technique, which detected other elements like Al, Si, and Fe in oxide forms. FTIR spectrum analysis of WTS identified various chemical bonds, with interpretations relying on prior studies. TGA analysis showed a significant mass loss due to non-structural water and the burning of organic matter. In terms of performance, the highest adsorption capacities for phosphorus and COD occurred with 10g mass and 120 minutes of contact. pH was insignificant for these adsorptions. Maximum nitrogen adsorption happened at pH 4. For total coliforms and *Escherichia coli*, maximum removals (97% and 96%) occurred with a mass of 20g and 200 minutes of contact. In conclusion, centrifuged WTS's potential as an adsorbent highlights the sustainable waste management possibility, offering alternatives to minimize environmental impact and supporting the fulfilment of SDG 6.

Keywords: Water treatment plant sludge; Adsorption; Effluent

1. Introduction

There is an escalating global focus on ensuring a sustainable and healthy environment. Central to this discourse is the topic of basic sanitation. In Brazil, this is not merely a matter of public welfare, but a fundamental right enshrined in legislation. It encompasses facets such as the provision of potable water, sewage management, rainwater drainage, and urban solid waste management (Brasil, 2007).

According to the National Sanitation Information System (SNIS) report, Brazil has successfully extended potable water services to an 93.4% of its urban population (SNIS, 2021). To attain the potability standards mandated within the country, water, predominantly sourced from surface reservoirs, undergoes rigorous treatment in Water Treatment Plants (WTP) (Brasil, 2021). A consequential outcome of this treatment regimen is the generation of a distinctive solid waste named Water Treatment Plant Sludge (WTPS). This waste is primarily a by-product of the decantation and filtration processes inherent to conventional water treatments (Wagner et al., 2019). It is the tangible manifestation of coagulation and flocculation stages (Nair and Ahammed, 2015), and potentially from desanders or equipment used to remove sand and silt particles from incoming water if integrated within the plant infrastructure.

The composition of WTPS is a matrix of organic and inorganic constituents. These originate from the raw water sources and compounds employed during treatment (Ahmad et al., 2016). Without appropriate processing, the indiscriminate discharge of this by-product can instigate multiple environmental repercussions. These encompass increased concentrations of metals and suspended particulates, heightened turbidity, alterations in the chemical composition, and disruptions in the natural nutrient cycling processes (Molina, 2010). However, it is pivotal to recognize that while WTPS can pose challenges, there are also viable avenues for its constructive utilization. These potential uses are intrinsically aligned with the Sustainable Development Goals (SDGs) tenets. Beneficially deploying WTPS not only resonates with SDG 6, advocating for sustainable water and sanitation access but also harmonizes with SDG 12 and SDG 13, which emphasize sustainable consumption patterns and climate action, respectively (UN, 2015). Furthermore, repurposing WTPS for terrestrial ecosystem restoration correlates with SDG 15, while fostering collaborative partnerships for these ventures underscores the essence of SDG 17.

Several promising avenues for the utilization of WTPS have been identified. These include coagulant recovery (Mora-León et al., 2022), its application as an adsorbent for endocrine disruptors (Martins et al., 2022), organic material mitigation in surface water bodies (Zhou et al., 2018), and its potential use as a coagulant in effluent post-treatment processes (Nair and Ahamed, 2015).

Considering the importance of effluent post-treatment, a phase aimed at eliminating residual contaminants to ensure legislative compliance (Brazil, 2011), the present study endeavors to discern the adsorption efficacy of centrifuged WTS sludge. By examining its capacity to remove nutrients and other physicochemical elements from post-treatment effluents, this investigation seeks to elucidate the feasibility of employing WTPS as an adsorption medium. The findings aspire to inform sustainable WTPS management strategies, providing alternatives to diminish the environmental footprints of such by-products.

2. Methods

2.1. Sample collection and preparation

A composite sample of WTPS was sourced from a water treatment plant situated in São Paulo state, Brazil. This plant follows a conventional treatment procedure encompassing stages such as coagulation, flocculation, decantation, filtration, disinfection, fluoridation, and pH correction to purify surface water drawn from a reservoir. Aluminum coagulants are employed in the coagulation phase, while a polyacrylamide polymer aids in thickening the WTPS.

For the research, WTPS samples were gathered daily over a 60-day span in the summer of 2022, a period marked by heightened rainfall. After accumulation, these samples were centrifuged within the treatment plant. Following collection, the WTPS samples underwent a homogenization process and were air-dried under ambient conditions for a fortnight. The dried samples were then crushed, passed through a sieve with a 600 mm aperture, and subsequently subjected to a physical-chemical analysis.

The wastewater sample acquisition adhered to the guidelines set forth in NBR 9896 (ABNT, 2018). Preparatory procedures for the effluent complied with the stipulations of EPA Standard 600/4-79-020 (EPA, 1983).

2.2. Physical-Chemical and Geoenvironmental characterization of the samples

Morphological and spectroscopic investigations of Water Treatment Plant Sludge (WTPS) were meticulously carried out. The morphological nuances were captured using scanning electron microscopy (SEM) on a Quanta 250 (FEI) model. Enhanced with EDS EDAX, this equipment offered magnifications at levels of 50x, 75x, and 100x. Notably, before this rigorous examination, all WTPS samples underwent a metallization stage. For spectroscopic characterization, Fourier Transform Infrared Spectroscopy (FTIR) was employed, specifically through an IRPrestige-21 Shimadzu spectrophotometer, to delineate the functional groups inherent in the WTPS sample structure.

On the elemental front, X-ray spectrometry played a pivotal role. The elemental composition within the sludge sample was both identified and quantified using the MiniPal 4 model from PANalytical, which is fitted with a Rhodium (Rh) anode X-ray tube.

Diving into thermal analysis, the Thermogravimetric Analysis (TGA) stood out. With the assistance of TGA/DSC/MS equipment from TA Instruments, evaluations of the WTPS sample spanned a temperature spectrum from 25 °C to 1400 °C. This was executed in an open porcelain crucible, in the embrace of an N2 atmosphere, ensuring a consistent flow of 100 mL min-1 and an oven heating rate of 10 °C min-1. Central to TGA is its ability to monitor fluctuations in mass, either gain or loss, in relation to varying temperatures.

Complementing this, the Derivative Thermogravimetry (DTG) method, which represents the derivative of mass changes concerning time (dm/dt) set against temperature, was utilized. Furthermore, Differential Scanning Calorimetry (DSC) came into play, effectively measuring the enthalpy alterations in the sample when juxtaposed with an inert reference. This technique also assessed heat capacity and notable phase changes, such as melting and crystallization, alongside calorimetric reactions, as described by Mothé & Azevedo (2009).

To round off the comprehensive analysis, the WTPS was subjected to additional evaluations, focusing on diverse geotechnical and physicochemical parameters, all of which are meticulously tabulated in Table 1.

Table 1. Parameters analyzed for wastewater and WTPS samples.

WTPS		**Wastewater**	
Parameters	**Methods**	**Parameters**	**Methods**
Conductivity	Soil Analysis Method - Embrapa	Total coliforms	SMWW, Method 9221 B
Liquidity limit	NBR 6459	Conductivity	POPFQ-UNI212, Method 2510 B
Plasticity limit	NBR 7180	Color	POPFQ-UNI214, Method 2120 B
Density	NBR 6508	Chemical Oxygen Demand (COD) *	NBR10357
Organic matter	NBR 13600	*Escherichia coli*	SMWW, Method 9221 F
pH	Soil Analysis Method - Embrapa	Total phosphorus *	HACH, Method 10072
Moisture Content	NBR 6457	Total nitrogen *	HACH, Method 10127
		Turbidity	POPFQ -UNI211, Method 2130 B

(*) Were used for both tests.

2.3. Factorial design

Factorial experiments, specifically 2^3 and 2^2, were systematically designed using MATLAB software, as detailed in Tables 2 and 3. This experimental design approach allows for a comprehensive assessment of the interactions among independent variables and their singular impacts, thereby facilitating the optimization of the process. In essence, factorial designs provide a comprehensive, efficient, and rigorous method for experimental studies, ensuring that the potential relationships between factors are neither overlooked nor underestimated.

Table 2. Variables in factorial design 2^3 (Test I)

Variable	Low level (-1)	High level (+1)	Results
pH	4	7	Adsorption capacity (*q*) COD; Total Phosphorus (P) and Total Nitrogen (N)
Mass (g)	10	50	
Contact time (min)	15	120	

Table 3. Variables in factorial design 2^2 with center points (Test II)

Variable	Low level (-1)	High level (+1)	Center Point (0)	Results	
Mass (g)	50	100	75	Adsorption capacity (*q*): COD; Total Phosphorus (P) and Total Nitrogen (N)	Removal efficiency (%): Conductivity; Turbidity; Color; Total coliforms and *Escherichia coli*
Contact time (min)	40	200	120		

Two experiments were conducted, denoted as Test I and Test II. In Test I, the variables under investigation included: WTPS mass (measured in g L^{-1}), effluent pH, and contact time (expressed in minutes). This experiment followed a 2^3 factorial matrix and served as a preliminary study, primarily focused on concentration analysis. Conversely, Test II employed a 2^2 factorial matrix, examining the WTPS mass (in g L^{-1}) and contact time (in minutes), with a consistent pH level of 4 maintained throughout the experiment. The chosen values for these variables were determined through an extensive literature review.

2.4. Analysis of the adsorbent dosage

The adsorptive potential of WTPS was assessed based on its efficacy in removing Phosphorus, Nitrogen, and COD from the effluent. To quantify this, the adsorption value *q* was determined for each observed result, employing Equation (1).

$$q = \frac{(C_0 - C_1).k}{m} \quad (1)$$

In the given formula, *q* represents the adsorption capacity, expressed in milliliters of effluent per gram of adsorbent. The term C_0 denotes the initial concentration of the responses (P, N, and Chemical Oxygen Demand – COD), measured in mg L^{-1}, while C_1 is the concentration after interaction with the sludge, also quantified in mg L^{-1}. Additionally, *v* signifies the volume of the solution, in liters, utilized in the adsorption experiment, and *m* stands for the mass of the adsorbent, measured in grams.

2.5. Statistical Analysis

Statistical evaluations were executed with Jamovi software (version 2.3.21). The *t*-test was employed to compare the studied parameters. Data normality was assessed using the Shapiro-Wilk test, and a significance level of $p<0.05$ was deemed noteworthy.

3. Results

3.1. Physical-Chemical and Geoenvironmental Characterization of WTPS

The surface and morphology features of the WTPS sample particles, verified by SEM, are shown in Figure 1.

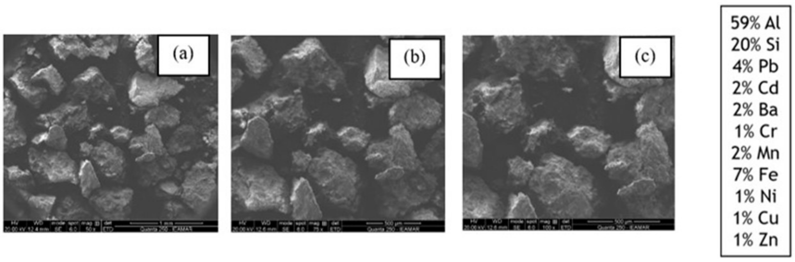

Fig. 1. SEM images of sludge particles with magnification of (a) 50x; (b)75x and (c) 100x.

The WTPS presents irregular morphological particle structures, composed mainly of silicon oxide and aluminum oxide. This characteristic has been substantiated through chemical microanalysis using EDS performed on the particles. The analysis demonstrated significant concentrations of Al, Si, and Fe, alongside minor traces of Pb, Cd, Ba, Cr, Mn, Ni, Cu, and Zn. These findings are consistent with the identifications made by Nguyen et al. (2023) and Ahmad et al. (2016).

The functional groups of the adsorbent materials are shown in Figure 2, which shows the transmittance spectra obtained in the infrared region through Fourier Transform Infrared Spectroscopy (FTIR).

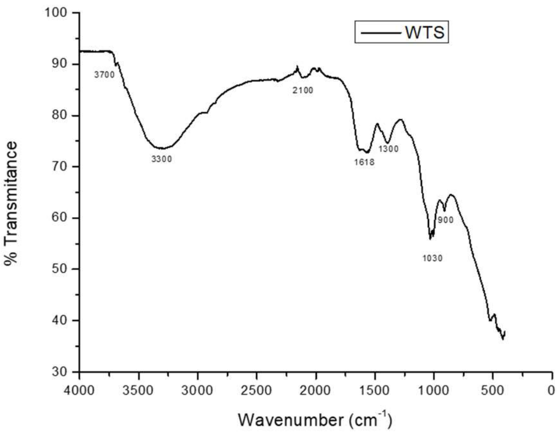

Fig. 2. FTIR Spectra of WTPS.

When examining the peaks identified in the WTS FTIR spectrum, we noticed a pattern of distinct absorptions. The peak at 1030 cm^{-1}, typical of C-O bond vibrations This suggests the potential existence of functional groups like alcohols, ethers or ketones in the sludge and the peak at 1300 cm^{-1}, which is characteristic of C-N bond vibrations as observed by Nadiyanto et al., 2019. The peak at 1618 cm^{-1} indicates absorptions associated with C=C bonds in aromatic rings. Peak at 2100 cm^{-1}, suggests vibrations of C≡N bonds. This absorption can indicate the presence of nitriles or cyanide groups, whose origins can vary between chemicals used in water treatment and industrial waste. Absorption at 3300 cm^{-1} is related to O-H bonds, suggesting the possible presence of hydroxyl groups (Siswoyo et al., 2019). Finally, the peak at 3700 cm^{-1} points to vibrations of N-H bonds, indicating the potential existence of amines or similar groups in the sample.

Table 4 presents the elements that were present in higher concentrations in the sludge sample, using the X-ray fluorescence spectrometry technique.

Table 4. Analysis by X-ray spectrometry in the sludge.

Elements	100% m/m	Oxides	100% m/m
Al	36.414	Al_2O_3	43.984
Si	19.980	SiO_2	24.261
P	0.949	P_2O_5	1.171
S	4.599	SO_3	6.074
Cl	1.767	K_2O	0.643
K	1.035	CaO	0.931
Ca	1.309	TiO2	0.923
Ti	1.115	MnO	0.795
Mn	1.321	Fe_2O_3	19.551
Fe	30.057	CuO	0.730
Cu	1.453	Cl	0.936

The elements with the highest percentages in the composition of WTPS are: Al, Fe and Si. In studies by Lucena et al. (2016), Santos et al. (2018) and Costa & Souza (2019), the chemical composition followed the same behavior for the oxides, following the same order of oxide composition as in the present study, with Al_2O_3 being the most present, followed by SiO_2 and Fe_2O_3.

Figure 3 shows the thermogravimetric analysis curves for the evaluated WTPS sample.

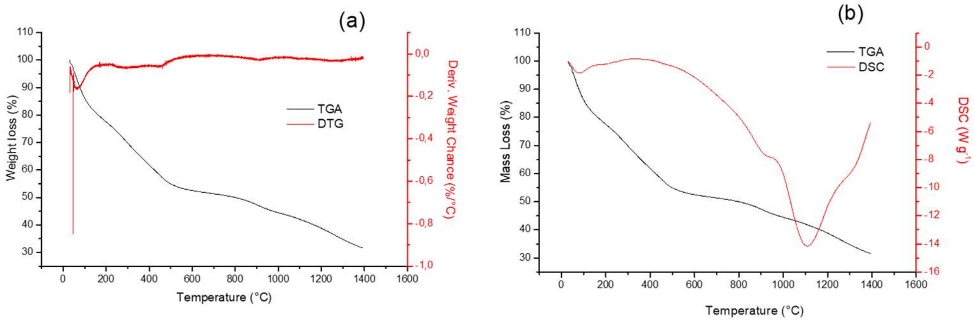

Fig. 3. TGA/DTG (a) and TGA/DSC (b) thermograms of WTPS

The TG profile shows an initial mass loss (T < 100 ◦C) of around 30%, due to non-structural water (moisture). Then, between 200 and 600°C, mass loss occurs due to the burning of organic matter and hydroxyls (structural water). What agrees with what was observed by Mouratib et al. (2020), in which the aluminum sludge had its weight constantly decreased with increasing temperature. According to the authors, an increase in temperature up to 250◦C causes the loss of free and adsorbed water from the residue, whereas the oxidation of organic matter occurs in the range of 250 to 350 ◦C.

3.2. Geoenvironmental Characterization

The WTPS sample had a pH of 7.0, suggesting neutrality, as observed by Santos et al (2018). The conductivity of 465.5 μS cm^{-1} indicates a low concentration of dissolved ions, which is a positive aspect for application or disposal considerations, as there is no excessive presence of soluble salts.

The high moisture content (82.88%) (Mora-Léon et al., 2022) has direct implications for the transportation and handling of WTPS, as does the specific mass value of 2.14 g cm^{3-1} (Lucena et al., 2016), indicating a relatively high density. The organic matter content of 18.73% points to a substantial amount of organic carbon present in WTPS.

