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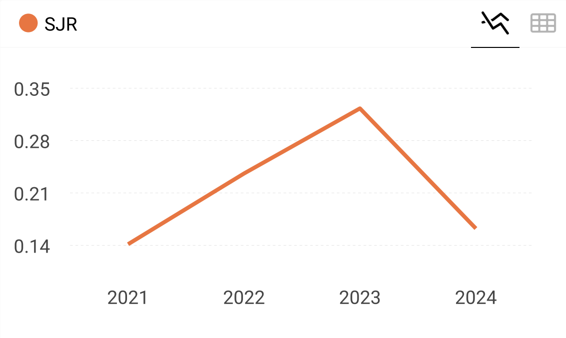

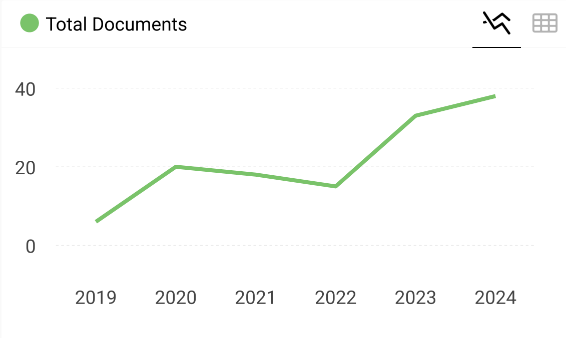

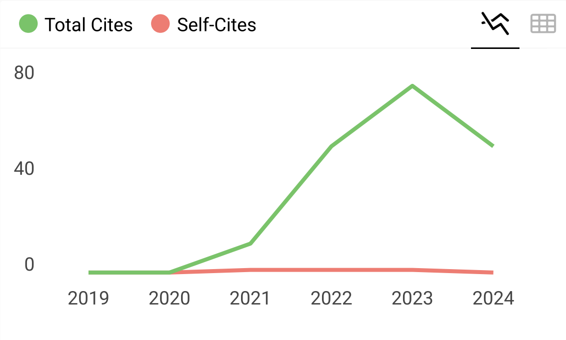

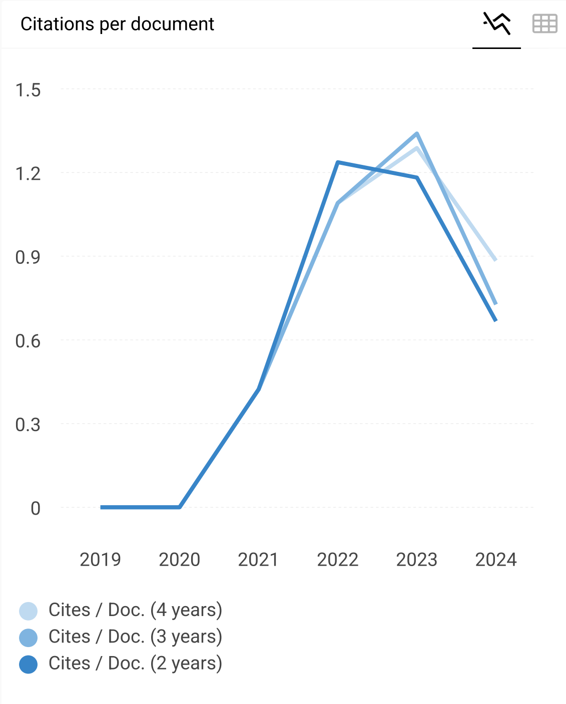

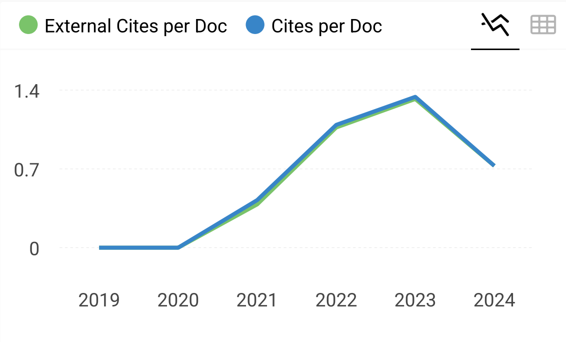

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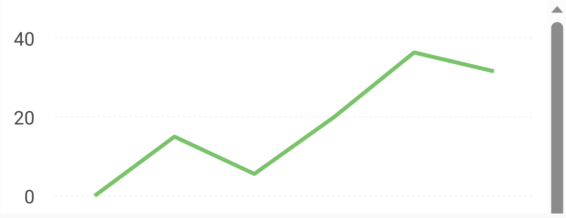