The exceptionally high values of liquidity limit (505%) and plasticity limit (412%) reveal extreme plasticity. This means that the material can retain large amounts of water, like clay materials (Costa and Souza, 2019) and acquire cohesive characteristics when wet.

3.3. Adsorption and removal of parameters

Table 5. shows the factorial designs matrix 2^3 (Test I) and its responses obtained from the interactions between the variables (contact time, mass and pH), considering the adsorption capacity (q), revealing important information about the influence of the variables in the processes studied.

Table 5. Factorial designs matrix 2^3 (Test I)

Experiments	Mass (g)	pH	Contact time (min)	Results Adsorption Capacity (*q*)		
				COD	P	N
1	10 (-1)	4 (-1)	15(-1)	1.04	0.04	-0.04
2	50 (1)	4 (-1)	15(-1)	0.36	0.03	0.05
3	10 (-1)	7 (1)	15(-1)	0.76	0.04	0.06
4	50 (1)	7 (1)	15(-1)	0.29	0.04	-0.05
5	10 (-1)	4 (-1)	120 (1)	1.28	0.17	0.18
6	50 (1)	4 (-1)	120 (1)	0.34	0.07	0.11
7	10 (-1)	7 (1)	120 (1)	1.84	0.06	0.00
8	50 (1)	7 (1)	120 (1)	0.37	0.08	0.01

In the case of COD, in Test I, the condition that obtained the best response was in experiment 7 where the most significant variables were low mass and high contact time. In the case of P and N the best condition was experienced in experiment 5, in which for N, the variables pH and contact time, as well as the interaction between these two variables, were shown to be happening where low pH and high contact time were the conditions that most influenced the process. For P, the condition of greater mass and longer contact time were more efficient, helping to improve these responses; these variations were studied once more in Test II (Table 6).

Table 6. Factorial designs matrix 2^2 with center points (Test II)

Experiments	Mass (g)	Contact time (min)	Results Adsorption Capacity (*q*)		
			COD	P	N
1	50 (-1)	40 (-1)	1.1	0.2	0.1
2	100 (1)	40 (-1)	0.5	0.1	0.1
3	50 (-1)	200 (-1)	0.8	0.1	0.2
4	100 (1)	200 (-1)	0.3	0.1	0.1
5	75 (0)*	120 (0)*	0.5	0.1	0.1
6	75 (0)*	120 (0)*	0.5	0.1	0.1
7	75 (0)*	120 (0)*	0.6	0.1	0.1

*central points

In Test II, a lower mass was observed, but the contact time did not seem to have a significant impact. This may indicate that, below a certain mass threshold, contact time may not be a crucial variable for this process.

Similar results on P adsorption were obtained in the studies by Maqbool et al. (2016) and Nguyen et al. (2022) not with regard to the pH variable. It is noteworthy that, in the cited studies, the WTS was thermally treated.

In the case of COD, it was confirmed by test II that the significant variables were low mass and high contact time. However, it is important to emphasize that the contact time did not reach 120 minutes, where the results show the importance of low mass and low contact time for the COD process. This may indicate that, for this process, it is crucial to keep the mass at low levels and limit the contact time.

For N, in Test II, the results indicated that lower mass and shorter contact time were more important for the process. The study by Qiu et al. (2015) demonstrated that a longer contact time and a lower mass increased the adsorption capacity proportionally to the initial nitrogen concentration. It is noteworthy that in this study the sludge was activated by KOH.

For the other parameters in Test II, the percentage removal values were taken into account, as shown in Figure 4:

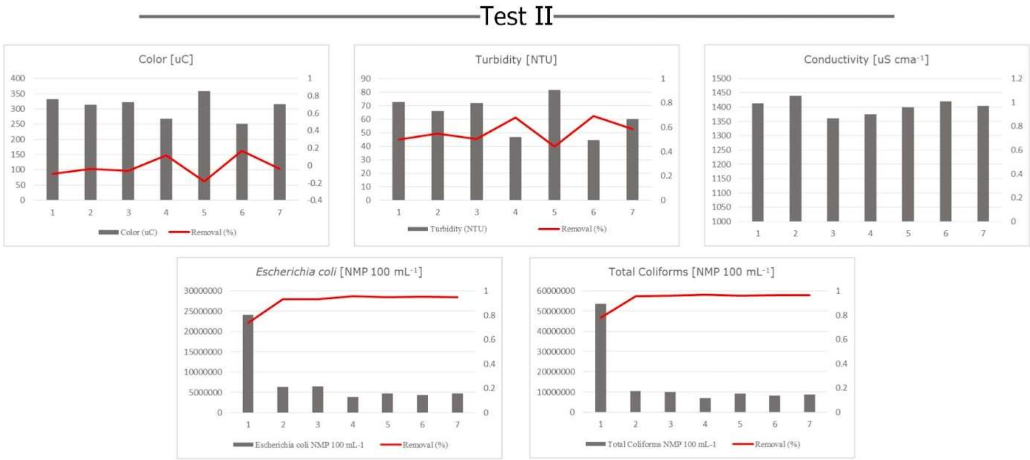

Fig.4. Removal efficiency of test II.

For Test II, only conductivity showed no significant difference between the data (p>0.05). Analyzing the parameters, it was observed that, for color, the best results were for experiments 4 and 6 (17% and 12%, respectively); analyzing turbidity, it was observed that the highest removal efficiencies occurred for experiments 4 and 6 (68% and 69%), with initial concentration and pH conditions similar to the study by Zainol et al. (2022), and results consistent with those found in the study by Mora-Léon et al., 2022. In the case of conductivity, there was an average of 1391.2 (us cm-1), close to that found by Mora-Léon, et al. (2022) indicating higher values for samples 2 and 6, and lower values for experiments 3 and 4; as for the removal of Escherichia coli, the best result was 96% for experiment 4, coinciding with the removal of total coliforms, which showed higher removal percentages of 97% for experiments 4 and 6, compatible with the results detected by Nair and Ahmed (2015).

4. Conclusions

The study underscores the efficacy of centrifuged WTPS in adsorbing nutrients and various physicochemical constituents from wastewater. The outcomes demonstrate its potential as a cost-effective and pragmatic solution. By repurposing this by-product from the water purification process, we contribute significantly to its sustainable management and align with the Sustainable Development Goals (SDGs), especially SDG 6.

The financial implications of this approach are considerable. The Water Treatment Plant (WTP) witnesses marked savings, largely stemming from diminished sludge dewatering and disposal costs. This financial relief can be redirected to bolster other pivotal infrastructure and maintenance sectors. It's imperative to highlight that most related studies utilize the centrifuged

LETA drying technique. This research accentuates the imperative nature of innovative and inventive strategies in crafting sustainable responses to intricate environmental dilemmas.

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The Role of Lean in Sustainability Transitions in Healthcare: An Index and Conceptual Framing

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Abstract

Socio-technical transitions in healthcare systems are increasingly being evaluated to understand how such systems may be (re)designed to increase their sustainability, and thus increasingly contribute towards realising the sustainable development goals. Given the global sustainability challenge in healthcare systems, it is deemed necessary to develop methods and approaches to support and facilitate the transition process to more sustainable system states. Lean thinking and sustainability are interconnected regarding their objectives and aims in system processes. Therefore, incorporating lean thinking into sustainability transitions may strengthen the value creation of system processes by efficiently allocating and consuming resources while ensuring waste elimination during system processes. This research showcase how lean thinking may support the progression of sustainability transitions in healthcare systems. Literature shows that lean implementation is a significant driver for increased sustainability. Thus, implementing lean thinking into sustainability transitions holds potential to strengthen a sustainability transition. The aim of the research is achieved by developing the lean thinking for sustainability transitions in healthcare index and framework, that outlines which lean thinking approaches or principles could be used to address specific aspects of sustainability transitions in relation to healthcare systems.

Keywords: lean thinking, sustainability transitions, healthcare

1. Introduction

Long-term sustainability is a contemporary topic, and most organisations are challenges by the need to be (increasingly) sustainable. Similarly, the healthcare sector is increasingly challenged to move away from the status quo towards increased sustainability. Furthermore, the healthcare industry is progressively required to deliver high-quality, full-access, affordable, and sustainable healthcare services (Word Economic Forum, 2013). Sustainability, however, is a concept that is relatively less prominent in the healthcare industry compared to other industries, but its popularity has proliferated in the past two decades (Altpeter, et al., 2014). The health systems that are currently operating are fundamental to achieving a high level of social health and welfare. High levels of social health and welfare in health systems are also critical factors required for development and economic growth. However, significant challenges in terms of economic-, social, and environmental challenges remain evident in healthcare systems across the world. Furthermore, from a theoretical perspective, there is a knowledge gap in the combined focus areas of this research, i.e., healthcare, sustainability transitions, and lean or lean thinking (Cromhout & De Kock, 2021)

The problem that this research thus aims to address can be considered from two perspectives. The practical perspective considers that there are multiple challenges in the healthcare industry, including unsustainability, which can be addressed using multiple solutions. Preliminary research indicates a need to identify and understand how sustainability transitions in healthcare can be supported (Broerse & Grin, 2017). There is thus a need to develop practical approaches and frameworks to support sustainability transitions in healthcare. From a theoretical perspective, research has proven that lean thinking and sustainability align in terms of objectives and achieving the primary goal of processes (Khodeir & Othman, 2016), however there is a knowledge gap regarding the implementation of lean thinking to support sustainability transitions in healthcare. The aim of the research presented in this article is thus to develop a conceptual framework that supports and facilitates the understanding of how lean thinking may contribute towards sustainability transitions in healthcare.

2. Background

2.1 Lean

The Lean methodology is an approach to systematically eliminating waste within a process or production system (Dondofema et al., 2017). Lean is a concept that can be explained in several ways (De Souza, 2009; Pettersen, 2009). Lean is an approach that focuses on improvement; by aligning specific actions that create value in the best possible sequence, lean actions can be performed effectively without interruptions (Costa et al., 2015). Lean tools' effectiveness depends on their ability to develop and sustain a culture that supports continuous improvement (Holweg & Pil, 2001). Most lean assessment methodologies set specific goals for the level of use of lean tools. However, this method is flawed because lean implementation is an ongoing continuous improvement process (De Treville & Antonakis, 2006). Womack, Jones, and Roos (1990) stated that improvements need to be sustained to become current states. The new (increasingly sustainable) current state, therefore, becomes the baseline for further improvements to reach a higher level of performance. The implication is that lean implementation creates a "never-ending cycle of improvement". Lean is a frequently used methodology in the manufacturing industry, but also highly applicable in the healthcare industry (D'Andreamatteo et al., 2015). According to Womack et al. (2007), lean implementation provides opportunities to create a positive and fulfilling working environment. The increased level of employee involvement, ownership of problem-solving and improvements, diversified work functions requiring various skills and abilities, and increased cross-functional and inter-organisational functions can positively impact the work environment.

2.2 Sustainability transitions

The European Environment Agency (2018) identified five perspectives in the approach of systemic transition towards sustainability. These perspectives include socio-economic, socio-ecological, action-oriented perspectives, integrated assessment models, and socio-technical approaches. Socio-technical transitions are strongly correlated to concepts about sustainability and sustainable development (Baxter & Sommerville, 2011). It is a large-scale transformation of unsustainable socio-technical systems which involves long-term processes to effect changes to an alternative sustainable socio-technical configuration. These configurations target specific sustainability issues, and in this context, socio-technical transitions are often interchangeably referred to as sustainability transitions (Geels, 2011) . Technology and society are vital components because they determine which socio-technical transition occurs, provide the required resources, and affect the change's dynamic toward sustainability (Baxter & Sommerville, 2011). The critical role of society in socio-technical transitions highlights the importance of considering economic, political, and social factors within the dynamics of socio-technical transitions. Incorporating technology and society in socio-technical transitions increases complexity as it adds stochasticity and variability to the system dynamics. The complexity of such a system is in contrast with a purely technological perspective, which is less complex. It is further argued that solutions to sustainability challenges cannot be achieved through the incremental development of technology. However, it needs to be incorporated in conjunction with all aspects of society (Tran, 2014).

2.3 Healthcare

According to the World Health Organisation (WHO) (2012), health is a "state of complete, physical and social well-being and not merely the absence of disease or infirmity". This definition has created controversy due to the lack of value it adds to healthcare operations and the use of the word "complete". However, this definition has remained timeless and applicable throughout history (Callahan, 1973). On the other hand, healthcare is described as "the prevention, treatment, and management of illness and the preservation of mental and physical well-being through the services offered by the medical and allied health professions" (Medical Dictionary, 2012).

The healthcare industry is under increasing pressure to operate with limited resources available (De la Maisonneuve & Oliveira Martins, 2014). Rising healthcare costs result from the healthcare industry being under constant pressure to impose drastic measures to improve services and general patient safety while simultaneously reducing costs, waiting times, and errors (Costa et al., 2015). Furthermore, healthcare is often not affordable, not accessible, and/or not acceptable quality and thus are we faced with numerous health systems that are deemed unsustainable and in need of a transition. Healthcare professionals and decision-makers recognise that innovative implementation strategies can be used to aid in these challenges to increase the quality, safety, and effectiveness of patient care (Department of Health, 2018).

3. The knowledge gap: Sustainability transitions and lean thinking

Literature regarding the integration of lean thinking and sustainability transitions is limited, and the integration and/or linking of these fields of research has not yet been formalised (Cromhout & De Kock, 2021). However, the interrelatedness of lean thinking and sustainability transition characteristics are evident, and used in this research to identify whether the incorporation of lean into sustainability transitions is supported.

3.1 Lean principles

According to research, there are 12 basic lean principles. These lean principles are illustrated in Table 6 below.

Table 6: The 12 lean thinking principles (Tăucean *et al.*, 2018)

No.	Lean's principle
L1	Reducing/Eliminating activities that do not add value
L2	Reducing uncertainty
L3	Focus on customer requirements
L4	Reduce cycle time
L5	Simplifying the process
L6	Increase production flexibility
L7	Increase process transparency
L8	Controlling the entire process
L9	Improving the process continuously
L10	Gathering information about competitors
L11	Reduction of raw materials
L12	Efficient allocation of human resources

Taiichi Ohno (1988) developed a concept of lean management that consists of aspects such as identifying value, value stream mapping, continuous flow creation, establishing a pull system, and seeking perfection (Mourtzis et al., 2016). These principles focus on simultaneous waste elimination and value creation (Womack et al., 2007). The sequential flow of the principles is described below:

i. Identifying value as viewed from the perspective of the customer (Pampanelli et al., 2014);
ii. According to the previously defined definition of value, identify and conduct value stream mapping (Pampanelli et al., 2014; Mostafa et al., 2013);
iii. Ensure the smooth creation of information, material, and other resources flow while creating value (Seth et al., 2017);
iv. Eliminate overproduction and excess inventory by establishing a pull system where production is dependent on customer demand (Sundar et al., 2014); and
v. Seeking perfection by implementing strategies to ensure a culture of continuous improvement while continuously eliminating non-value-adding activities and other occurrences of waste (Pampanelli et al., 2014; Vlachos, 2015).

3.2 Sustainability principles

The United Nations proposed 12 sustainability principles that address sustainability at an enterprise level. The sustainability principles are illustrated in Table 7.

Table 7: The 12 sustainability principles, the implications, and SDGs of Agenda 2030 (United Nations, 2022)

No.	Sustainability's Principle	Implication	SDG
S1	Reduce resources	Reducing process losses contributes to improving financial results.	9, 12
S2	Time efficiency	Improving the time of the operational processes contributes to increased production capacity and reduced cost.	9, 12
S3	Reduce waiting time	The reduction in waiting time improves the production capacity.	9,12
S4	Monitor fixed cost	Reducing energy consumption improves the financial results and reduces environmental impacts.	12, 17
S5	Stakeholder involvement in strategic decisions	Strategic decisions need to be agreed upon by stakeholders to increase attractiveness and efficiency (involving stakeholders from within).	6, 8, 17
S6	Support community activities	The company must meet the communities' needs, which can contribute to an improved level of competitiveness.	2, 3, 16
S7	Train human resources	Continuous training of human resources improves the company's performance level.	4,5
S8	Corporate Social Responsibility (CSR)	The company's level of involvement in CSR can improve attractiveness and competitiveness.	1,10
S9	Increase recycling capacity	The company must be able to recycle the waste generated to reduce the environmental impact.	14,15

No.	Sustainability's Principle	Implication	SDG
S10	Increase capacity of reuse, remanufacture, and recondition	Process-generated waste must be informed of other processes to reduce the amount of waste generated.	7, 12
S11	Reduce energy consumption	Improving the operational processes of a company reduces energy consumption. Companies are required to increase their capacity to generate energy.	9, 13
S12	Reduce Greenhouse gas emissions	Reducing pollution to the environment.	11, 13

3.3 *Interrelatedness of lean and sustainability transitions*

Lean and sustainability transitions have different methods of reaching their shared goals of "waste elimination" and "value creation", as illustrated in Table 8 below.

Table 8: Waste and value of lean and sustainability transitions

	Lean	Sustainability Transition
Waste	Waste is defined as a non-value-adding activity as perceived by the customer (Campos & Vazquez-Brust, 2016). "Anything other than the minimum amount of equipment, materials, parts, space, and time which are essential to add value to the product" (Russell & Taylor III, 2011). Waste is classified as transport, inventory, movement, waiting, overproduction, overprocessing, and defects (Ohno, 1988). An additional waste identified by western industries during the 1990s is the underutilisation of worker talent and skills (Triagus et al., 2013).	"Waste can be both generated from a resource or an environmental problem" (Sustainable Development Goals, 2011). The wastage of usable (thus valuable) resources It is identified as wasted resources, lifecycles, capabilities, and embedded values (Lacy & Rutqvist, 2015).
Value	Value is viewed as perceived by the customer (Martínez León & Calvo-Amodio, 2017). By identifying customer requirements, the perceived idea of value is determined (Hines et al., 2004).	Waste can be reduced by recycling waste (van Buren et al., 2016; United Nations, 2011) . Producing as little waste as possible. Where waste must be produced, the aim should be that it is as non-hazardous as possible (Sustainable Development Goals, 2011).

As described in Table 8, it is evident that lean and sustainability transitions have common elements and goals which support the interrelatedness between the two concepts. Incorporating lean thinking into sustainability transitions can enhance value creation by efficiently using resources. The efficient use of resources can lead to cost reduction and increased revenue generation. Waste elimination using only the required types and amounts of resources is crucial for the efficient use of resources. Lean principle implementation increases competitiveness and improves production efficiency (Cherrafi et al., 2017; Ruben & Asokan, 2017). According to Cherrafi (2017), sustainable development is essential during any lean approach. It reduces energy consumption and environmental pollution and streamlines material consumption, which covers sustainability principles (Cherrafi et al., 2017). Table 9 illustrates the interaction, similarities, and complementarities between the 12 Sustainability Principles and the 12 Lean Principles (Tăucean et al., 2018; United Nations, 2022).

Table 9: Interaction matrix between lean and sustainability (adapted from Tăucean et al., 2018; United Nations, 2022).

Sustainability's Principle	Lean's Principle												Similarities	Complementarity	SDG
	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12			
S1	x	x		x			x		x		x	x	Reducing resources	Lean responds punctually to different resources.	SDG 9 SDG 12
S2		x	x				x						Time efficiency	Lean streamlines operations; sustainability plans.	SDG 9 SDG 12
S3			x		x								Waiting time	Lean gets the product in a short time; sustainability reduces the time allotted.	SDG 9 SDG 12
S4									x		x		Process costs	Lean gets the product in a short time; sustainability reduces the time allotted.	SDG 12 SDG 17
S5										x		x	Stakeholder interest	Lean evaluates competitors' operations and allocates efficient human resources; sustainability involves stakeholders in decision-making.	SDG 6 SDG 8 SDG 17
S6			x									x	Activities for people	Lean involves employees; sustainability supports the organisation's involvement in society.	SDG 2 SDG 3 SDG 16
S7								x				x	Human resources	Lean pursues resource efficiency; sustainability supports employee training.	SDG 4 SDG 5
S8												x	CSR	Lean sustains organisational efficiency; sustainability activities for society.	SDG 1 SDG 10
S9					x	x			x				Recycling	Lean aims to reduce losses; sustainability aims to increase the recycling rate.	SDG 14 SDG 15
S10	x					x		x					Reverse logistics	Lean supports loss reduction; sustainability supports reverse logistics (returning waste to production as raw materials).	SDG 7 SDG 12
S11		x			x	x	x	x	x				Energetic efficiency	Lean reduces loss; sustainability sustains the production of green energy.	SDG 9 SDG 13
S12	x			x	x			x	x		x		Pollution Reduction	Lean reduces waste; sustainability is aimed at reducing greenhouse gases.	SDG 11 SDG 13

4. The lean thinking for sustainability transition in healthcare (LT4STHC) framework

In this section, the identified lean thinking principles or approaches that are deemed applicable in healthcare systems (as a socio-technical system) are synthesised into an index along with the transition approaches, providing a link between lean thinking and transitions in healthcare as these lean thinking principles and approaches are deemed appropriate intervention strategies to support sustainability transitions in healthcare. The integration strategy, which details the research products' development process, is also presented. The developed index and framework contribute towards the implementation of lean thinking to support sustainability transitions in healthcare. In this section, the purpose of the LT4STHC framework, the LT4ST index (as a foundational part of the LT4STHC framework), and the approach used to develop the framework are discussed.

4.1 LT4STHC framework purpose

To identify which lean thinking approach or principle could be implemented to support and/or facilitate specific aspects, occurrences, or phases in sustainability transitions in healthcare, the LT4ST index was developed. The LT4ST index is accompanied by the LT4STHC framework, which is a visual presentation of the LT4ST index. The development of the index and framework aims to facilitate an understanding of how lean thinking can support sustainability transitions in healthcare.

4.2 LT4STHC index and framework development approach

This study employed Van Aken et al. (2007)'s development process model as the methodology for the development of the index and framework, as illustrated in Figure 9. This model for the design process management is a stepwise process model that describes the process of developing an intended object (i.e., a framework), as it is broken down into sub-steps. At the same time, the action in each step is controlled by process management. These steps do not follow a fixed sequential occurrence in the development of the framework. However, it is conducted iteratively to explore the steps and modify the framework as needed. This ensures that the development process is flexible and agile (Van Aken et al., 2007).

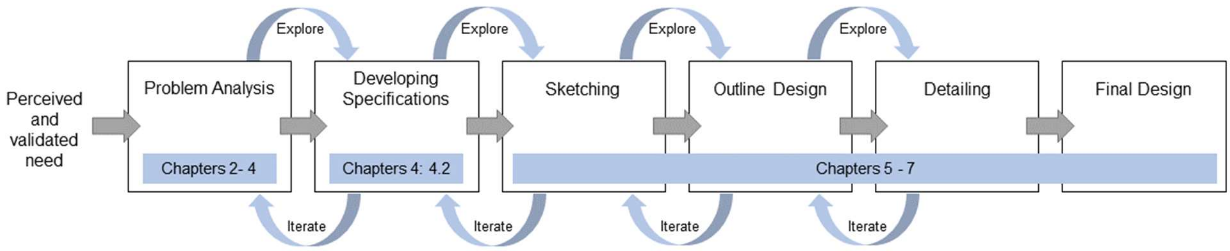

Figure 9: General model for a development process (Process Management) (Van Aken et al., 2007)

4.3 LT4ST index

The LT4ST index, as illustrated in Figure 12 in Appendix A, showcases the role of lean thinking in sustainability transition approaches. The index was developed by conducting an analysis of the approaches for transitional change in healthcare, to determine which identified lean thinking approach or principle, if implemented successfully in healthcare, and could support the:

i. Forces and conditions for transitional Change (landscape tensions, regime stresses, and niche pressures in healthcare) see (De Kock, 2020; Frantzeskaki & De Haan, 2009; De Haan 2010; and Schilling et al. 2018)
ii. Transitional and Transformational failures (Lock-ins, System breakdown, Backlash, Directionality failure, demand articulation failure, policy coordination failures, reflexivity failures occurring in healthcare) (Van Der Brugge & Rotmans, 2007) (Walrave & Raven, 2016; Weber & Rohracher, 2012);
iii. Innovation System Approach (TIS) (Jacobsson & Bergek, 2011);
iv. Strategic Niche Management (SNM) (Schot & Geels, 2008);
v. Resilience of Sustainability Transitions (progress, stability, and adaptability in healthcare) (Schilling et al., 2018); and
vi. Transition pathways (transformation pathway, de-alignment and re-alignment pathway, technological substitution, reconfiguration pathway in healthcare) according to Geels and Schot (2007) and Geels et al. (2016).

The aim is to determine at which organisational level in the healthcare system the respective lean thinking approaches or principles can be implemented, and how they can be implemented to determine what happened, why it happened, what could happen, and what should happen. Thus, the lean thinking approaches or principles will be stipulated against strategic, tactical, operational, and reflexive operational levels, and descriptive, predictive, prescriptive, and diagnostic analytical perspectives.
Transition management (Elzen et al., 2004), further detailed by integrating several analytical perspectives, has been selected to conduct the analysis to understand "at which system level" the identified lean thinking approaches and principles can contribute towards supporting sustainability transitions in healthcare. Transition Management is selected to understand and identify at which level in the system (strategic (TMS), operational (TMO), tactical (TMT), or reflexive (TMR)) the identified lean thinking approach or principle can contribute towards supporting the sustainability transition in healthcare. The analytical perspectives are selected to understand to which extent (descriptive, predictive, prescriptive, or diagnostic) the identified lean thinking approach or principle can contribute to supporting sustainability transitions in healthcare.
Four analytical perspectives (InsightSoftware, 2021), which will indicate the extent to which the lean thinking approaches and principles could support sustainability transitions in healthcare, were considered. These perspectives are:

- Descriptive analytical perspective (APDS), which pertains to understanding what has happened;
- Predictive analytical perspective (APPD), which pertains to understanding what could happen in the future based on previous trends or patterns;
- Prescriptive analytical perspective (APPS), which pertains to understanding what the system should do moving forward; and
- Diagnostic analytical perspective (APDN), which pertains to understanding why what happened.

Each lean thinking approach or principle was classified and assigned according to these two analytical approaches. The approach is graphically illustrated in Figure 10 below.
The first step was to determine whether the lean thinking approach or principle could contribute to supporting the sustainability transition approach. A tick mark was allocated to the respective sustainability transition where the lean thinking approach or principle was deemed applicable in addressing the sustainability transition. If the lean thinking approach is deemed viable to address the sustainability transition, it was further determined how the lean thinking approach or principle could contribute to support the progression of the sustainability transition. The viability of the lean thinking approach or principle to support the sustainability transition was determined based on the definition of the respective lean thinking approaches and principles. The goal of the lean thinking approach or principle was the determining factor in determining whether the lean thinking approach or principle could support the progression of the sustainability transition.
The second step entailed determining in which way the individual lean thinking approach or principle could contribute toward supporting the progression of the sustainability transition. The strategic level implies that the lean thinking approach or principle could assist in achieving sustainable visions and the purpose of a sustainable business model at a large scale. A tactical level implies that the lean thinking approach or principle could assist in achieving a set of networks and collaborations toward sustainability with key stakeholders identified in a sustainable business model. The operational level implies that the lean thinking approach or principle could assist in establishing a sustainable business model vision and purpose and start implementing sustainable-related practices. The reflexive level implies that the lean thinking approach or

principle could assist in monitoring or evaluating the current situation at the strategic, tactical, and operational levels, as well as the interrelation or misalignment.

Different analytical perspectives – as outlined earlier - were also considered to determine the way the respective lean thinking approach or principle could assist in supporting the progression of the sustainability transition in healthcare. The different analytical approaches were allocated to the respective lean thinking approach or principle based on their definitions and goals in healthcare, as stated by the literature. The final step was allocating a tick mark and the respective analytical methods to the lean thinking approach or principle that could support the progression of the sustainability transition in healthcare.

The LT4ST index, as illustrated in Figure 12 in Appendix A, is a representation of the role of lean in sustainability transitions in healthcare. The viability of the lean thinking approach was determined based on the definition of the respective lean thinking approaches and principles as well as the use of the implementation in existing examples. These existing examples comprised literature resources that indicate the successful use of the specific lean thinking principle in similar scenarios. The LT4ST index indicates which respective lean thinking approach or principle, successfully implemented, could support the progression of sustainability transitions in healthcare. The LT4ST index is further conceptualized in the form of the LT4STHC framework, which is outlined in Section 4.4.

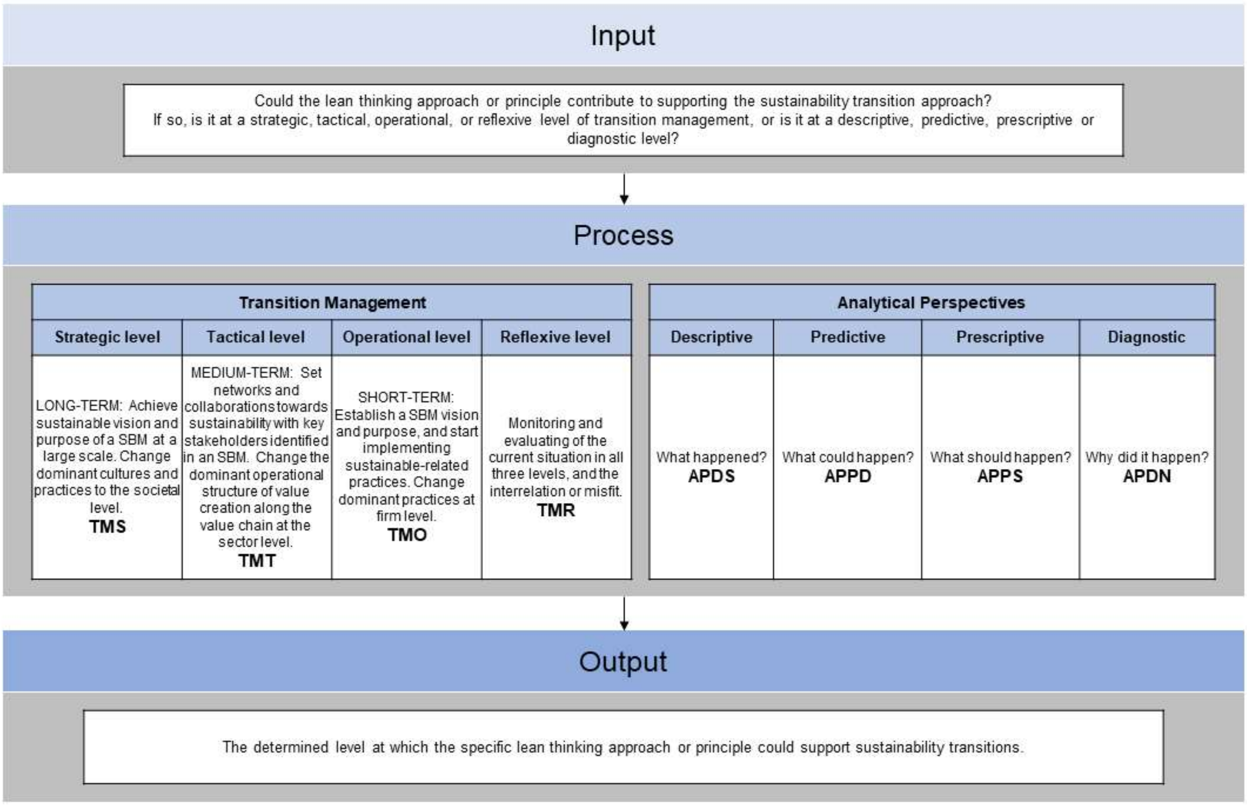

Figure 10: Approach used to determine at which system level and to which extent lean thinking can support sustainability transition

4.4 LT4STHC framework

The LT4STHC framework, as illustrated in Figure 11, is a visual representation of the LT4ST index. The LT4ST index and LT4STHC framework link lean thinking to healthcare sustainability transitions. The framework becomes a methodology, guiding customized lean thinking approaches for specific aspects in a sustainability transition in a healthcare systems. It addresses a knowledge gap about lean implementation in sustainability transitions in healthcare. The framework utilizes the intervention strategy analysis of socio-technical transitions and has been identified as a key consideration for analysing contemporary global systems in transitions to more sustainable states. Lean thinking aligns with sustainability, bolstering global sustainable development understanding. The development of a framework will facilitate an understanding of how lean thinking can support sustainability transitions in healthcare. Lean thinking and sustainability transitions also pertain to global systems and can contribute towards an in-depth understanding, orientation, and implication for global sustainability and sustainable development.

Using the various approaches to understand aspects of sustainability transitions, specific combinations of lean thinking approaches and principles have been identified and placed in their respective areas/scenarios of implementation. The identified combination of lean thinking approaches and principles could be used to support the progression of the sustainability transition during the transition process. The progression of the sustainability transition could be supported by utilizing the lean thinking approaches and principles that have been identified to successfully aid in:

- addressing the occurrence of landscape tensions {(1)Lean4Tension}, regime stresses {(2)Lean4Stress}, niches pressures {(3)Lean4Pressure};
- addressing the lack of progress support {(4)Lean4Progress} , stability {(5)Lean4Stability}, and adaptability {(6)Lean4Adaptability};
- guarding against the occurrence of transition and transformational failures {(7)Lean4Failures} , and the presence of a system weakness {(8)Lean4Weaknesses} ;
- supporting the emergence and introduction of a technology niche {(9)Lean4SNM}, and the presence of different transition pathways {(10)Lean4Pathways}.