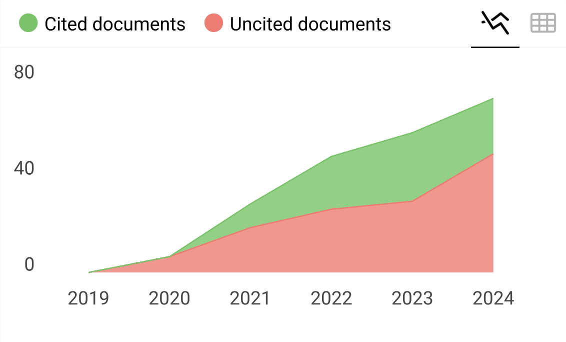

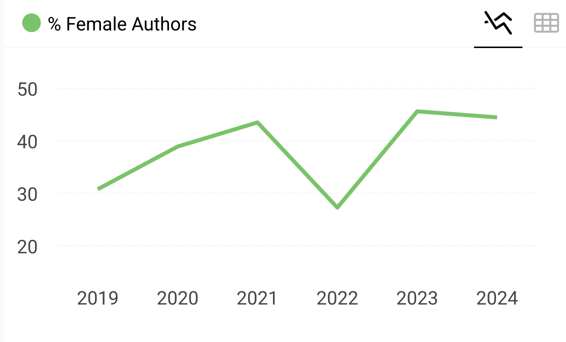

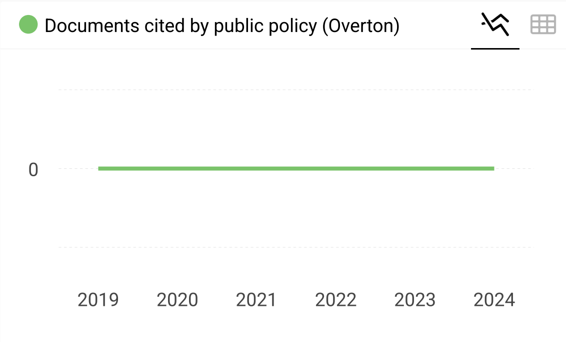

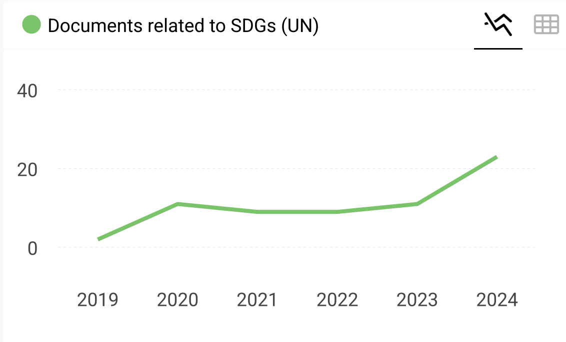

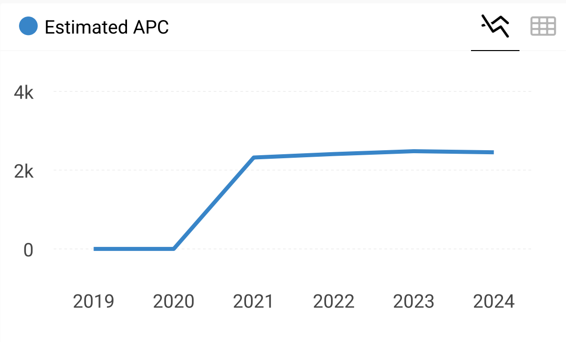

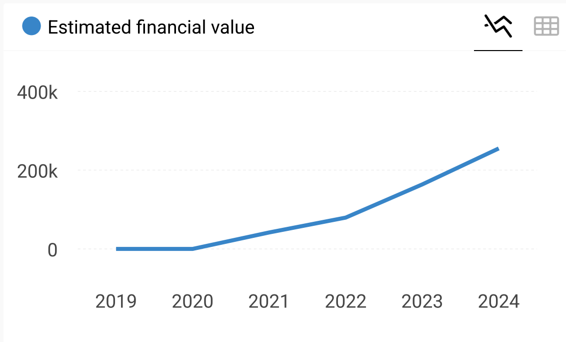

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Unlocking Green Potential in Indonesian Small Medium Enterprises: Challenges and Opportunities for Sustainable Vermicelli Production

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ARTICLE

Unlocking Green Potential in Indonesian Small Medium Enterprises: Challenges and Opportunities for Sustainable Vermicelli Production

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Abstract

Due to limited initiatives and support, the transition to green manufacturing among small and medium enterprises (SMEs) in developing countries remains challenging. Through a critical literature review and case study of the Indonesian vermicelli industry, this study highlights the importance of collaboration and strong policies to address this. Other findings also reveal that the energy intensity and emissions in the sector exceed best practice benchmarks, with the cooking and drying stages contributing significantly to emissions due to high energy consumption. Lack of government regulations, company awareness, and understanding of applicable practices and technologies creates challenges in green manufacturing. The study has utilized a multifaceted approach, including energy efficiency, green technologies, and renewable solutions like hybrid solar dryers. The study helps SMEs in developing countries implement green manufacturing and sustainable practices by providing empirical data and energy-emission benchmarks.

Keywords: Benchmark, Developing countries, Green manufacturing, Initiatives, Small and medium enterprises, Vermicelli

1. Introduction

The manufacturing sector, both small, medium, and large-scale industries, significantly utilizes resources, such as energy, water, and other raw materials for its operational activities (Fu et al., 2020; Liang, 2019; Zheng et al., 2023). It leads to significant greenhouse gas (GHG) emissions emitted globally (Jakob, 2022; Lamb et al., 2021), up to one-fifth of the world's GHGs (Liu et al., 2024). Addressing these issues is paramount, as climate change could lead to various forms of environmental damage, such as waste production, declining water and air quality, and the depletion of natural resources (Bastas, 2021; Fu et al., 2020). Therefore, this sector, including small-medium enterprises (SMEs), should gradually transform from business-as-usual to environmentally friendly practices to avoid adverse environmental consequence (Ghazilla et al., 2015).

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Food and beverage (F&B) manufacturing is a significant emitter within the industrial sector, contributing to global food-system emissions, which total 15.8 $GtCO_2e$ and account for 30 % of worldwide GHGs (Li et al., 2022). In many developing and emerging regions, such as Indonesia, rice is a significant staple, but other staples, such as noodles, are also popular, which is still the second largest noodle consumer in the world (Baral & Shrestha, 2021; Kingwell et al., 2021). In 2022, the total number of instant noodles served in Indonesia reached 14,260 million, the second largest after China, which reached 45,070 million (WINA, 2024). From 2020 to 2027, the global instant noodle market is expected to grow by 14.2 % annually (Kumar et al., 2023). While noodles, such as vermicelli, might seem like simple foods, their production process contributes to GHGs in several ways, mainly due to the large amount of energy used to process and dry them, and often comes from fossil fuels.

Although SME emissions are often insignificant, their contribution to the global economy is significant. In Indonesia, Micro and SMEs contribute 61 % of the GDP, 97 % of the workforce, and approximately 99 % of the business (Indonesia Investments, 2023). Even though their emissions are negligible, their contribution to collective emissions is significant. Therefore, SMEs should assess their environmental performance, especially regarding resource consumption and emissions generated (Baffo et al., 2023; Hertwich, 2021).

Green manufacturing adoption allows a company to analyze or examine environmental performance and identify the steps needed to improve it (Bagchi & Sahu, 2020; Jorge et al., 2022). Unfortunately, scholarly exploration concerning green manufacturing parameters for small and medium-sized vermicelli enterprises in developing areas such as Indonesia remains limited, underscoring a critical knowledge deficit that obstructs the sustainability advancement of SMEs (Alam et al., 2022; Bendig et al., 2023; Vásquez et al., 2024). Prior research, predominantly centered on large industries within developed nations, reveals that adopting green manufacturing may not always produce favorable outcomes and may introduce several challenges (Agyemang et al., 2019; Asmawati et al., 2021).

Therefore, this study investigates and examines green manufacturing practices in SMEs in developing countries to fill this gap. A research that can fill a critical research gap by examining green manufacturing in SMEs, such as in vermicelli production in the Indonesian context. To meet the research objectives, the following research questions were developed:

1. What is vermicelli production's current energy and emission intensity in the SMEs studied?
2. What are the main challenges that hinder the implementation of green manufacturing practices in this sector?
3. What strategies can enhance energy efficiency and reduce emissions to facilitate sustainable production?

The limited studies on green manufacturing practices and their environmental implications in high-consumption markets in developing countries make this study important (Alam et al., 2022; Vásquez et al., 2024). This study on the rice noodle industry will provide a unique perspective and an ideal context to investigate sustainable manufacturing practices in SMEs as they combine traditional production methods with a substantial market presence. This study measures environmental performance and proposes practical and measurable solutions to advance green manufacturing in SMEs. This study can bridge a significant knowledge gap by focusing on SMEs in the context of developing countries, particularly Indonesia. It can also identify opportunities for adopting sustainable practices in the same context.

2. Literature review

Implementing environmentally friendly, sustainable, or green manufacturing can reduce the environmental impact of climate change. This initiative can reduce GHGs, conserve natural resources, increase operational efficiency, and, at the same time, improve the company's reputation (Abdul-Rashid et al., 2017; D'Angelo et al., 2023; Dolge et al., 2021; Kalyar et al., 2020; Liang, 2019; Nti et al., 2022). It also can minimize hazardous materials utilization, embrace eco-innovative technologies, and execute recycling and waste reduction initiatives (Bendig et al., 2023; Kubule & Blumberga, 2019).

Meanwhile, sustainable or green manufacturing practices can be assessed by supervising the intensity and quantity of raw materials, energy, and water consumption and the waste or pollutants produced. The challenges in adopting these practices in SMEs underscore the need for clearly defined policies and supportive systems, particularly in developing and emerging economies. Studies identified that inadequate involvement from personnel or stakeholders, lack of environmental regulations or standards, insufficient financial support and expertise, restricted access to sustainable technologies, and deficient organizational frameworks significantly potentially hamper the adoption

(Goni et al., 2021; Graham et al., 2023; Panjaitan et al., 2023; Taliento et al., 2019).

Xia et al. (2022) found that energy costs and fiscal decentralization substantially determine the possibility of adopting green or sustainable production because businesses must balance financial resources and industrial structures. Additionally, Li et al. (2023) stated that public perception or involvement is necessary to foster adopting green practices. Studies by Alam et al. (2022) and Vásquez et al. (2024) have also identified inhibiting factors that cause low participation of SMEs, especially in developing countries, in adopting green practices. These inhibiting factors include a lack of knowledge and access to environmental resources and technology, a low innovation culture, and a perception of green practices as optional, combined with limited external support and ecological programs.

SMEs prioritize capturing market opportunities over meeting regulatory demands. It is exacerbated by the lack of comprehensive environmental policies and rigorous performance evaluation systems (Chourasiya et al., 2024; Madrid-Guijarro & Duréndez, 2023). Even studies have stated that strengthening environmental awareness and financial support can enhance company motivation and commitment to adopting green manufacturing practices (Farooq et al., 2022; Panjaitan et al., 2023; Thanki & Thakkar, 2020; Thimm & Rasmussen, 2021; Yusr et al., 2020).

3. Method

A mixed methods approach was used to analyze current energy consumption and emission levels associated with rice vermicelli production in SMEs in Indonesia while identifying key challenges faced in implementing environmentally friendly sustainable production practices in developing countries. Furthermore, it seeks to investigate approaches to improve energy efficiency and mitigate emissions by adopting sustainable manufacturing technologies. Addressing these inquiries is crucial for comprehending SMEs' ecological performance and formulating effective strategies to facilitate a shift towards sustainable production methodologies.

3.1. Data collection

The data collection process was performed as follows:

- Primary Data: Operational documentation from manufacturing facilities describing material inputs, energy utilization (including electricity, firewood, and diesel), water consumption, and production outputs was gathered over twelve months (April 2022 to March 2023). This dataset provides comprehensive quantitative insights into the production process's environmental performance.
- Secondary Data: An extensive reviewing scientific journal articles, industry reports, and government publications to gain valuable insights into best practices for moving towards sustainable production techniques. This information is critical to benchmarking company performance by identifying effective carbon management strategies. The data on emission factors, energy intensity, and best practices obtained from this stage serve as benchmarks to assess current operations and guide potential improvements. Integrating these findings ensures a comprehensive and well-supported analysis, with relevant references cited throughout, to maintain transparency and analytical rigor.

This study acknowledges that the dataset collected from the case company is limited from April 2022 to March 2023. However, the dataset could offer initial insights into energy consumption and emissions. Therefore, future research should include broader data and extended periods to improve model robustness and contextual generalization.

3.2. Analytical framework

This study utilizes a green manufacturing assessment framework to assess the case firm's ecological performance and suggest strategies for improvement. The framework consists of three principal elements:

1. Flow material analysis: This stage measures and analyzes the flow of incoming and outgoing materials, including energy, emissions, and products, throughout the production cycle. It will also measure emission intensity (kg CO_2e/kg) and energy intensity (GJ/kg) to pinpoint significant environmental impact areas.
2. Benchmarking: This study attempts to assimilate previous industry benchmarks while applying new benchmarks derived from exemplary practices of companies observed throughout the study. This high-performance scenario is expected to be a reference metric for increasing energy efficiency and reducing emissions in similar settings, especially for the company observed.
3. Scenario Modeling: This approach uses comparative benchmarking rather than a predictive

model. Comparing the case company's energy consumption, emissions intensity, and technologies used with other studies and best (technology) practices identified from previous studies to assess how they align with industry best practices. It could directly highlight potential areas for improvement rather than simulating alternative future scenarios. The limited studies on the carbon footprint of the vermicelli industry make this comparative analysis a valuable reference for understanding performance gaps and identifying feasible efficiency improvements.

This study uniquely focuses on Indonesia's SME vermicelli sector, providing empirical benchmarks for energy and emissions and context-specific strategies for improving green manufacturing practices. This is gained through a robust case study and analytical framework that aligns theory with green manufacturing applications. Future research should expand this approach by incorporating multi-year datasets and sector-specific comparisons to refine green manufacturing benchmarking further.

3.3. Hypothesis

This study developed the following hypotheses to provide a structured analysis in exploring the challenges and critical factors influencing the implementation of sustainable manufacturing practices in SMEs:

1. Higher energy intensity is associated with more significant emissions per production unit.
2. Production processes that adopt energy-efficient technologies lead to lower carbon footprints.
3. Financial and knowledge-based barriers significantly hinder the implementation of sustainable manufacturing practices in the SME sector.