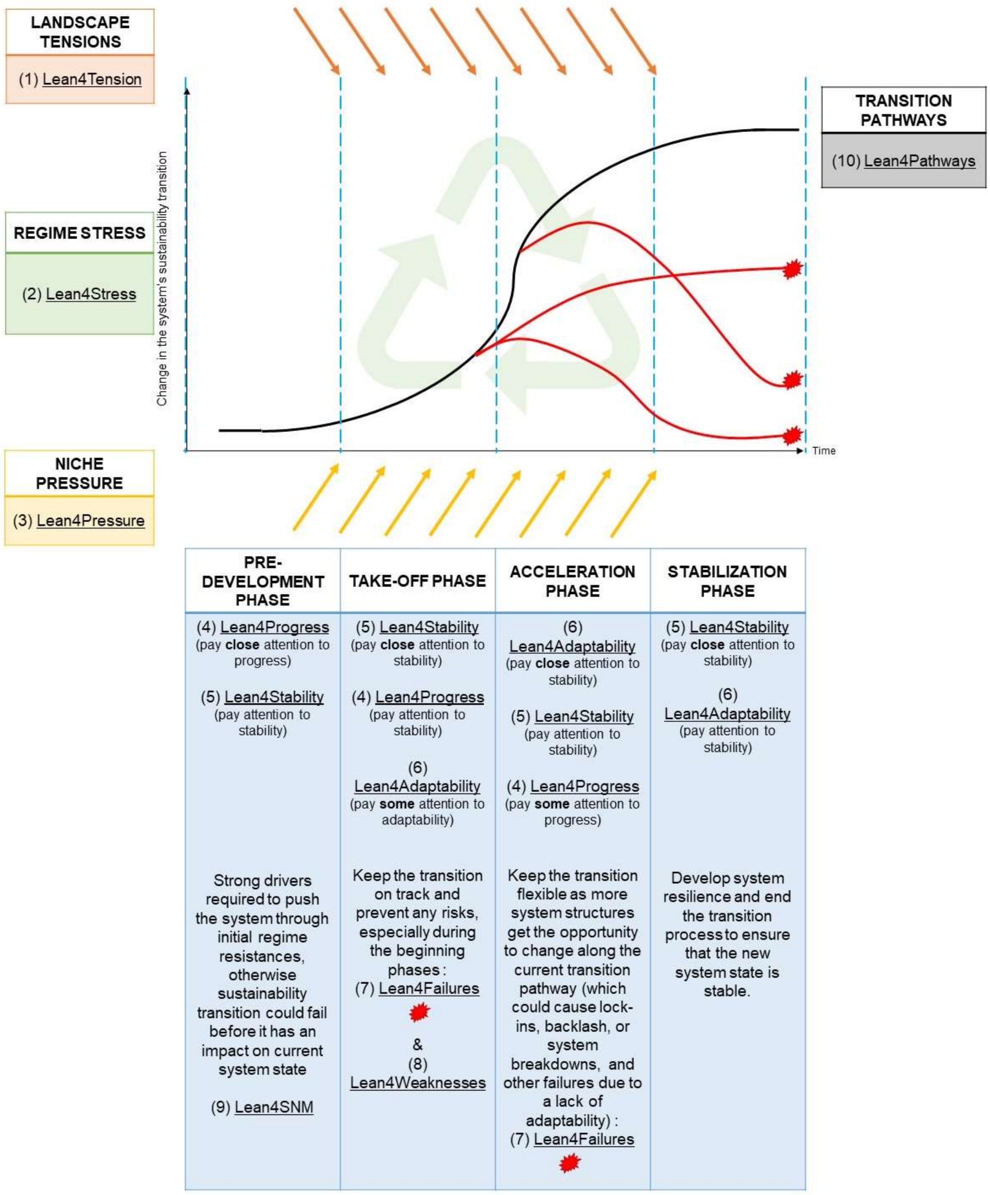

Figure 11: LT4STHC framework

5. Conclusion and future work

This research introduces the LT4ST index and LT4STHC framework, bridging lean thinking and sustainability transitions in healthcare. Addressing a gap, it provides tools for lean thinking integration in healthcare transitions. Also, it highlights the scarcity of studies on this topic, emphasizing the synergy between lean thinking and sustainability in healthcare.This research, therefore, aimed to further contribute to the implementation of lean thinking to support sustainability transitions in healthcare through:

i. Making the integration of lean thinking into sustainability transitions practical and applicable to modern societal systems; and
ii. Providing a premise for developing new perspectives and approaches towards the facilitation of socio-technical transitions in the form of sustainability transitions in healthcare.

The following recommendations are identified as viable options for future work which elaborates on this research:

i. Expand the research to the application of the framework in other societal systems and present case studies on the implementation of lean thinking to support sustainability transitions;
ii. Expand the LT4STHC framework, LT4ST index to include other sustainability transition aspects which possibly occur during a transition and could require support;
iii. Expand the research to examine the possible negative effect that lean thinking could have and its effect on sustainability transitions, i.e., socio-technical transitions;
iv. Expand the framework, and index to ensure that it is applicable in both the private and public healthcare sectors;
v. Expand the LT4STHC framework to include other system demarcations, such as value streams and supply chain interactions; and
vi. Expand the LT4STHC framework into and operationalisation strategy to provide the user with an outlet for exercising strategic intent from the understanding developed by utilising the framework in analysis.

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Appendix A

		Lean Thinking											
		4P Model of the Toyota Way & Liker's Lean											
		Philosophy - long term thinking	Process - Eliminate waste					People & Partners - respect, challenge and grow			Problem Solving - continuous improvement & learning		
		Base management decisions on **long-term philosophy** (even at expense of short-term financial goals)	**Standardize tasks** for quality improvement	**Jidoka** : stop when there is a quality problem; automation with a human touch, to help workers in their daily labors	**Heijunka** : level out the workload	Use **pull system** to avoid overproduction	Create process **flow**	Respect, challenge and help **suppliers**	Respect, develop, challenge **people and team**	**Grow leaders** who live the lean philosophy	**Slow decision-making** by consensus, considering all options (rapid implementation)	**Genchi Genbutsu**: physically going to and observing a location (and its conditions) to understand and solve problems faster and more effectively	Continuous organisational learning through **Kaizen** (continuous improvement, letting the workers think in solutions)
Approaches for Transitional Change in Healthcare: Forces for Change	Landscape Tension (1. Lean4Tension)	✓	✓	✓	×	✓	×	✓	✓	✓	✓	✓	✓
	Regime Stress (2. Lean4Stress)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Niche Pressure (3. Lean4Pressure)	✓	×	✓	×	✓	✓	✓	✓	×	✓	✓	✓
The Resilience of Sustainability Transitions	Progress (4. Lean4Progress)	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	×	✓
	Stability (5. Lean4Stability)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Adaptability (6. Lean4Adaptability)	✓	×	×	×	✓	×	✓	✓	✓	✓	×	✓
Transition Failures (7. Lean4Failures)	Lock-ins	✓	✓	✓	×	✓	✓	×	×	×	✓	✓	✓
	System breakdown	✓	×	✓	×	✓	✓	×	×	✓	✓	✓	✓
	Backlash	✓	✓	✓	×	✓	✓	×	×	✓	✓	✓	✓
	Directionality failure	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓
	Demand articulation failures	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓
	Policy coordination failures	✓	✓	✓	×	✓	×	×	×	✓	✓	✓	✓
	Reflexivity failures	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓
Innovation System Approach (8. Lean4Weaknesses)		✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓
Strategic Niche Management (9. Lean4SNM)		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Transition Pathways (10. Lean4Pathways)	Transformation pathway	✓	×	✓	✓	×	✓	✓	✓	✓	✓	✓	✓
	De-alignment and re-alignment pathway	✓	×	✓	×	✓	×	✓	✓	×	✓	×	✓
	Technological substitution	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Re-configuration pathway	✓	×	✓	×	✓	✓	×	✓	×	✓	×	✓
At what organisational level and how the lean thinking approach or principle can contribute	**Strategic Level**	✓	✓	×	×	×	×	✓	✓	✓	✓	✓	✓
	Tactical Level	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Operational Level	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Reflexive Level	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Descriptive	×	×	✓	×	×	×	✓	✓	✓	✓	✓	✓
	Predictive	✓	×	×	×	×	×	×	×	✓	✓	✓	✓
	Prescriptive	✓	✓	✓	✓	✓	✓	×	×	✓	✓	✓	✓
	Diagnostic	×	×	✓	×	×	×	×	×	✓	✓	✓	✓

Approaches for Transitional Change in Healthcare		Lean Thinking – Lean Practices & Approaches: **Mindset and attitude:** understand and communicate; ensure that cogninitive dimension, tools and concepts are learned	**Leadership and management:** in-depth understanding of lean journey to manifest a lean culture; skilled people are used in the right place	**Employee involvement:** ensure willingness to change; employee development (human capital)	**Tools and techniques: 5S** (It is a discipline to increase productivity with the standardization of cleanliness and organization habits) ,**VSM** (is the identification of all the operations in the company, showing the value and non value ones), **Bottleneck Analysis**, **Overall Equipment Effectiveness**, **Plan-Do-Check-Act**, **Error Proofing**, **Root Cause Analysis**, **SQDC** (Safety, Quality, Delivery, Cost), **A3 Lean Thinking Process**, **Waste Observation Chart**, **Process Flow Map**, **Change management plan**, **Poka Yoke** (mistake proofing), **Hoshin Kanry** (This technique define all the company objectives under Lean principles), **Kanban** (mechanism to flow control and production control, letting produce only what is needed in the moment when it is needed and in the quantity needed), **Andon** (visual signal to inform when something is wrong or is in an abnormal condition), **SMED** (created by Shingo, reduce the set up times - complete as many steps as possible while the equipment is running (or processing), so as to save time and quickly change-over to processing the next product)	**Six Sigma:** reduce the occurance of defects in products/services; speeds up deliveries, reduces costs, increase quality
Forces for Change	Landscape Tension (1. Lean4Tension)	✓	✓	✓	✓	✓
	Regime Stress (2. Lean4Stress)	✓	✓	✓	✓	✓
	Niche Pressure (3. Lean4Pressure)	✓	✓	✓	✓	✓
The Resilience of Sustainability Transitions	Progress (4. Lean4Progress)	✓	✓	✓	✓	✓
	Stability (5. Lean4Stability)	✓	✓	✓	✓	✓
	Adaptability (6. Lean4Adaptability)	✓	✓	✓	✓	✓
Transition Failures (7. Lean4Failures)	Lock-ins	×	✓	✓	✓	✓
	System breakdown	×	✓	✓	✓	✓
	Backlash	✓	✓	✓	✓	✓
	Directionality failure	×	✓	✓	✓	✓
	Demand articulation failures	✓	✓	✓	✓	✓
	Policy coordination failures	✓	✓	✓	✓	✓
	Reflexivity failures	✓	✓	✓	✓	✓
Innovation System Approach (8. Lean4Weaknesses)		✓	✓	✓	✓	✓
Strategic Niche Management (9. Lean4SNM)		✓	✓	✓	✓	✓
Transition Pathways (10. Lean4Pathways)	Transformation pathway	✓	✓	✓	✓	✓
	De-alignment and re-alignment pathway	✓	✓	✓	✓	✓
	Technological substitution	✓	✓	✓	✓	✓
	Re-configuration pathway	✓	✓	✓	✓	✓
At what organisational level and how the lean thinking approach or principle can contribute	**Strategic Level**	✓	✓	✓	✓	✓
	Tactical Level	✓	✓	✓	✓	✓
	Operational Level	✓	✓	✓	✓	✓
	Reflexive Level	✓	✓	✓	✓	✓
	Descriptive	✓	✓	✓	✓	×
	Predictive	✓	✓	✓	×	×
	Prescriptive	✓	✓	✓	✓	✓
	Diagnostic	✓	✓	✓	✓	×

Lean Thinking

Lean Principles			L1	L2	L3	L4	L5	L6	L7
			Reducing/Eliminating activities that do not add value	Reducing uncertainty	Focus on customer requirements	Reduce cycle time	Simplifying the process	Increase production flexibility	Increase process transparency
			S1: Reduce resources; S10: Increase capacity of reuse, remanufacture and recondition	S1: Reduce resources; S2: Time efficiency; S11: Reduce energy consumption	S2: Time efficiency; S3: Reduce waiting time; S6: Support community activities	S1: Reduce resources; S12: Reduce Greenhouse gas emissions	S3: Reduce waiting time; S9: Increase recycling capacity; S11: Reduce energy consumption; S12: Reduce Greenhouse gas emissions	S9: Increase recycling capacity; S10: Increase capacity of reuse, remanufacture and recondition; S11: Reduce energy consumption	S1: Reduce resources; S2: Time efficiency; S11: Reduce energy consumption
Approaches for Transitional Change in Healthcare	Forces for Change	Landscape Tension (1. Lean4Tension)	✓	✓	✓	✓	✓	✓	✓
		Regime Stress (2. Lean4Stress)	✓	✓	✓	✓	✓	✓	✓
		Niche Pressure (3. Lean4Pressure)	✓	✓	✓	✓	✓	✓	✓
	The Resilience of Sustainability Transitions	Progress (4. Lean4Progress)	✓	✓	✓	✓	✓	✓	✓
		Stability (5. Lean4Stability)	✓	✓	✓	✓	✓	✓	✓
		Adaptability (6. Lean4Adaptability)	✓	✓	✓	✓	✓	✓	✓
	Transition Failures (7. Lean4Failures)	Lock-ins	×	✓	✓	×	×	✓	✓
		System breakdown	✓	✓	✓	×	✓	✓	✓
		Backlash	×	✓	✓	×	×	✓	✓
		Directionality failure	×	✓	✓	×	×	✓	✓
		Demand articulation failures	×	✓	✓	×	✓	✓	✓
		Policy coordination failures	✓	✓	×	×	×	✓	✓
		Reflexivity failures	✓	✓	×	×	✓	✓	✓
	Innovation System Approach (8. Lean4Weaknesses)		✓	✓	✓	×	✓	✓	✓
	Strategic Niche Management (9. Lean4SNM)		✓	✓	✓	×	×	✓	✓
	Transition Pathways (10. Lean4Pathways)	Transformation pathway	✓	✓	✓	✓	✓	✓	✓
		De-alignment and re-alignment pathway	✓	✓	✓	✓	✓	✓	✓
		Technological substitution	✓	✓	✓	✓	✓	✓	✓
		Re-configuration pathway	✓	✓	✓	✓	✓	✓	✓
At what organisational level and how the lean thinking approach or principle can contribute		Strategic Level	✓	✓	✓	✓	✓	✓	✓
		Tactical Level	✓	✓	✓	✓	✓	✓	✓
		Operational Level	✓	✓	✓	✓	✓	✓	✓
		Reflexive Level	✓	✓	✓	✓	✓	✓	✓
		Descriptive	×	×	×	×	×	×	×
		Predictive	×	×	×	×	×	×	×
		Prescriptive	✓	✓	✓	✓	✓	✓	✓
		Diagnostic	×	×	×	×	×	×	×

Lean Thinking

Lean Principles

		L12	L11	L10	L9	L8
		Efficient allocation of human resources	Reduction of raw materials	Gathering information about competitors	Improving the process continuously	Controlling the entire process
		S8: Corporate Social Responsibility (CSR); S7: Train human resources; S6: Support community activities; S5: Stakeholder involvement in strategic decisions; S1: Reduce resources	S12: Reduce Greenhouse gas emissions; S4: Monitor fixed cost; S1: Reduce resources	S5: Stakeholder involvement in strategic decisions	S12: Reduce Greenhouse gas emissions; S11: Reduce energy consumption; S9: Increase recycling capacity; S4: Monitor fixed cost; S1: Reduce resources	S12: Reduce Greenhouse gas emissions; S11: Reduce energy consumption; S10: Increase capacity of reuse, remanufacture and recondition; S7: Train human resources
Approaches for Transitional Change in Healthcare						
Forces for Change	Landscape Tension (1. Lean4Tension)	✓	✓	✓	✓	✓
Forces for Change	Regime Stress (2. Lean4Stress)	✓	✓	✓	✓	✓
Forces for Change	Niche Pressure (3. Lean4Pressure)	✓	✓	✓	✓	✓
The Resilience of Sustainability Transitions	Progress (4. Lean4Progress)	✓	✓	✓	✓	✓
The Resilience of Sustainability Transitions	Stability (5. Lean4Stability)	✓	✓	✓	✓	✓
The Resilience of Sustainability Transitions	Adaptability (6. Lean4Adaptability)	✓	✓	✓	✓	✓
Transition Failures (7. Lean4Failures)	Lock-ins	×	×	×	✓	✓
Transition Failures (7. Lean4Failures)	System breakdown	✓	×	✓	✓	✓
Transition Failures (7. Lean4Failures)	Backlash	✓	×	✓	✓	✓
Transition Failures (7. Lean4Failures)	Directionality failure	×	×	×	✓	✓
Transition Failures (7. Lean4Failures)	Demand articulation failures	✓	×	✓	✓	✓
Transition Failures (7. Lean4Failures)	Policy coordination failures	×	×	✓	✓	✓
Transition Failures (7. Lean4Failures)	Reflexivity failures	×	×	✓	✓	✓
Innovation System Approach (8. Lean4Weaknesses)		✓	✓	✓	✓	✓
Strategic Niche Management (9. Lean4SNM)		×	×	✓	✓	✓
Transition Pathways (10. Lean4Pathways)	Transformation pathway	✓	✓	✓	✓	✓
Transition Pathways (10. Lean4Pathways)	De-alignment and re-alignment pathway	✓	✓	✓	✓	✓
Transition Pathways (10. Lean4Pathways)	Technological substitution	✓	✓	✓	✓	✓
Transition Pathways (10. Lean4Pathways)	Re-configuration pathway	✓	✓	✓	✓	✓
At what organisational level and how the lean thinking approach or principle can contribute						
	Strategic Level	✓	✓	✓	✓	✓
	Tactical Level	✓	✓	✓	✓	✓
	Operational Level	✓	✓	✓	✓	✓
	Reflexive Level	✓	✓	✓	✓	✓
	Descriptive	×	×	✓	×	×
	Predictive	×	×	✓	×	×
	Prescriptive	✓	✓	✓	✓	✓
	Diagnostic	×	×	✓	×	×

Figure 12: LT4ST index – "The role of lean in sustainability transitions in healthcare systems"

Towards a Cleaner Production of an Underutilised Legume, Bambara Groundnut

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Abstract

Soilless cultivation systems such as aeroponics provide a more efficient, and clean food production of in areas where there is limited access to arable land for agricultural practices and drought-prone countries. The objective of this study was to evaluate the yield performance of seventy Bambara groundnut (BGN) landraces cultivated in aeroponics and compared with a traditional drip-irrigated hydroponic system with sawdust as a growing medium. The result showed that BGN landraces cultivated in aeroponics accumulated a high number of seeds, as compared to those landraces cultivated in hydroponics. However, BGN landraces cultivated in hydroponics recorded a high shoot dry weight and one hundred seed weight. The root length that could only be measured in BGN landraces cultivated in the aeroponics systems, showed that BGN root length can extend beyond one meter. Soilless cultivation systems with their high-water use efficiency have the potential of reducing production costs, thus making them accessible to farmers in countries where drought is a reality.