3.4. Company overview

The case company is a medium-sized local company that employs up to 200 employees and produces almost 90,000 kg of vermicelli monthly. The production process consists of several stages, namely, (1) washing and soaking the raw material, (2) filtering and color inspection, (3) drying using a vacuum machine that utilizes waste heat from the wood-burning process during cooking, (4) stirring using a horizontal mixer, (5) filtering continuing using a filtering machine, (6) cooking in an oven at approximately 55 °C, which uses firewood as an energy source, (7) molding with a mopan machine, (8) cutting process using a cutting machine, and (9) packaging. Apart from stoves, all the equipment and machines used use electrical energy. Diesel fuel is used in forklifts, but in early 2023, an electric forklift started to be used. The company still uses semiautomatic mixing and molding machines that require operators to set the time and speed of stirring and manually regulate the speed and thickness of the vermicelli. An oven that consumes fossil energy is unsupported by reasonable temperature control for cooking and drying. Packaging is also semiautomatic; operators must manually organize and insert packaging materials.

4. Results

This chapter presents the energy sources and consumption, emissions generated, and efficiency performance of the case company. This study also integrates secondary data from prior studies or publications, such as emission factors and energy content, to provide a broader perspective on the case company's performance. These sources establish energy intensity and emission, enabling a comparative analysis of the company's environmental performance against best practices within the vermicelli processing sector.

4.1. Material, energy, and production output

The energy sources are electricity, firewood, and diesel oil. The first two are used in primary plant activities, while the last is used for vehicle fuel. From April 2022 to March 2023, the company used 235,589.40 kWh of electricity, 587.50 L of diesel oil, 282,878.00 kg of firewood, and 965,900.00 L of water to produce 772,720.00 kg of vermicelli (Table 1).

4.2. Intensity and emissions

4.2.1. Intensity

The intensity metrics provide a robust picture of the energy and resource demands, highlighting areas with the most significant potential for efficiency improvements. The firewood consumption intensity value is obtained from the amount of firewood consumed divided by the amount of vermicelli product outputs. As shown in Fig. 1, the intensity of firewood consumption has gradually increased over the past year, with an average of 0.336081 kg of firewood/kg of vermicelli product or 0.0054 GJ/kg. The highest firewood consumption intensity occurred in March 2023, with 0.459 kg/kg of vermicelli product or 0.0068 GJ/kg.

Table 1. Energy sources, water, and production output.

Month	Electricity (kWh)	Diesel oil (liter)	Firewood (kg)	Water (liter)	Output (kg)
Apr-22	11,864.16	37.50	16,324.00	55,000.00	44,000.00
May-22	10,884.64	39.80	15,124.00	62,250.00	49,800.00
Jun-22	10,221.55	40.00	14,278.00	49,900.00	39,920.00
Jul-22	12,853.82	43.00	17,421.00	82,150.00	65,720.00
Aug-22	13,792.10	50.00	18,741.00	86,250.00	69,000.00
Sep-22	24,692.03	67.80	22,428.00	92,300.00	73,840.00
Oct-22	22,578.27	53.90	21,687.00	88,100.00	70,480.00
Nov-22	21,649.59	55.40	26,741.00	81,850.00	65,480.00
Dec-22	20,970.77	54.80	25,471.00	71,850.00	57,480.00
Jan-23	25,793.68	61.00	32,471.00	93,750.00	75,000.00
Feb-23	25,926.04	44.30	32,651.00	94,800.00	75,840.00
Mar-23	34,362.75	40.00	39,541.00	107,700.00	86,160.00

(Source: Operational records of the case company, April 2022 to March 2023).

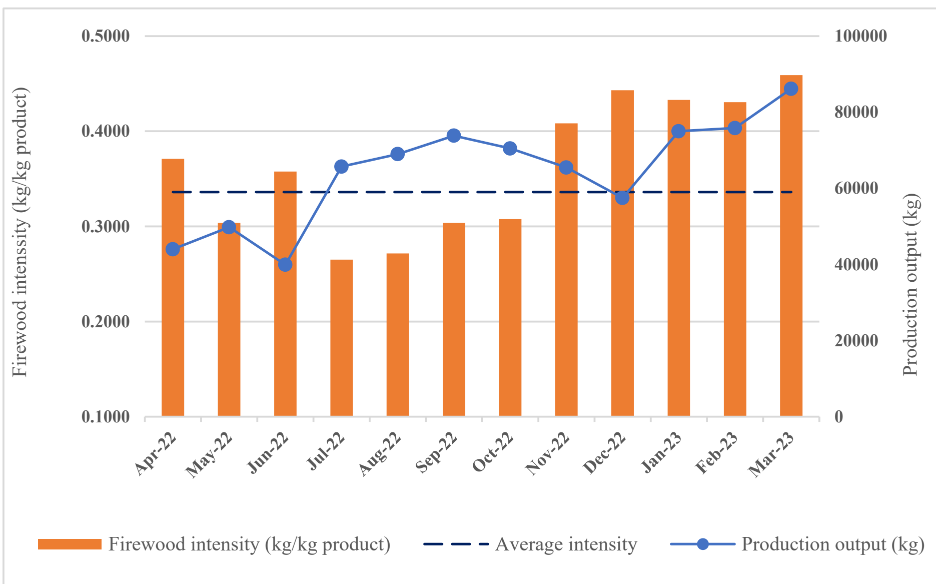

Fig. 1. Firewood consumption intensity vs vermicelli production output (Source: Author's analysis based on company operational records, April 2022–March 2023).

Moreover, the lowest yield, which can be used as a best practice, occurred in July 2022, when 0.265 kg/kg of product was produced. There are a few possible reasons for this increase in firewood consumption intensity. Some types of vermicelli products could influence this process, such as being more firewood-intensive than others, or the production efficiency process could decline. Other factors, such as weather conditions or the condition of the equipment, can affect the intensity of firewood consumption.

Next, the intensity of diesel consumption (for transportation purposes) is also obtained from the amount of diesel consumed divided by the output of the product. Based on Fig. 2, the diesel consumption intensity will be relatively stable over 2022, with an average of 0.00076 L per kilogram of vermicelli product over a year. The highest intensity occurred in June 2022, at 0.001002 ltr/kg product or 0.000037 GJ/kg, while the lowest occurred in March 2023, at 0.00046 ltr/kg or 0.000017 GJ/kg. There are a few potential causes for these results, namely, (1) variation in production output, which could impact the efficiency of transportation, and fuel consumption intensity may decrease when production output is higher; and (2) intensity has decreased periodically since 2023 due to the use of electric forklifts.

The electricity intensity has increased over time, as shown in Fig. 3. In March 2023, the electricity intensity was 0.3988 kWh/kg of vermicelli product or 0.00144 GJ/kg of product, which was 31 % higher than the average or 104 % higher than that in July 2022 (only 0.1956). There are a few possible reasons for this increase, namely, (1) increased production, which would have led to an escalation in electricity consumption, even if the efficiency remained the

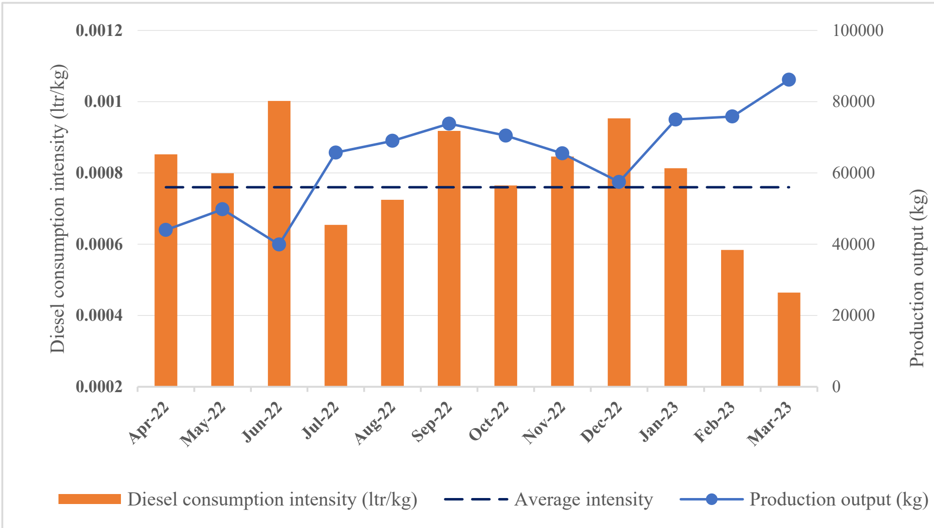

Fig. 2. Diesel fuel consumption intensity vs vermicelli production output (Source: Author's analysis based on company operational records, April 2022–March 2023).

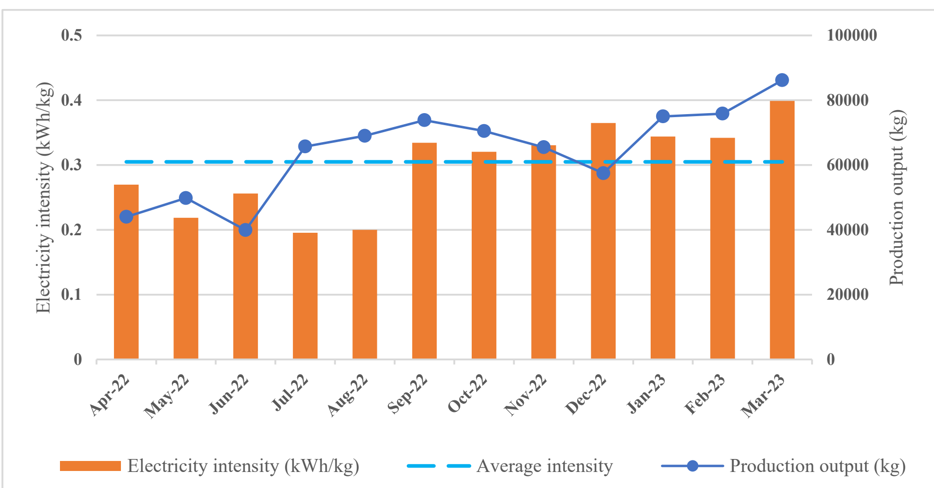

Fig. 3. Electricity intensity vs vermicelli production output (Source: Author's analysis based on company operational records, April 2022–March 2023).

same; (2) decreased efficiency, which would have led to a surge in electricity usage for a similar level of production; or (3) product change, such as utilization of electric forklift which would have led to an increase in electricity consumption.

In addition, water consumption per kg of product is relatively stable, ranging from 1.25 to 1.32 L, and the average is 1.28 ltr. Sasongko et al. (2021) reported that making 1 kg of vermicelli could take approximately 1.25 L of water. Irreversible circumstances, such as raw materials (rice flour and shogun) and production procedures (dry or wet vermicelli), determine water usage during production.

The practical way to set a best practice available for green manufacturing is based on the lowest intensity value achieved. In this case, the best condition ever achieved by the case study company was when the intensity of use of firewood, diesel, electricity, and water was 0.265 kg/kg product, 0.00046 ltr/kg product, 0.1956 kWh/kg product, or 1.28 ltr/kg product, respectively. Thus, to improve its current performance, a company needs to examine potential measures or innovations that can increase the efficiency of equipment or processes, especially for the drying and cooking stages, which consume much nonrenewable energy, such as electricity and firewood.

4.2.2. Emissions

The energy content (GJ/unit) represents the energy content of each emission source in gigajoules per unit. The emission factor (kg CO_2e/GJ) indicates the amount of GHGs emitted per unit of energy consumed. The unit is kilograms of carbon dioxide equivalent per gigajoule from each emission source. Total emission (kg CO_2e) represents the total sum of GHGs obtained from all calculated emission sources, while emission intensity (kg CO_2e/kg) is obtained by dividing the total GHGs by the weight of vermicelli produced. The energy content and emission factors were obtained from established methodologies and previous studies (Adicita et al., 2021; Irzon, 2012; Joint Credit Mechanism, 2018; Perindustrian, 2014; Kurvits et al., 2020).

Table 2 shows that the emissions from Scope One (direct emissions) total 484,877.51 kg CO_2e. The primary source is the combustion of firewood, which results in 482,363.56 kg of CO_2e emissions. Scope 1 accounts for 99.5% of the total emissions from Scope 1, or 70% of the total GHGs emitted. Emissions from Scope Two (indirect emissions from electricity use) are 3,040.37 kg CO_2e, or approximately 29.5 % of the total GHGs. The annual emission intensity equals 0.89 kg CO_2e/kg of vermicelli, consisting of direct emissions with 0.627 kg CO_2e/kg and indirect emissions with 0.263 kg CO_2e/kg.

Furthermore, referring to best practices during the observation period, the lowest energy consumption intensity achieved by the company showed that firewood reached 0.265 kg/kg of rice noodles in July 2022, diesel fuel of 0.00046 L/kg of product in March 2023, electricity of 0.1956 kWh/kg in July 2022, and water of 1.25 L/kg. Using these values, the emission intensity (Scope One and Two) could reach 0.66 kg CO_2e/kg of vermicelli, around 26 % lower than the current status (0.89 kg CO_2e/kg product).