Keywords: *Aeroponics, Bambara groundnut, Climate smart farming, Hydroponics, Internet of things*

1. Introduction

The African agricultural sector faces many challenges (Muller *et al*., 2011; Middelberg, 2013), and for the sector to continue producing enough food for the growing population, it needs to undergo fundamental transformations (de Graaff, 2011; Collier and Dercon, 2014; Wiggins, 2014; Shimeles *et al*., 2018). In sub-Saharan Africa (SSA) alone, by 2022, there were approximately 123 million people already food insecure (Baptista *et al*., 2022). Owing to the lack of access to nutritious and healthy food, the SSA population is at risk of malnutrition and health-related complications (Binga *et al*., 2019). The African Union Agenda 2063 highlights the importance of healthy and well-nourished citizens and the use of modern agriculture to increase productivity and production (AUC & AUDA-NEPAD, 2022). Accordingly, to overcome food insecurity problems, SSA must explore the production of nutrition-dense food while conserving the environment (Ojiewo, *et al*. 2015). In line with sustainability transitions, climate-smart farming technologies have shown to increase crop productivity and food security, while reducing environmental impacts and saving natural resources (Branca et al.,2021). Despite the low adoption of climate-smart farming technologies in SSA (Makate *et al*., 2018; Ogunyiola *et al*., 2022), their implementation in certain regions has demonstrated a positive impact on crop production (Makate *et al*., 2019). Africa is disproportionately affected by the consequences of climate change, making it crucial for governments to prioritise the efficient use of available land and water resources (Kumssa and Jones, 2010; Tedesse, 2010). To achieve cleaner and more environmentally friendly agricultural practices, all stakeholders must adopt a mindset that prioritises minimising risks to the environment.

Several approaches can be pursued to achieve cleaner agricultural production. First, the utilisation of climate-smart farming technologies, such as aeroponics and hydroponics can significantly reduce the required space and water when compared to traditional farming methods (AlShrouf, 2017; Tunio *et al*., 2020; Mamatha and Kavitha *et al*., 2023). Second, the integration of monitoring and automation technologies through the Internet of Things (IoT) can serve as an innovative tool to promote cleaner agricultural production (Ragavi *et al*., 2019; Ahmed *et al*. 2022). Embracing these practices presents a promising path towards sustainable agriculture in Africa.

Aeroponics is an advanced agricultural technique that involves growing plants in a mist or air environment without using soil or traditional hydroponic growing medium (Christie *et al*., 2003; Mithunesh *et al*., 2015; Eldridge *et al*., 2020). In aeroponics, plant roots are suspended in air, and a fine mist of nutrient-rich water is frequently sprayed onto the roots (Gopinath *et al*., 2017; Lakhiar *et al*., 2019). This mist provides the necessary nutrients and moisture directly to the roots, allowing plants to thrive (El-Kazzaz and El-Kazzaz, 2017; Li *et al*., 2018). In this context, the primary objective of cleaner production is to minimise risks that could lead to adverse consequences in the future. In addition, this technology offers more opportunities to the agricultural industry, as it allows those directly involved in research to most plants from their aboveground parts (leaves) to their below-ground parts (roots) (Cai *et al*., 2023). The ability of researchers to study all parts of a plant is crucial for plant improvement studies.

In addition to the lag in the adoption of climate-smart technologies, SSA has also neglected its underutilised crop species, which have the potential to alleviate food insecurity on the continent (Massawe *et al*., 2015; Koch, *et al*., 20201). Neglected and underutilised crop species (NUCS) refer to a group of plant species that have been historically overlooked or underappreciated, despite their potential value in terms of food security, nutrition, and agricultural sustainability (Chivenge *et al*., 2015; Mabhaudhi *et al*., 2015). One such crop is the indigenous African legume Bambara groundnut (*Vigna subterranea* L. Verdc.). Bambara groundnut, a neglected and underutilised legume, is often referred to as a "complete food" due to its exceptional nutritional profile (Mazahib *et al*., 2013; Khan *et al*., 2021).

Bambara groundnut has evolved to thrive under conditions where other crops might struggle, making it a suitable candidate for cultivation in areas with limited access to nutrients and marginal soils. However, this also provides possibilities for exploring climate-smart technologies for the cultivation of this crop to improve its productivity. While the focus of research on aeroponic cultivation primarily targets commodity crops rather than underutilized crops, as awareness grows regarding the importance of consuming nutrient-rich food, there is now an increasing interest in exploring underutilised crops, such as Bambara groundnut. Therefore, this study evaluated the yield performance of seventy Bambara groundnut (BGN) landraces groundnut landraces cultivated in climate-smart technologies (aeroponics and drip irrigated hydroponics).

2. Methods

2.1 Plant material study site description

Bambara groundnut landraces (BGN) were sourced from subsistence farmers in Limpopo Province, South Africa (23.4013 °S, 29.4179 °E). The seeds were separated according to IPGRI Bambara groundnut descriptors, and successful separation seventy were chosen and used in this study. Before planting, the seeds were visually inspected to detect any abnormalities or defects that might limit seed germination and, subsequently, the overall performance of the plant. The study was performed at Welgevallen Experimental Farm, Stellenbosch University, in a tunnel (location:33°56'52.5″ "S, 18°52'19.9"″ E) over two trials. The recorded minimum and maximum temperatures of the tunnel ranged from 10-34ºC throughout the planting season. The data was collected using sensors, via the IoT system.

2.1.1. Aeroponics and Hydroponics system design

Seventy Bambara groundnuts were planted in two climate smart cultivation systems: aeroponics and drip irrigated hydroponics. The aeroponics system was composed of 30 units, and each unit was able to accommodate 12 plants. The system design was described by Mabitsela et al. (2023). The hydroponic systems followed a traditional drip irrigation method, with sawdust incorporated as the growing medium. The system consisted of 350, 10 L polyethylene planting bags. The nutrient solution supplied to the plants in both systems, was a modified Hoagland’s solution prepared from (*Arachis hypogea* L) fertiliser recommendations.

2.1.2. Internet of things

To better understand the growth conditions in aeroponic systems. An IoT-based remote air and water temperature monitoring system was developed using DS18B20 temperature and humidity. The sensors were used to collect air and water temperature data every 5 minutes. The output was sent to a Telegram bot via cellular connectivity, which allowed real-time monitoring of the aeroponics system. The air and temperature data collected from the sensors were sent to a CSV file as numeric values, which enabled data visualisation. Bambara groundnut is said to thrive in harsh environmental conditions, and the use of IoT-based monitoring can be a tool to validate the information and understand how certain growth stages in a plant are affected at different temperatures.

For temperature and humidity control inside the tunnel, an extraction fan and evaporative cooling pads (wet wall) were simultaneously switched on to regulate the temperature inside the tunnel. The IoT solution was described by Mabitsela et al. (2023).

2.2 Data collection and analysis.

At the end of the trial, plants were removed from both the systems. In the aeroponics system the number of seeds were counted (NS), root length (RL), shoot dry (PBM), one hundred seed weight were determined (100SW). In the hydroponics system, all parameters were collected and recorded besides the root length (RL). Determining the root length and root dry weight in sawdust was not viable because of the decomposing nature of sawdust over time during the planting season.

The Shapiro-Wilk test was used to determine if the data set was normally distributed. The data was not normally distributed as such non-parametric tests were used. The Kruskal-Walli's test was used to determine the effect of the aeroponics and hydroponics systems on the measured parameters.

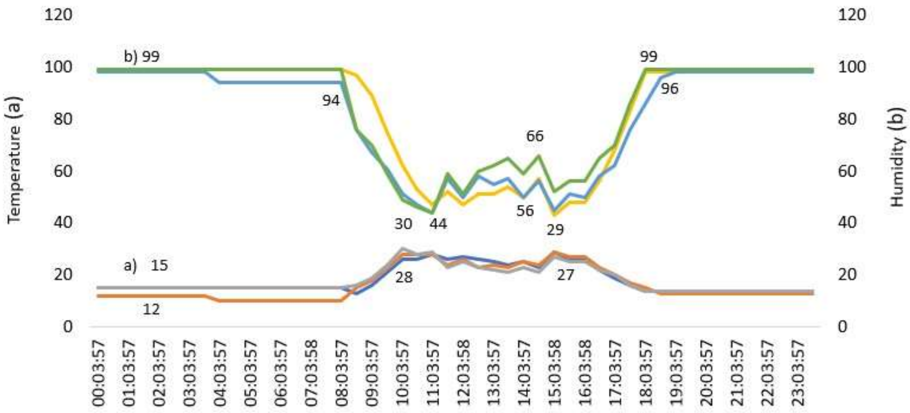

Fig. 1. Temperature (◦C) and humidity trends inside a tunnel. The data shown represent the tunnel conditions on May 23, 2023.

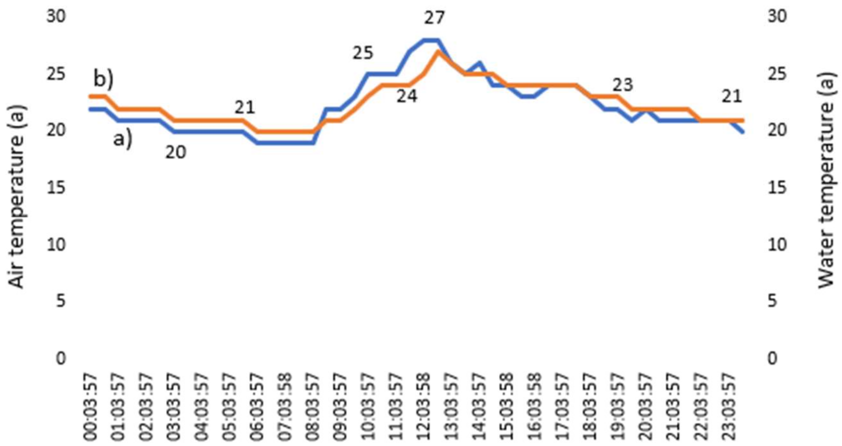

Fig. 2. Air and water temperature trends inside the aeroponics system. The data shown represent the tunnel conditions on May 23, 2023.

3. Results

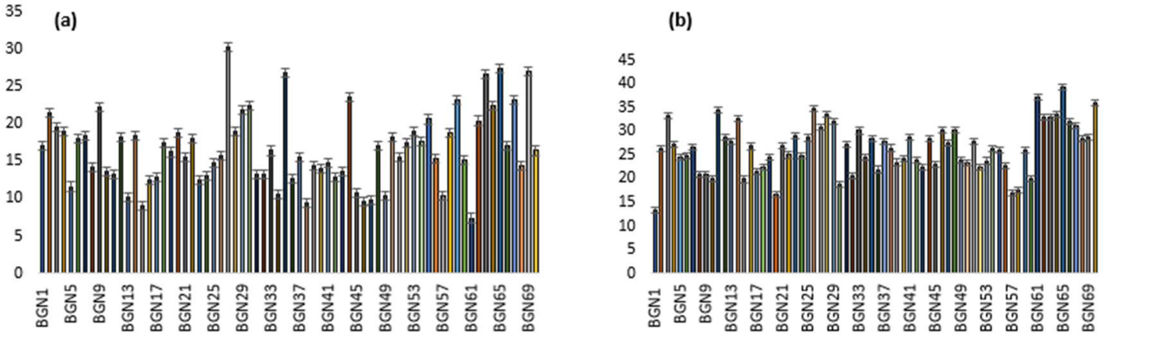

Fig.3. Mean shoot dry weight of 70 Bambara groundnut landraces cultivated in a) hydroponics b) aeroponics

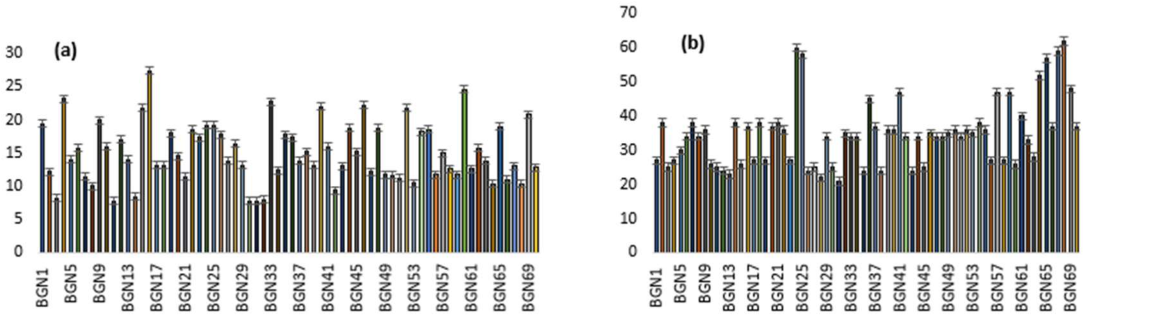

Fig.4. Mean number of seeds of 70 Bambara groundnut landraces cultivated in a) hydroponics b) aeroponics

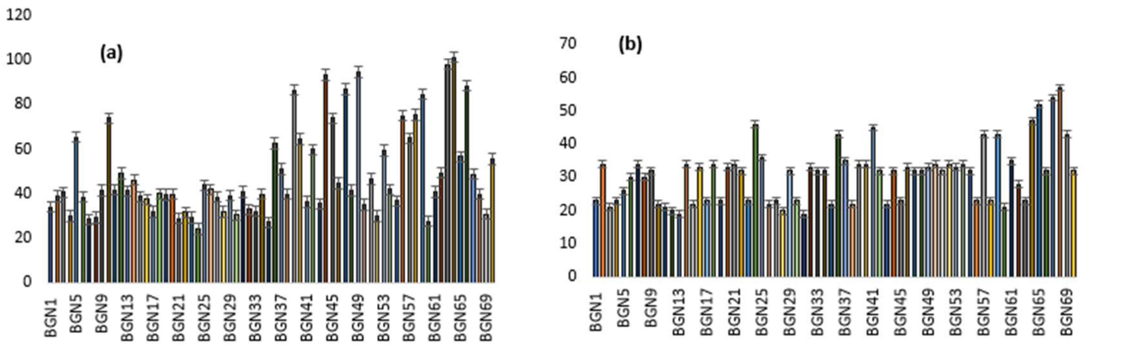

Fig.5. Mean 100 seed weight of 70 Bambara groundnut landraces cultivated in aeroponics (a) and sawdust media (b).

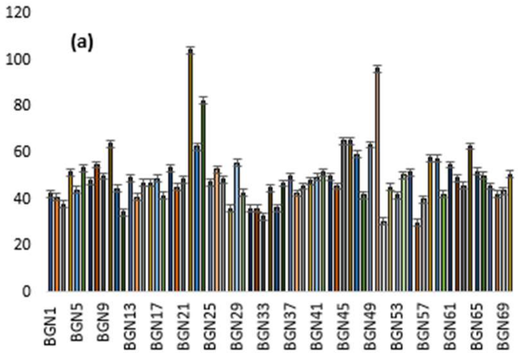

Fig.6. Mean root length of 70 Bambara groundnut landraces cultivated in aeroponics (a).