Meanwhile, the company's average annual electricity intensity was recorded at 0.305 kWh/kg, 20–40 % higher than previous research in Italy, with values between 0.187 and 0.255 kWh/kg of product. The emission intensity, especially in Scope Two, tends to be higher than in Italy's noodle industry. Therefore, the company should maintain operations at the best efficiency levels achieved while considering the transition to renewable or more environmentally friendly energy sources. In addition, increasing energy efficiency by applying the latest technology is also a strategic step to reducing carbon footprints sustainably.

Therefore, it is necessary to perform a comparative analysis of emission intensities using industry best practices to assist businesses in finding ways to utilize the best available or greener technology. It can minimize their environmental impact and achieve sustainability. A comparative analysis of emission intensity against industry best practices can reveal substantial prospects for adopting cleaner technologies. Furthermore, there is a significant correlation between energy intensity and emissions. This indicates that increased energy consumption is directly related to increased carbon output. This condition is in line with the first hypothesis in this study, which states that there is a direct relationship between increased energy use and higher emissions per unit of production.

5. Discussion

5.1. Finding

This study has identified significant barriers to green manufacturing practices, such as a lack of government oversight, low corporate awareness, and limited knowledge of relevant practices and technologies. Addressing these barriers is critical, as climate change could trigger a multitude of environmental challenges, including flooding, waste proliferation, air, water, and resource degradation or depletion (Bastas, 2021; Fu et al., 2020), with the intensification of flooding risks emphasized in Zeng

Table 2. Emission.

Source	Amount	Energy content (GJ/unit)	Emission factor (kg CO_2e/GJ)			Total emissions (kg CO_2e)	Emission intensity (kg CO_2e/kg product)
			CO_2	CH_4	N_2O		
Direct (Scope One) emissions							
Firewood (kg)	282,878.00	0.0147[a]	112[c]	3	1	482,363.56	0.620
Diesel fuel (ltr)	587.50	44.12[b]	74[d]	3	1	2021.80	0.003
Water (m^3)	965.00	–	0.51[d]	–	–	492.15	$0.63.10^{-3}$
Indirect (Scope Two) emissions							
Electricity (kWh)	235,589.40	0.0036	239.4[e]	–	–	203,040.37	0.263

Note:
Source: Case company operational records (April 2022 to March 2023).
[a] (Kurvits et al., 2020).
[b] (Irzon, 2012).
[c] (Perindustrian, 2014).
[d] (Adicita et al., 2021).
[e] (Joint Credit Mechanism, 2018).

et al. (2024)examination of sponge cities as a feasible strategy for promoting circularity and mitigating the effects of climate change.

The subject company's annual emission intensity was 0.89 kg CO_2e/kg. This value significantly exceeds the practical threshold of 0.66 kg CO_2e/kg when referring to the best practices that the company has experienced during the study. This difference mainly arises from the significant energy expenditure during the cooking and drying phases, representing more than 70 % of the total GHGs (Scope One). Emissions associated with electricity use (Scope Two) reached 29.5 %. These results are consistent with studies that advocate the implementation of emission mitigation strategies that target processes characterized by high thermal energy consumption (Szymańska & Mroczek, 2023; Wang et al., 2017).

Furthermore, to determine the best practices to be achieved, it should be implemented simultaneously by setting performance indicators based on the lowest intensity value achieved. However, the absence of benchmarking standards for the vermicelli industry has also hampered firms' ability to measure or compare their performance to others (Trujillo-Gallego et al., 2021; Zeng et al., 2020). The Indonesian Government has issued a benchmark table for average energy intensity in the F&B industry. It only focuses on the instant noodle industry, whose market dominates all types of noodle products and is owned by large players but has not yet explicitly addressed vermicelli.

Several studies have analyzed energy intensity and emissions from noodle production (Table 3), but establishing and achieving desired manufacturing performance standards remains challenging. The indicators shown may not be suitable for direct benchmarking due to differences in characteristics, such as geographical location and size; at least, they could provide an initial indication of the performance. Table 3 shows the energy indicator usage from several studies on noodle production. China's large noodle industry, leveraging advanced clean technology, The large noodle industry in China, supported by advanced or clean technology, achieves significantly lower energy consumption at 0.001 GJ/kg or 0.04 kg coal/kg noodles, five times less than the case study company. These differences are influenced by several important factors, such as the type and quality of the raw materials and the best available technology used (Baral & Shrestha, 2021; Abdi et al., 2021; Panjaitan et al., 2021).

The study also emphasizes the substantial opportunity for improvement in energy efficiency. A list of some of the best available technologies, such as hybrid solar dryers, hot-air drying, and ohmic heating technologies, are needed to improve energy efficiency and reduce GHGs for the noodle industry, as shown in Table 4. Studies also highlighted the importance of integrating advanced technologies and establishing comprehensive environmental performance metrics (Liu et al., 2021; Suherman et al., 2020). For example, the case company still uses semiautomatic machines without long tunnel dryers or vertical mixers, which causes the emission intensity to remain high. Utilizing electric forklifts has reduced diesel fuel consumption, but not strategically, because diesel fuel use only contributes to around 0.3 % of total emissions.

Furthermore, secondary data analysis from previous studies and literature shows that SMEs often face significant challenges in adopting sustainable manufacturing practices due to limited capital and no access to financial incentives or subsidies. A lack of technical knowledge and regulatory constraints compounds this. SMEs are also less aware of green manufacturing practices and their long-term benefits, leading to reluctance to adopt environmentally friendly solutions. This condition results in them prioritizing cost efficiency over environmental considerations. Targeted interventions, such as capacity-building programs, financial incentives, and policy reforms, are needed to facilitate the transition to sustainable production.

Table 3. International comparisons of production indicators.

Location	Product	Electricity intensity (kWh/kg product)	Energy intensity (GJ/kg product)	Source
Case study company	Vermicelli	0.305	0.0054	–
Italy	Dry pasta	0.255	0.0075	Brunetti et al. (2015)
	Fresh pasta	0.187	0.0037	
Nepal	Instant noodle	n/a	0.0017	(Baral & Shrestha, 2021)
China	Noodle	n/a	0.0007–0.0010	Wang et al. (2017)
Ethiopia	Pasta & Macaroni	1.305	0.0055	Abdi et al. (2021)
Sweden	Pasta	n/a	0.0024	Carlsson-Kanyama and Faist (2000)

Table 4. Available innovation techniques and best technologies for the noodle industry.