There was a significant difference ($p < 0.001$) in SDW between the BGN landraces grown in aeroponics and hydroponics. Shoot dry weight ranged from 30.2 g to 7.4 g in the sawdust media and from 39.2 g to 13.2 g in the aeroponics system (Fig.3a). In the hydroponics system, BGN 27 accounted for the highest SDW, while BGN 65 recorded the highest SDW in the aeroponics system (Fig.3 a & b). Significant differences ($p < 0.001$) were observed for NS in all BGN landraces. Bambara groundnut landrace 16 recorded the highest NS in the hydroponics system, while BGN 68 performed better than all other landraces in the aeroponics system (Fig.4 a & b). Interestingly, BGN 31 had the lowest NS in both systems (Fig.4 a & b). The hydroponics and aeroponics system both significantly ($p < 0.001$) influenced the 100SW, in all the BGN landraces. In the hydroponics system the 100SW ranged from 101,2g to 24.2 g while in the aeroponics system the 100SW ranged from 57 g to 19 g (Fig.5 a & b). In the hydroponics system, BGN 64 recorded the highest 100SW, whereas in the aeroponics system, the highest 100SW was recorded for BGN 68 (Fig.5 a & b). Root length varied significantly among all the BGN landraces ($p < 0.001$). Bambara groundnut landraces 22 (104.3 cm), 50 (96.4 cm), and 24 (82.7 cm) all recorded a root length of > 80 cm; BGN 56 had the lowest root length (29.9 cm, followed by BGN 51 (30.4 cm) and BGN 33 (32.6 cm) (Fig.6).

4. Discussion

During the life cycle of a crop, multiple factors can limit or enhance its growth and productivity. With the IoT-based solution, the environmental factors within the tunnel and aeroponics system were monitored or controlled. This was done to minimise any variability that might be influenced by external factors and for a more accurate comparison of yield parameters under the two soilless cultivation systems. The findings from this study showed that shoot dry weight in the aeroponics system was lower in some landraces than in those cultivated in the hydroponics system. Two scenarios are presented to explain the higher shoot development in hydroponics compared to the aeroponics system. First, sawdust, being the growth medium in the hydroponics system, provided the BGN landraces with uninterrupted moisture, were in the aeroponics system, and root proliferation in some BGN landraces could have restricted water and nutrient supply to their other landraces, thus compelling those landraces to increase their root surface area. The high variation in the root length of BGN landraces can be classified as an adaptive mechanism to restrict water and nutrient supply due to the misting intervals in the aeroponics system. Bambara groundnut landraces grown in aeroponics produced a high number of seeds than those grown in sawdust medium. The aeroponics system provided optimal aeration and a fresh mist of nutrients to the BGN landraces, which was a major factor in the BGN yield performance. In the hydroponics system, the physiochemical changes in the sawdust media over time might have restricted its yield performance in terms of the number of seeds per plant. It is interesting to note that the BGN landraces in the hydroponics recorded the highest one hundred seed weight compared to the aeroponics system. Because BGN is a *subterranean plant that* ripens its pods underground, the sawdust media in the hydroponics system provided an ideal darkened environment for their development. Unlike in the aeroponics system, sawdust was used as a "earthing up" material forty-five days after panting. High-yielding landraces, which also recorded a higher shoot dry weight in both systems, are desirable to farmers, as both the shoots and yield can be used. These landraces can be used as livestock feed and seeds for human consumption. In sub-Saharan Africa, BGN is used as an alternative feed for animals when farmers cannot afford the required feed. Even though there was a high variability within the landraces in the yield parameters, BGN 64, 65, 68, 50, and 22 performed better than all other landraces in the measured parameters when compared to BGN 31, which showed a negative response in both systems.

5. Conclusion

The findings from this study showed that the aeroponics system has a beneficial effect on the number of seeds, root length, and development, while the hydroponics system provided an ideal environment for shoot development. As such high yielding landraces in soilless systems were identified, showing that cleaner production of Bambara groundnut is possible. The different responses of all the landraces in the measured parameters in both systems showed the diversity in the adaptivity of the BGN in soilless cultivation systems.

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Towards a Forecasting Framework for Strategic Electricity Demand Forecasting in a Rapidly Evolving Power System Environment: A Set of Requirements

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Abstract

The landscape of energy utilisation is experiencing rapid evolution, driven by the need to integrate renewable energy resources in the migration towards a sustainable carbon-free footprint. Progression in technology associated with renewable electricity sources introduces new opportunities, increased system complexity and uncertainty. These changes in the energy industry pose significant challenges to forecasting the peak demand for electricity supplied by the electrical networks. Forecasting the electricity demand for a utility serves as the foundation of the network planning of the utility grid. The availability of forecasting frameworks was investigated through literature and a case study analysis to gain real-world insight. Literature provided several frameworks for short term energy forecasting, and limited research was found on long-term forecasting frameworks, with none including the influence from renewable integration. A distinct need was presented to identify factors and interlinking concepts to forecast a utilities' demand and combine these analytically within a forecasting framework. The focus of this paper is to present the foundational concepts – in the form of a set of requirements – to guide the development of such a framework that could, ultimately, assist an electricity demand forecaster in formulating strategic forecast scenarios in line with business strategy and goals for a utility.

Keywords: Electricity demand, long-term forecasting, utility forecast frameworks, renewable integration.

1. Introduction

The challenge posed to this research is the change experienced in the energy sector and how these changes will contribute to the forecast methods followed to model electricity demand forecasts for utilities. In collaboration with Bain and Company, the world economic forum did a study on the future of technologies influencing the electricity grid [1]. The fourth industrial revolution builds on the legacy of the digitalisation of the third revolution. This paradigm shift involves the transformation of entire systems and, in particular, within the electricity landscape where the scope of the power sector is becoming more complex than ever before, with rapidly changing technologies in power generation and storage, emerging innovative business models, and shifting regulatory landscapes [2]. As we head into the future paradigm, it is imperative to support a reliable, economically competitive, and environmentally sustainable electricity system as a cornerstone for a modern society into the future [1].

The International Energy Agency (IEA) contributes mainly to the global drive to a carbon-free world. It drives initiatives to assist governments in driving the transition towards a cleaner and more efficient energy future [3]. Three main scenarios from the IEA support the latest ambitions for the energy sector. The first scenario is the highly ambitious "Net zero emissions by 2050" scenario (NZE). Secondly, the "Announced pledges scenario (APS) falls slightly short of the NZE decarbonisation targets. Finally, the "Stated policies scenario" (STEPS) provides a bottom-up sector insight on how energy demand might evolve, taking climate control ambitions and renewable penetration into consideration [3]. Figure 13 shows the increased flexibility forecasted for both advanced and emerging market economies. The high carbon-intensive generation sources are maintained as primary generation plants. However, several new generation sources and technology advancements will be included moving into the future. This shows that it is imperative not to take the energy transition into account when planning future electricity networks.

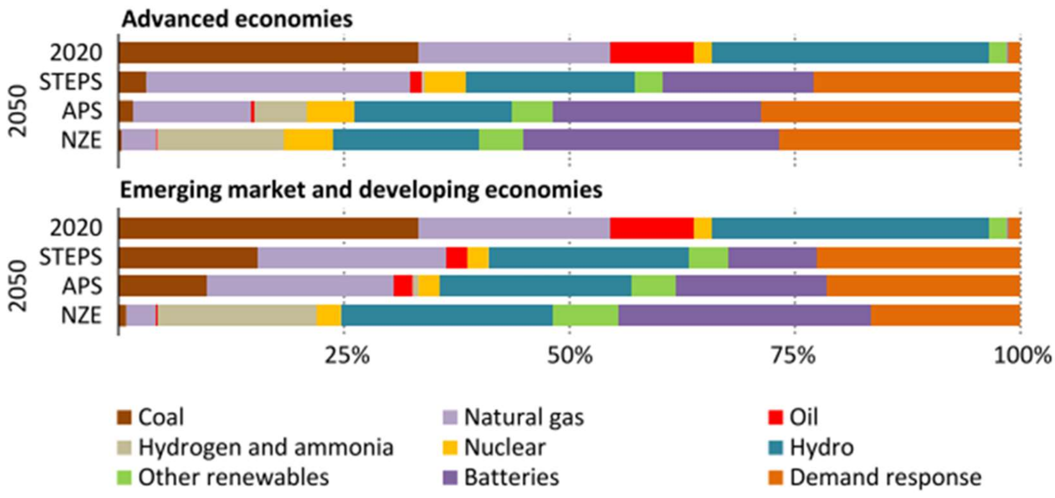

Figure 13: WEO electricity system flexibility by source and scenario between 2020 and 2050 [3]

For most of the past century, the world's electric utilities were primarily stable, reasonably predictable, and essentially operated in a vertically integrated supply chain [4]. Conventional power stations mainly used traditional generation sources (coal-fired, gas, or hydro generation plants), transferred through a high voltage transmission grid to distribution substations. As a result, the utilities had fairly predictable load growth, and sales were governed and periodically adjusted to keep utilities reasonably profitable [5]. Vertically and horizontally integrated supply chains are strategies adopted by companies to establish synergies in their value chain to achieve more profits and competitive advantage in the particular industry in managing its supply sources to serve the needed demand [6]. The power industry and utility business can relate to the vertically or horizontally integrated strategies by determining how the supply chain will be operated. Traditionally, a vertically integrated supply chain was evident in the utility's generation sources supplying its customers from centralised generation. However, when considering a competitive energy market into the future, a horizontally integrated system can be envisaged. The horizontally integrated supply system is associated with the new structures of independent or consumer-owned generation sources that connect to the central grid and contribute to the total energy demand for the country [1]. The changes seen in the power sector over the past two decades has introduced several new types of players into the electricity markets [7]. It is estimated 600 stakeholders from the electric industry showed that utilities actively prepare for the increased penetration of renewables and distributed energy resources [8].
New technologies for electricity generation, especially on the customer side of the value chain, started to emerge [9]. A "Prosumer" is a customer that can use energy and simultaneously play an active participant in the market by supplying power back into the networks, which now creates bi-directional power flows [10]. The addition of such a connected customer and new localised generation sources significantly changes the configuration of the network operations.
Furthermore, renewable integration becomes a key trigger to forming a horizontally integrated supply chain in the future to sustain market share and competitive advantage in future utility-scale grids. Most utilities worldwide have already merged and collaborated with renewable energy resources to build a carbon-free generation capacity [11]. However, increased technology, electrification and end-user flexibility will change usage patterns and profiles of the energy demand and supply interaction. Despite the importance of grid expansion and operation, analysis of the long-term load forecast accuracy and models have not received preference [12]. Therefore, adapting and further researching forecast methods to serve the new electricity demand forecast scope and network complexities becomes a priority that cannot be underrated.
This study thus aims to outline the design requirements that will guide the development of an integrated forecasting framework to provide a holistic overview of the changing components influencing forecast modelling for long-term electricity demand forecasting, considering the fast infiltration of renewable energy generation.

2. Background: A review of literature

2.1 Forecasting methods

Forecasting models can be grouped into eras of development [13]. The first group of techniques can be grouped into the "Pre-Personal Computer" area, which pertains strongly to techniques used mainly before the 1980s. Second, as computers evolved and became common, a new set of forecasting techniques was launched. Thirdly, the latest methods can be classified as strategic or "smart grid" era techniques leading us to intelligent and scenario-based forecasting techniques [13]. Energy forecasting has received more modelling attention; however, forecasting the peak demand and including the effect of renewable penetration on the network is yet to be refined [12]. Techniques such as scenario planning, complex thinking, multi decision criteria modelling, machine learning and incorporation of artificial intelligence are considered favourable to a complex and interlinked energy environment. Delphi techniques and panel consensus on the expected changes from the industry will also add value to the evaluation of possible future forecasting scenarios to be modelled [14].
The unpredictability of the future needs reinforcement of processes to assist in modelling the forecast scenarios. A forecasting process will assist in identifying and evaluating all factors which are likely to influence the course of the future. Therefore, the PEER forecasting process was adapted, which includes stages, Prepare, Execute, Evaluate, and Reconcile (PEER) [13].Critical elements of a demand forecasting process are the frequency of the forecast and its time horizon, both of which depend on the nature of the industry and the business operating model where the forecast will be implemented [15].

2.2 Change in the power sector structure

Power industry leaders are envisaging a future energy system as close to 100% renewable as possible. It is foreseen that a power system is driven by renewable sources, apart from bio-energy and solar thermal, and such a renewable energy system will be mainly based on electricity [12]. Renewable penetration into the network can change the energy component measured by the utility. From a network capacity perspective, the peak load should still be planned. Localised generation as connected at this substation will reduce the energy, but not the peak network capacity requirements. With increased penetration of localised generation, the peak loading at the substation might also be increased [10].
Recent approaches in the literature have shown that spatial-temporal autocorrelation models and techniques can be used in renewable forecasting. A new forecasting method based on temporal exploration and tensor decomposition, which assists in extracting new feature space for learning renewables for forecasting models, have been derived and is still being tested [16]. Another avenue of forecasting net load for high renewable penetration is integrating micro-grids with the macro grid and then comparing two approaches: additive and integrated net load forecast models. As a result, a heuristic-based solar forecasting technique was proposed [17].

2.3 Forecast business integration

In the highly acclaimed book "Games Foxes Play", a sequel to their first "Mind of a Fox", strategic decisions and execution of plans for extraordinary times are explained [18]. Strategic scenario planning is linked with tactics. Energy transition in the power sector is driven by megatrends interacting with the paradigm shift experienced [19]. A framework in Figure 14 **Erro! Fonte de referência não encontrada.** depicting the impact of megatrends shown in the figure gives the five areas of disruption and its impact. Together these components contextualise which future market and business models will be framed [19]. The importance of addressing new problems in the power industry in a holistic approach has been revealed. Therefore, a collaboration of different factors into one framework seems plausible.

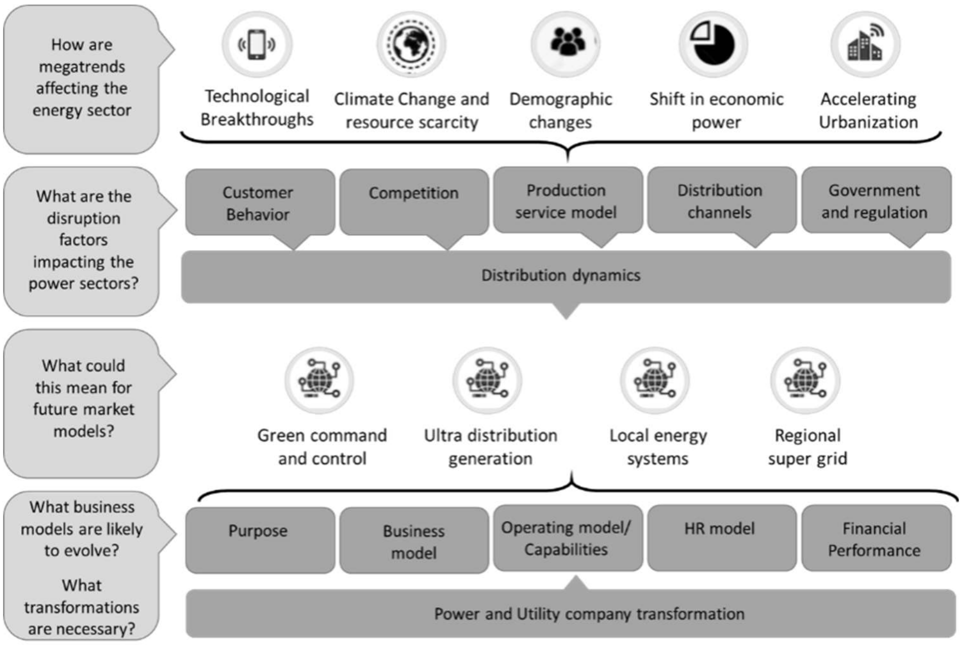

Figure 14: Change in forecast model with IPP generation input across the country's electricity flow model [19]

3. Case study selection and paradigm shift observations

The South African national utility, Eskom Holdings SOC Limited (Eskom), has been selected as the case study utility to gain in-depth, real-world insight into the utility environment. Eskom and several international utilities have started introducing independent power procurement initiatives from independent companies (IPPs) to their generation fleet. The introduction in South Africa was governed and formalised by establishing the "Renewable Energy Integration Power Procurement Programme" (REIPPP) program. Since implementing IPP connections in 2014, a rise in contribution to system peak could be noticed [20]. Renewable energy is primarily driven by natural resources and tend to not contribute at their peak capacity during system peak hours (between 17:00 and 20:00) [21].
Traditionally, the total system peak was modelled strategically in line with the South African government's National Development Plan (NDP). The forecast is then proportionally disaggregated based on a top-down transhipment nodal mathematical model. The model was built based on historical trends for each subsection of the transhipment model, such as provincial areas, regional forecast areas and transmission substation supply areas [22].Figure 15 represents the structural change in the nodal hierarchy of the network-based transhipment model used to disaggregate the national forecast. The change in the forecast model by integrating renewable connections is shown in Figure 15.

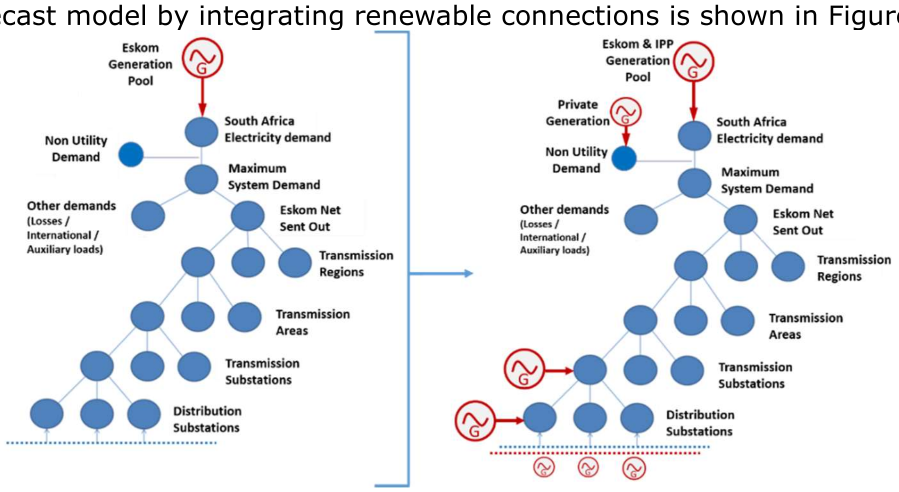

Figure 15:Change in forecast model with IPP generation input across the country's electricity flow model

Data were analysed at the national, provincial and substation levels for the Eskom utility to understand the effect of the renewable penetration at different granularities. Over the past six years, renewable

penetration expanded rapidly. Therefore, sample data were chosen from the following years: 2014 – the onset of IPP's, 2016 – remarkable production from IPPs, 2018 – all contracted IPPs up to bid window 4b, in place. Data was sourced from national peak data and is available on the Eskom website data centre [5].
The last set of nodes in the transmission substations and subsequent bus bars are connected to the distribution feeders when moving further down in the supply chain model. This is also predominantly where IPPs are connected to the transmission grid, and hence the most significant implication can be observed. Two substations from the provinces studied were selected to analyse the exact change in base demand analysis needed to start the forecasts and correct actual demand trends. Figure 16shows an example of two substations, one connected to a solar IPP, and the other to wind IPP.

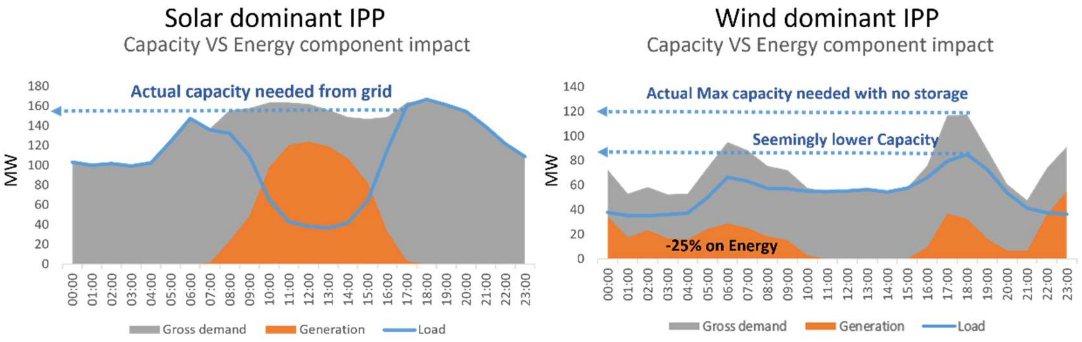

Figure 16: A case study on a solar and wind IPP connected to a substation

Different energy displacements will be seen from renewable or other generation sources connected to the grid. It can once again be observed that the IPP serviced 23% and 25 % of the energy capacity respectively before the Eskom grid served it, and therefor influencing the demand measurement that Eskom can observe from the network nodal measurement points at the respective lines or transformer point loads.

An important observation is a clear distinguishment between energy usage and capacity needed from the network perspective. Figure 16 show an area representing the energy usage per hour generated by the IPP shown as a percentage of the total energy for the particular day. Integrating local generation at the substation level can support the local demand needs and mitigate the demand at the distribution system level [23]. Therefore, despite the influence of the IPP, the Eskom network should still be available and therefore reserve capacity for the peak period where there is no generation from the PV solar component. Consumer behaviour and behind the meter usage of renewable energy will continue to affect the networks going forward, especially on the network's distribution level.
All applicable forecasting modelling techniques found relevant in the assessed literature was fitted to the current implementation within Eskom. Figure 17**Erro! Fonte de referência não encontrada.** summarises which tools are currently utilised within Eskom peak demand forecasting and have not been used to date.

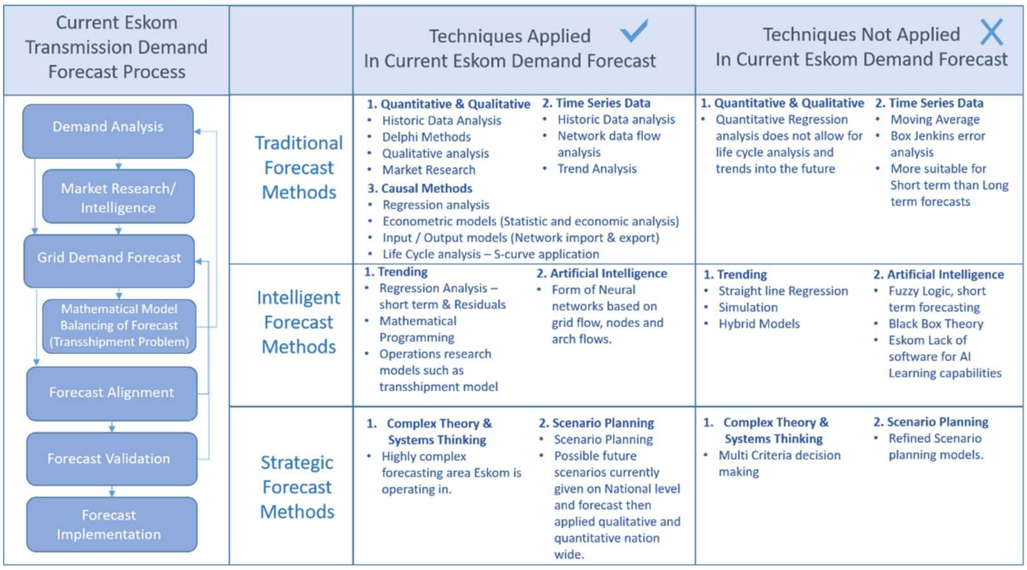

Figure 17: Case study tools and techniques evaluation

The current forecast process implemented in the South African utility, Eskom Transmission, includes a range of internal and external factors using an integrated process to analyse, formulate, align, validate, and implement the demand forecast. The process was benchmarked against processes found in literature and found to align. The base of all forecast processes includes the four steps, including modelling, base analysis, evaluation and implementation.

4. Identification of framework requirements

In order to address the research questions posed and develop a set of design requirements to ultimately guide the (future) development of a framework to assist an electricity demand forecaster in formulating strategic forecast scenarios in line with business strategy and goals for a utility, a number of specific conclusions were made from literature and case study observations. This was workshopped with industry experts, and semi-structured interviews were conducted to ensure all requirements for the framework was captured. Below the components that should be included in a framework that aims to assist an electricity demand forecaster in formulating strategic forecast scenarios in line with business strategy and goals for a utility. Is outlined, the proposed change in modelling approach with renewable integration consideration, the load growth factors, and system disruptors are discussed, the forecast and business strategy alignment that should be considered is discussed. And ultimately the proposed design requirements for the development of a framework that assist an electricity demand forecaster in formulating strategic forecast scenarios in line with business strategy and goals for a utility are presented.

4.1 Components to include in the framework

The primary focus areas to assess where a change in the forecasting process is needed and which components will need to be incorporated were identified and analysed in detail. Many disruptors have been identified through both case study analysis and literature. These disruptors and fundamental shifts in the power sector technology changes lead to a change in customer behaviour and, therefore, electricity needs. Thus, consumer behaviour, together with technology evolution, has a significant impact on the demand forecast. As literature has shown, the energy system is rapidly transforming, driven by political, economic, climate, and generation source changes, including fuel source changes and technological advances [24]. Changes in consumer behaviour in technological innovation and smart grid planning can influence the energy intensity and consumption behind the meter [25]. Most points of interest that was analysed within the case study environment included the following aspects:

- The forecast process followed;
- Governance components influencing the forecast;
- Mechanisms that might influence the modelling approach or assumptions;
- Main load drivers and new technology influencing these load drivers;
- The integration of the forecast and the business strategy for feasible implementation of the forecast.

Each of these components will host several factors that influence the design requirements for the forecast framework's decision-making and scenario building capacity.

4.2 Change in modelling approach with renewable integration consideration

The progression of renewable infiltration was explored by analysing the case study utility data for the past six years. Penetration of IPPs on the system level, provincial, and substation level was calculated and plotted to show how an increase in granularity show a more significant impact on the system components. The effect of decentralisation is visible by the increase in penetration at the smaller load areas. Detailed analysis on the nodal balancing was done to establish how the analysis should adapt to renewable generations' introduction throughout the supply chain.
In the current system, this will include utility load as well as IPP generated load. Depending on the future scenario, the gross demand will be calculated using smart metering. The customer electricity use will need to be calculated irrespective of the supply source. Should the forecast be focussed on the total grid-connected demand for the country, the customer's network connection and its measurement should be taken into account. This is considered a requirement in modelling network nodes in the future. The primary finding of this analysis is that the aggregated load formula needs to be adjusted to include the IPPs or Renewables. The formula can be adapted for any time or level in which the network is studied. This formula can be applied to each nodal point in the hierarchy and be adapted accordingly:

$$L_t^{\text{Area node}} = \sum (L_t^{\text{MTS}}) + L_t^{\text{Losses}} + P_t^{\text{Imports}} + L_t^{\text{Exports}} + \boxed{P_t^{\text{RE}}} \quad (1\text{-}1)$$

Where:
L = Load
P = Power generated
P^{RE} = Renewable energy generation source
t = Time of network study
Losses = Transmission system losses
Imports = Generated power imports or load flow between substations
Exports = Exports from national generation to neighbouring countries or substations
MTS = Main transmission substations
Area node = aggregated demand at hour of study for selected area node

Kirchhoff's current law states that "the net current entering a node is zero". When considering a point in an electrical network where two or more circuits are joined together, this point can be considered a "node" [14]. The gross demand can be calculated by adding the load data and the generated data that enters/leaves the point on the network grid in the same hour. Therefore, it can be confirmed that the gross load for a nodal point in the network should be calculated by combining both load and generation metering. The base data analysis component of the forecast process should be adapted to ensure that the correct baseload values are used within the balancing of the nodal points and assist in answering the second research question.

4.3 Load growth driving factors and system disruptors

Relevant process components were identified that the utility should consider when constructing a demand forecast. First, an integrated forecast process is still highly suggested to include data anlysis, modeling, verifying, and implementing a forecast. Secondly, top-down and bottom-up alignment was identified. Figure 18 shows the integration of balancing top-down and bottom-up forecasts, both ensuring synergy in strategic business directives and bottom-up analysis.

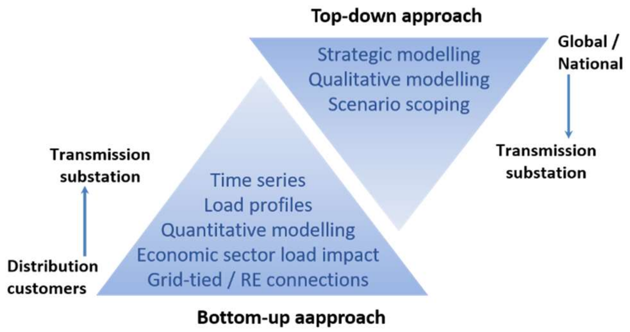

Figure 18: Case study tools and techniques evaluation

Lastly, analysing customer behavior is a pivotal point in understanding the forecasting scope. The essence lies in analysing the number of customers who move off-grid, stay grid-tied or remain fully supplied by the utility grid.

4.4 Forecast and business strategy alignment

Adjustment to new business models and the supply chain operational changes that goes hand in hand with the changes in the energy sector will need to be considered. Pollit and Nillesen [19] have examined how the traditional system will need to evolve; it was also noticed by the case study that demand analysis will now need to take on horizontal integration where local generation is matched with local demand nodes. The inherent business capabilities need to be identified as a strategy, and the forecast should be designed to address the business strategic goals and objectives. With a migration towards more uncertainty and the integration of scenario planning for long term strategies, it becomes virtually impossible to make confident decisions. Introducing criteria evaluation techniques such as multi-criteria decision-making analysis can assist decision makers in a business to attempt to model future scenarios quantitatively. This is beyond the scope of this research, and modelling the forecasted scenarios is suggested for further research.

4.5 Design requirements

A base set of framework requirements was deduced from the inputs gathered from the literature and the case study analysis. Next, the concepts were tested with workgroups within the case study environment, Eskom. Furthermore, industry expert views were gathered by conducting semi-structured interviews and focus group discussions. A set of requirements have been identified for the conceptual forecast framework from a deductive approach to literature findings in the research and inductive reasoning from the case study observations and expert views gathered.
Foremost the framework should provide a holistic view of the components needed to design a demand forecast (DR 1). It should further assist in contextualizing global and local influencing factors and policies that can have an impact on the forecast (DR 2). The framework should assist the user to identify all components needed to use as input to an integrated approach for modeling (DR 3). The user or organization should be able to use the framework to identify and sumarise changes in the energy industry (DR4). Furthermore, the framework must allow the user to identify and evaluate qualitative and quantitative data sources to be used as input data to the forecast (DR 5). The framework should provide a set of likely disruptive factors (DR 6) as well as demand drivers (DR 7), that will influence the forecast. For a holistic approach the framework should also include external factors that play a role in the forecast. These can be non-utility factors influencing economic growth, development possibilities, customer preferences, and environmental concerns (DR 8), it should therefore highlight components needed to enable growth and development from the forecast (DR 9). A clear distinction between energy and peak demand influencing factors should be made (DR10), and the framework should ultimately assist in tunneling the components into a probable forecast (DR 11). For final implementation purposes the framework should link forecast outcome with integrated business strategies (DR12) and should be easily interpreted and enable the combining of complex requirements (DR 13).

5. Discussion and conclusion

The key finding from the research included (i) highlighting the importance of an integrated framework to provide a holistic approach in implementing an electricity demand forecast, and (ii) the development of a set of design requirements that any framework that aims to formulate strategic forecast scenarios in line with business strategies and goals for a utility should adhere to. It was found that the success of a forecast depends highly on an integrated system, and the the importance of collaboration and strategic planning as a holistic business approach were eximplified.
The energy environment, the penetration of renewables and the inclusion of these factors into the forecasting methodologies of utility-scale forecasting were outlined. Each component was analysed, and recommendations for future implementation were made to adjust to the changing environment. Deductive reasoning was applied from the literature analysis. An inductive reasoning approach was used to conclude on factors observed from the case study and work environment to compile a set of framework requirements.
The research gap was addressed by providing a combined set of factors to guide an electricity demand forecaster. In addition, the research contributes to the forecasting environment by providing a base for further research, such as developing a conceptual framework to guide the modelling of the identified factors into integrated forecasting models of the future.
The study contributed to practice by providing a fresh insight into integrated components of the evolving power industry and how these can be combined to produce an optimised forecast framework for forecasting electricity demand.

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Value Analysis in Circular Economy: A Systematic Literature Review

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Abstract

In recent years, growing awareness of environmental challenges and the scarcity of natural resources has driven the search for sustainable approaches that can transform the way society produces, consumes, and discards products. In this context, the concept of circular economy has emerged as a promising paradigm, presenting itself as a viable alternative to the traditional linear model of production and consumption. The circular economy aims to minimize waste, extend the lifespan of products, and promote resource regeneration, with the ultimate goal of achieving a more resilient and environmentally responsible system. The essence of the circular economy lies in a shift of perspective, moving from an approach centered on resource extraction and disposal to a mindset that values the reuse, recovery, and recycling of materials. This concept not only applies to the environmental sphere but also carries significant implications for economic and social aspects. Companies are reevaluating their business models, governments are implementing policies that encourage the transition to the circular economy, and consumers are becoming more conscious of the choices they make. However, despite the growing interest and adoption of the circular economy, there is a wide range of approaches, strategies, and practices that have been explored and discussed in the literature. Understanding the various facets of this multifaceted concept is essential for guiding future research, public policies, and business practices. Therefore, a systematic literature review in this field is imperative to synthesize existing knowledge, identify research gaps, and provide valuable insights for decision-makers across various sectors. In this article, we conducted a systematic review of the literature on the circular economy, with the aim of mapping key approaches and trends, assessing the impact across different domains and sectors, and highlighting areas that require further investigation. Through this comprehensive analysis, we seek to contribute to a profound understanding of the circular economy as a catalyst for positive change towards a more sustainable future. In summary, this article offers an overview of existing research on the circular economy, exploring its environmental, economic, and social implications. By synthesizing and critically analyzing the available literature, we hope to provide a valuable resource for researchers, policymakers, and professionals interested in promoting the transition to a more circular and regenerative economic model.