No.	Abatement measure	Superiority/abatement/value during scenario	Source
1.	Modified new (long tunnel) dryer (MND)	The daily production of noodles, energy efficiency, and specific heat consumption have increased by 22.8 % and 10 %, respectively, and decreased by 18 %.	Wang et al. (2017)
2.	Hot-air-drying (HAD)	Higher production efficiency and product quality compared to natural air drying (NAD).	Xiang et al. (2018)
3.	Ohmic heating	Instant noodles can be rapidly cooked with good textural qualities and energy efficiency.	Jo and Park (2019)
4.	Ultrasonic vibration for 15 min	Conducive to the quick improvement of production efficiency and quality of control noodles.	Li et al. (2020)
5.	Hybrid solar dryer	It is quicker than natural sunlight and open-sun drying. It increases dryer efficiency, energy utilization ratio and exergy from 13.02 to 17.02 %, 0.18 to 0.32, and 67.4−83.6 %, respectively.	Suherman et al. (2020)
6.	Laser puncturing combined with a mixture of leavening agents	Noodle drying time can be reduced by up to 34.15 % and energy consumption by up to 33.17 %.	Liu et al. (2021)
7.	• Vertical mixer (low-scale production), Horizontal (large-scale)	Competitive manufacturing cost and operating efficiency.	Obadi et al. (2022)
	• Continuous high-speed mixers	Shorter mixing time and improved product quality.	
	• Water addition	The optimal water content of white noodles depends on the wheat cultivar. Soft and mixed cultivars require 35 % water, while hard cultivars require 36 %.	
	• Water temperature	Adjust the temperature to ±50 °C to achieve the final dough temperature of 25−30 °C to avoid excessive heat and reduce low-tensile, stretchy noodles.	
8.	Natural convection greenhouse dryer (NCGHD)	Greater simplicity and performance and low financial and energy requirements.	Kumar et al. (2023)

Therefore, the findings show a direct correlation between energy intensity and emission levels; the higher the energy consumption, the more likely it is to increase carbon emissions significantly. This correlation aligns with the hypothesis that the higher the energy intensity or energy use per production unit, the higher the environmental footprint.

5.2. Comparative benchmarking

The findings obtained from this study disclose that the case company's energy consumption and emissions intensity are comparatively elevated to recognized industry best practices. A comparative benchmarking strategy was utilized to elucidate these results further, wherein the company's operational performance was assessed against data derived from previous research and established industry standards. This scenario modeling technique does not engage in predictive simulations but instead functions as a direct comparative analysis to identify potential areas for enhancement.

Furthermore, this study determines the best practices in the company based on the minimum intensity ever achieved, where the best firewood intensity was found in July 2022 at 0.265 kg/kg of vermicelli, followed by diesel and electricity were 0.00046 ltr/kg in March 2023 and 0.1956 kWh/kg in July 2022, respectively. Should the company consistently operate at these efficiency benchmarks, its overall emission intensity (Scope One and Two) could be diminished by 26 % from the current observed annual mean. The subsequent comparative analysis is to align its energy consumption practices with the achievements of similar industries from previous studies. Through secondary data information, it was found that the electricity intensity of the companies studied was still 20−40 % higher than similar studies in Italy (Brunetti et al., 2015).

In addition, other studies related to available technologies show that implementing hybrid solar dryers and optimized drying processes can significantly reduce companies' dependence on firewood, which is a major contributor to Scope One emissions. This comparison illustrates the potential for increased efficiency and is in line with previous studies that highlight the role of green manufacturing in reducing emissions (Abdi et al., 2021; Panjaitan et al., 2021). Thus, SMEs that adopt energy-efficient technologies can achieve a lower carbon footprint. This is in line with one of the hypotheses in this study, which states that adopting sustainable technologies can significantly reduce emissions and improve environmental performance.

Due to the limited availability of carbon footprint assessments in the vermicelli sector, these benchmarking approaches are a critical reference for pinpointing efficiency deficits and potential avenues for enhancement. Although the company's energy consumption may be affected by production capacity, machine configurations, and operational methodologies, the benchmarking findings underscore the necessity of sustaining peak efficiency levels and adopting cleaner energy alternatives to mitigate emissions. By capitalizing on best practices both internally (through the lowest documented intensities) and externally (from comparative analyses), the company can strive towards a sustainable production paradigm that curtails its ecological footprint.

At the ned, this benchmarking-centric scenario modeling elucidates realistic and attainable sustainability advancements, emphasizing the imperative for ongoing efficiency assessment and a transition towards renewable or low-emission energy sources. The subsequent section delves into managerial tactics SMEs can employ to implement these enhancements effectively.

5.3. Managerial implications and barriers

Fig. 4 depicts an infographic encapsulating the obstacles and prospects for SME producers in developing nations concerning adopting environmentally friendly practices. The infographic underscored elevated or inefficient energy consumption and the lack of environmental regulations or standards pertinent to the sector studied. A factory emitting green smoke figure (middle section of the infographic) symbolizes green manufacturing or production. On the left side, figures represented barriers such as limited knowledge and cost concerns, and the opposite side figures suggested stakeholders' collaboration to enhance energy efficiency and embrace sustainable practices.