Keywords: *Circular Economy, Socio-environmental accounting, Value Analysis, Systematic Literature Review*

1. Introduction

The productive systems have been following, since the industrial revolution, the linear economy model, which consists of a sequence initiated by resource extraction, followed by production, then commercialization, and ending with the disposal of these products at the end of their useful life (WEETMAN, 2019). According to estimates from the United Nations (UN), the world population reached 8 billion people in November 2022. Considering that, as per UN data, in 1950, this same global population was estimated at 2.5 billion people, the world population has more than tripled in less than a century. As this population increase occurred, there was also a significant growth in product consumption, leading to a major environmental imbalance, given that more natural resources were used and more waste generated. In other words, the linear economic model is reaching its limit, even with greater productivity and technological advancements, as it has degraded over 60% of the planet's ecosystems in the last 50 years, affecting the environment's capacity to replenish natural resources and absorb generated waste (CARVALHO, 2021).

These high rates of resource scarcity and waste generation have prompted action plans to make the planet more sustainable, such as the 2030 Agenda, in which UN member countries created 17 Sustainable Development Goals, with 12 of them directly related to waste management, for instance.

With the expansion of sustainable thinking, the concept of Circular Economy (CE) has gained interest across various economic sectors, as it emerged as a way to operationalize industries to adapt to policies and adopt more sustainable actions (JUGEND et al., 2022).

Activities like recycling and reutilization have been increasingly carried out each day. With this, the concept of CE has been spreading globally to such an extent that for over a decade, CE has been gaining significance with the support of institutions like the Ellen MacArthur Foundation, British Standards Institution (BSI), Circle Economy, Waste and Resources Action Programme (WRAP), among others. They have initiated programs and partnerships with both public and private organizations to accelerate the transition from the linear economy to the circular model (BORSCHIVER et al., 2018).

Despite this gain in terms of representation, there is still resistance from companies and governments regarding the adoption of this circular economic model, and the reason behind this is the doubt about the economic viability of the circular economy. The reverse cycle present in the CE model proves to be quite costly, to the extent that recovered material can even cost more than new material. Besides this high cost, another issue to be addressed is that the processes of recovery and recycling are still not very efficient. In fact, the recycling process is inadequately incentivized, despite its positive externalities.

In light of this context, the following research question arise in relation to the systematic literature review of a value analysis in the circular economy:

What are the recent advancements in research concerning value analysis in circular economy, encompassing both conceptual developments and practical implementations?

This research question aims into the multifaceted aspects of assessing economic value in the context of circular economy practices, considering both theoretical frameworks and practical implementations.

2. Background

2.1. Circular Economy

According to Blomsma and Brennan (2017), the Circular Economy (CE) is an emerging concept that offers an alternative to the linear "take, make, dispose" model, where natural resources are extracted, produced, and discarded. The CE promotes the idea of a waste-resource cycle, where generated waste is reintroduced into the system as production resources. The authors add that CE is an umbrella concept that can accommodate different perspectives on resource production and usage within circular structures, including a global perspective – as seen in Cooper's foundational vision (1994) or EMF's (2015) – to a microeconomic or sectoral perspective, like the CE (2014). In this sense, the current proposal aligns with a sectoral perspective with an applied focus, limited to the management of non-durable consumer goods waste generated by end consumers (excluding production waste) and not inherently considering primary resource extraction. Therefore, it aligns with the CE (2014) model.

The circular framework assumed in this research is supported by Veleva and Bodkin (2018) contribution, which highlights that large corporations and small entrepreneurial initiatives or innovative business models can collaborate to advance the CE. They argue that strategic, technological, and knowledge partnerships between corporations and entrepreneurs play a critical role in cost reduction, time savings, energy efficiency, resource usage, and environmental impact reduction, helping to establish viable business models. The authors also present an analysis of 10 innovative CE business models involving these partnerships. Some of these models focus on post-consumer waste, although they consider specific waste types based on physical-chemical composition, with specialized disposal and collection systems. The current proposal aligns more closely with the public "Waste Management" model from Boston (USA), considering the end consumer as the primary driver of the process, but it acknowledges the technical challenges inherent in a complex mix of waste and regionally varied costs.

Lüdeke-Freund et al. (2018) identify 26 patterns for CE business models in the literature, categorized from four value perspectives: value proposition, value delivery, value capture, and value creation. According to this categorization, the CE framework proposed here, as a Business Model, can be categorized as pattern 6 - "Create value from waste," also containing elements of pattern 12 - "Product recycling/Recycling 2.0." The proposed value analysis can therefore follow the value directions presented by these patterns.

Considering the scope and differentiation of this research, some studies are highly specific regarding CE within post-consumer plastic waste (Dahlbo et al., 2018; Brouwer et al., 2018). The present research does not aim to delve into the technical details of waste recycling but does not a priori restrict the type of solid waste considered.

2.2. Socio-environmental Accounting

In broad terms, the value analysis and information structure of the process, including the identification of value indicators, which form the essence of this proposal, point towards a socio-environmental accounting system. The purpose here is not to delve into the extensive history and broad conceptual formulation of this field (DEEGAN, 2017), nor to discuss various theoretical currents (ROBERTS and WALLACE, 2015). From Socio-environmental Accounting, a fundamental aspect is taken: project feasibility relies not only on economic value but also on considering social and environmental values equally.

Regarding the proposed information system in this research, consisting of a database, processing systems, and a web portal, Dillard (2016) argument is noteworthy. He argues that the success of designing, applying, and evaluating an environmental accounting information system requires the involvement of all stakeholders. In this sense, Manetti and Bellucci (2016) emphasize the importance of using social media to engage stakeholders with social and environmental sustainability reports.

2.3. Value Analysis

According to Osterwalder and Pigneur (2011), creators of the Business Model Canvas (BMC) approach, widely applied in entrepreneurial and innovation projects, a Business Model describes how organizations create, deliver, and capture value. In the BMC approach, the Value Proposition is at the core of constructing the business model.

The practice of Business Analysis (BA) as per the BABOK version 3.0 (IIBA, 2015) innovates compared to the previous version (BABOK version 2.0 – IIBA, 2009) by directing the analysis approach towards identifying value generation. This is based on the principle that a project's success is conditioned by generating value for all stakeholders. Thus, value identification is a central premise of BA and is carried out using techniques such as BMC, Process Analysis, Indicator and Metric Definition, Financial Analysis, among others.

Manninen et al. (2018) emphasize that CE business models should establish value propositions with a focus on environmental value. They present a framework for this with a roadmap for conducting value analysis. While not explicitly addressing CE, Joyce and Paquin (2016) apply the fundamentals of BMC to create sustainable business models, proposing that all elements of the BMC be considered from a triple bottom line perspective and that the canvas be elaborated in three layers: economic, environmental, and social.

3. Methods

In this section, we outline the procedures adopted to conduct the systematic literature review on circular economy. Internationally recognized guidelines were followed, including the recommendations from PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses).

3.1. Research Question Identification

The research question was formulated to encompass the key aspects of the circular economy, addressing both theoretical principles and practical application studies. The guiding question for the review was: " What are the recent advancements in research concerning value analysis in circular economy, encompassing both conceptual developments and practical implementations?"

3.2. Inclusion and Exclusion Criteria

Clear criteria were established for the inclusion and exclusion of studies in the review. Studies published within the last 5 years (from 2019 to 2023) were considered, written in English, and addressing topics related to the circular economy. This encompassed theoretical and empirical studies, case studies, literature reviews, and implementation reports.

3.3. Bibliographic Search

A comprehensive search was conducted in the academic database Web of Science, using keywords related to the circular economy: "circular economy" AND "economic viability", "circular economy" AND "accounting", and "circular economy" AND "value analysis". This search strategy was designed to ensure the inclusion of a broad range of relevant studies.

3.4. Data Extraction and Synthesis

Relevant data were extracted from the selected studies, including information about authors, publication year, study objectives, methodology, key findings, and conclusions. The synthesis of results was carried out through a narrative approach, highlighting key themes and emerging trends in circular economy research.

3.5. Evaluation of Study Quality

The methodological quality of the included studies was assessed using an adapted approach from quality assessment tools specific to different study types, such as scoring scales for empirical studies and evaluation criteria for literature reviews.

3.6. Analysis and Discussion

Based on the synthesis of results and quality assessment, the studies were critically analyzed concerning their contribution to advancing knowledge in the field of circular economy. Research gaps and opportunities for future investigations were identified.

4. Results

For the search strings "circular economy" AND "economic viability," a total of 134 articles were found. For "circular economy" AND "accounting," 467 articles were found. And for "circular economy" AND "value analysis," 8 articles were found.

Filters were applied to the search that resulted in 467 articles, with the first restriction being based on the publication year and language of publication, choosing to restrict it to the years 2019 to 2023 and to the English language. This narrowed down the number of articles to 388. The second restriction was related to the field of study, limited to Environmental Sciences Ecology and Engineering, resulting in 265 articles.

Thus, it was established that the articles included in the analysis are the 134 that are related to the search strings "circular economy" AND "economic viability."

The first piece of information to be inferred from the analysis of the 134 articles is that the number of studies involving circular economy and economic viability is growing. As shown in the graph in Figure 1, there has been an increase in publications on this topic every year since 2016.

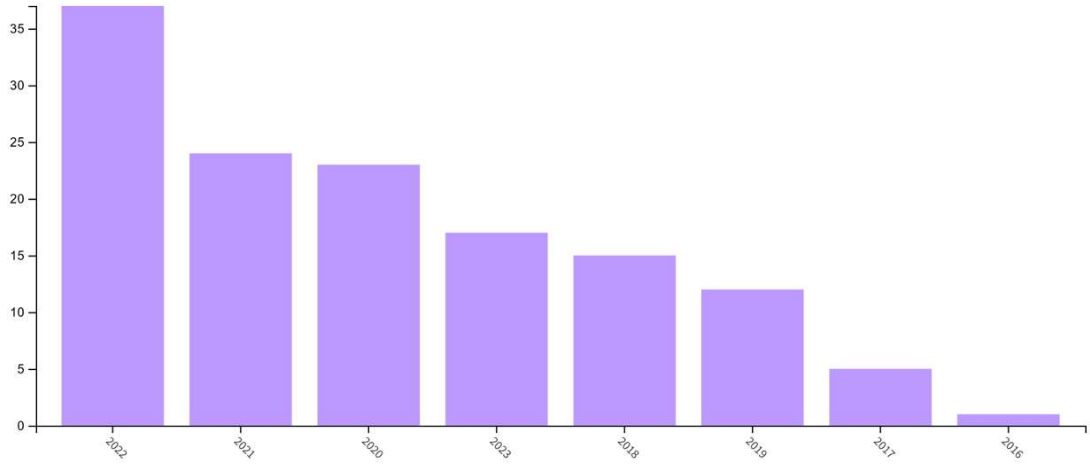

Fig. 1. Graph of the number of articles published per year from 2016 to 2022 on the subject of circular economy and economic viability.

Given that it's a text from a scientific article: As an expanding global topic, various fields explore the economic viability of the circular economy. Therefore, the 134 articles reviewed in this literature survey indicate the top 10 categories of study as follows: Environmental Sciences, Green Sustainable Science Technology, Engineering Environmental, Energy Fuels, Environmental Studies, Chemistry Multidisciplinary, Engineering Chemical, Materials Science Multidisciplinary, Biotechnology Applied Microbiology, Business. As showed in Figure 2:

Fig. 2. Graph illustrating the number of articles per category addressing the theme of circular economy and economic viability.

The context in which current literary studies address the circular economy and the approach to value analysis were also examined to determine the economic viability of transitioning from a linear to a circular economic model. The top 10 most cited articles in this theme were identified, and the results are presented in the Table 1:

Article	Circular Economy context	Value analysis approach
Sheldon (2017)	The transition to a sustainable circular economy is regarded as an essential component of the shift towards greener and more efficient practices, aligned with the principles of green chemistry and sustainability.	The approach to value analysis is related to the consideration of metrics that measure the effectiveness of chemical processes not only in terms of resource efficiency but also taking into account environmental impact and economic viability.
Sheldon (2018)	The context of the circular economy is related to the use of metrics from green chemistry and sustainability to measure the efficiency of processes and products, as well as the transition from a traditional linear economy to a circular economy based on resource efficiency and waste minimization.	The text emphasizes the importance of supplementing mass-based metrics (which reflect resource efficiency) with metrics that assess the environmental impact of waste and economic viability. This can be related to value analysis, as value analysis also involves considering both economic aspects and performance and impact aspects.
Yang et al. (2021)	The context of circular economy is related to the use of metrics from green chemistry and sustainability to measure the efficiency of processes and products, as well as the transition from a traditional linear economy to a circular economy based on resource efficiency and waste minimization.	The value analysis approach in the text is centered around the assessment of the economic viability and sustainability of battery recycling, considering the circular economy, the challenges involved, and the role of different stakeholders.
Di Maria et al. (2018)	The context of circular economy in the text is the pursuit of sustainable solutions in the management of construction and demolition waste, through the analysis of end-of-life scenarios, life cycle assessments, and life cycle cost evaluations. The goal is to increase high-quality recycling and reduce both environmental impact and economic costs.	Although the text doesn't explicitly mention value analysis, it addresses elements that relate to comparative option evaluation, identification of sustainability factors, and the pursuit of economic and environmental efficiency. These are principles often involved in the value analysis approach.
Sanchez et al.		Although not directly mentioning

(2020)	The text discusses the implementation of the circular economy through additive manufacturing, focusing on distributed recycling and sustainable production using recycled materials in 3D printing. It highlights the need for technical development and collaboration to achieve this vision.	"value analysis," the text shares similar principles, such as comparative assessment, process optimization, identifying improvement opportunities, and considering technical, economic, and environmental feasibility.
Nussholz (2018)	The text addresses the need to develop and utilize visualization tools to plan and implement circular business models, emphasizing their importance in extending product lifecycles and creating value through successive use cycles and closed material loops.	The importance of integrated product lifecycle planning and value creation for each usage cycle aligns with the approach of value analysis, which involves assessing how different components and processes contribute to the overall value.
Cristóbal et al. (2018)	The text addresses how the utilization of food waste in biorefineries aligns with the concept of circular economy by transforming waste into valuable resources. It also simultaneously analyzes the economic viability of these processes.	The article addresses elements related to economic feasibility assessment, profitability analysis, and the selection of more efficient and advantageous options, which are characteristics of the value analysis approach.
Antoniou et al. (2019)	The context of circular economy in the text is related to the sustainable and efficient utilization of organic waste through an integrated process.	The text mentions that the produced gas is suitable for generating electricity and improving the economic viability of the anaerobic digestion plant. A value analysis could be used to assess the cost-benefit relationship of this process and identify optimization opportunities.
Li and Chen (2020).	The text discusses how the transformation of agricultural waste into superabsorbent hydrogels for use in agriculture promotes the principles of circular economy by valorizing waste, optimizing resources, and promoting environmental	The article addresses elements that are relevant to a value analysis, such as the comparison of alternatives, cost-benefit evaluation, consideration of economic feasibility, and assessment of environmental

	sustainability.	impact.
Pitkänen et al. (2016)	The text discusses the transition to "green economies" and the exploration of concrete cases in different industrial sectors. The circular economy focuses on maximizing resource efficiency, minimizing waste, and promoting sustainability across various sectors, which can be considered a connection between the article's topic and the Circular Economy (CE).	While the text does not explicitly use the term "value analysis," it contains elements related to the approach of considering costs, benefits, and trade-offs in evaluating green economy initiatives.

Tab. 1. 10 most cited articles about the economic viability of circular economy.

As seen in this table, we have the following contexts of circular economy: Principles and Metrics, Waste Management, Additive Manufacturing, Business Models and Visualization, Food Waste Utilization, Sustainable Utilization of Organic Waste, Agricultural Waste Transformation, Transition to Green Economies.

As for the main approaches to value analysis in circular economy studies, they encompass: Value Analysis Metrics and Sustainability, Integration of Metrics for Sustainability, Economic Viability and Stakeholder Role, Principles of Comparative Evaluation, Alignment with Efficiency and Feasibility, Integrated Lifecycle Planning and Value Creation, Economic Feasibility and Profitability, Cost-Benefit Analysis and Optimization, Balancing Costs, Benefits, and Trade-offs, Evaluation of Green Economy Initiatives.

Conclusion

Considering the research question “What are the recent advancements in research concerning value analysis in circular economy, encompassing both conceptual developments and practical implementations?”, we observed that studies on value analysis in the circular economy have evolved over the past few years, showing a growth in the number of publications, with a notable increase in 2022, which had 37 publications. The most discussed topics, encompassing both conceptual developments and practical implementations, were Value Analysis Metrics and Sustainability, Integration of Metrics for Sustainability, Economic Viability and Stakeholder Role, Principles of Comparative Evaluation, Alignment with Efficiency and Feasibility, Integrated Lifecycle Planning and Value Creation, Economic Feasibility and Profitability, Cost-Benefit Analysis and Optimization, Balancing Costs, Benefits, and Trade-offs, Evaluation of Green Economy Initiatives.

Therefore, the objective of exploring the multifaceted aspects of assessing economic value in the context of circular economy practices, considering both theoretical frameworks and practical implementations, has been fulfilled. And the present study has contributed to a more relevant organization of the literature on topics related to circular economy and its economic viability. A limitation of this study becomes evident, as it only examined the top 10 most cited articles. Future studies are suggested to perform an analysis based on the presented Table 1, encompassing all articles and organizing the literature into clusters.

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