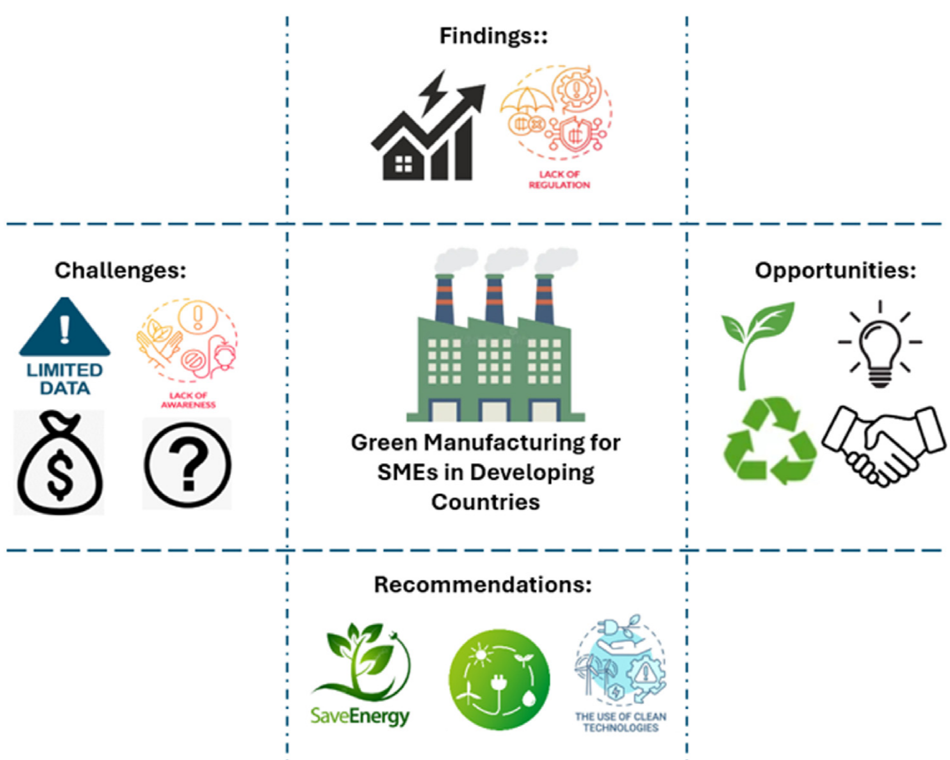

Fig. 4. A multifaceted approach toward green Vermicelli SMEs in a developing country context.

This study presents actionable guidance to boost green manufacturing within SMEs through a comprehensive approach by effectively addressing identified challenges for the transition to sustainable practices. The best available energy-efficient technologies, including hybrid solar dryers and high-performance motors, are required to curtail energy usage and GHG emissions and enhance production efficacy. Besides that, enforcing resource optimization initiatives, such as encompassing water recycling systems and waste minimization, can lessen resource consumption and ecological impact while enabling cost reductions. SMEs should assess their environmental performance, focusing on critical metrics such as energy intensity, emissions, and resource utilization (Larsen, 2022; Yassin et al., 2022). It can be a basis for formulating a phased strategy for businesses to adopt sustainable practices.

Additionally, the study shows that policymakers must develop standards for the green industry tailored to the particular sector and supplemented by financial incentives to promote investments in eco-friendly technologies (Panjaitan et al., 2023). Studies also highlight that globally, SMEs will face financial, knowledge-based, and regulatory constraints, which limit their ability to transition to greene manufacturing practices (Meath et al., 2016; Panjaitan et al., 2023; Yunikewaty & Siswahyudi, 2023). This hypothesis corresponds with the hypothesis that stated economic and informational barriers significantly hinder the adoption of green manufacturing, particularly in the SME sector. Thus, stakeholder partnership is critical for addressing knowledge gaps through advanced training initiatives and promoting sustainable methodologies (Farooq et al., 2022; Govindan & Hasanagic, 2018). This partnership could foster access to advanced technologies and scale sustainable or green practices across SMEs in the food processing sector.

Furthermore, economic variables, including energy costs and the decentralization of fiscal authority, are also pivotal in influencing the integration of sustainable initiatives. Shan et al. (2021) demonstrated that fiscal strategies could catalyze carbon mitigation initiatives. Integrating these strategies with (best) available technological innovations can form a holistic framework for achieving sustainability in MSMEs. Aligned with the United Nations' Sustainable Development Goals (UN SDGs) and ESG, and considering local challenges such as regulation and infrastructure, SMEs can be key contributors to environmental and economic sustainability.

Finally, this study can promote sustainable production for SMEs in similar sectors in developing countries. The role of government and stakeholders in establishing benchmark policies for the food processing sector that allow for consistent regional and industry comparisons to encourage environmentally friendly practices is greatly needed. Future research should examine the generalizability of these results across industries.

6. Conclusion

This study has identified a significant research gap in measuring environmental performance to drive cleaner production, particularly in the small-to-medium rice noodle industry sector in a developing country context. Previous studies have concentrated on large- and medium-scale noodle industries in developed countries. This underscores the need for tailored solutions that take into account the operational nuances of SMEs in developing countries like Indonesia to make green manufacturing a viable and profitable option for them.

The study found that the case study company's practices have not demonstrated commendable efforts or fall short in green manufacturing efforts. The company uses firewood and diesel fuel as its primary energy sources, followed by high-intensity electricity usage, especially during drying and cooking. The energy intensity is 0.04 GJ/kg vermicelli, and the emission intensity is 0.89 kg CO_2e/kg vermicelli. The predominant emissions are direct (Scope One) at around 70.5 %, while indirect emissions from electricity consumption (Scope Two) account for 29.5 %.

Therefore, a multifaceted strategy is developed to overcome emission sources, especially in activities that require thermal energy. First, adopting the advanced technologies in cooking and drying processes that are energy (thermal)-efficient, such as ohmic heating and modified new (long tunnel) dryers, hot-air drying, hybrid solar dryers, and natural convection greenhouse dryers. Second, utilizing advanced technologies that curtail electricity consumption, such as laser puncturing combined with a mixture of leavening agents and vertical and continuous high-speed mixers, should be adopted. Policymakers may utilize the findings from this investigation to formulate targeted strategies that facilitate the implementation of sustainable manufacturing practices. This may encompass financial subsidies for pioneering technologies, tax breaks, and capacity-enhancement initiatives intended to improve the operational proficiency of SMEs. Although this research primarily addresses the technological and operational aspects, subsequent studies should investigate the influence of economic variables, such as energy tariffs and taxation policies, on sustainability practices.

Future inquiries should also evaluate the potential for scaling the suggested sustainable manufacturing practices across diverse food processing industries and geographical locales. Such research can be pivotal in broader sustainability endeavors, particularly in developing countries where varied environmental and economic contexts necessitate tailored solutions. Collaborative initiatives involving partnerships between the public and private sectors and international organizations are critical to assisting SMEs by offering technical support and promoting knowledge dissemination. This can establish a strong framework for advancing sustainability in SMEs. Finally, to improve the generalizability of its conclusions, future research should integrate multi-year datasets and more expansive analytical frameworks. Such an approach would consider temporal and regional variations, facilitating more thorough and broadly applicable findings. These efforts would enhance the relevance and efficacy of green manufacturing strategies across various industries and regions.

Finally, this study provides empirical evidence supporting the research hypotheses, demonstrating that higher energy intensity results in more significant emissions, green or best available technology adoption leads to emission reductions, and financial and knowledge-based barriers hinder sustainability transitions. These findings answer the research questions by providing insights into energy consumption, sustainability challenges, and potential technological improvements in vermicelli production SMEs.

Ethical information

None.

Data availability

The data are available upon request to the authors.

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Conflict of interest

The authors declare no conflicts of interest.

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