ECO-EFFICIENCY AND ENVIRONMENTAL IMPACT MEASUREMENT OF FLOUR-BASED PROCESSED CHICKEN PRODUCTION AT MSMEs IN JOMBOR, SUKOHARJO, INDONESIA.

Abstract:

Growth of Flour-based chicken processing MSMEs in Jombor, Sukoharjo, Indonesia make a significant contribution to the local economy. However, these activities have the potential to increase energy consumption, raw material use, transportation, the use of single-use packaging, and waste generation, all of which impact the environment. This study aims to evaluate the environmental impacts and eco-efficiency levels of flour-based chicken processing SMEs in Jombor, Sukoharjo, Indonesia. This study use the Life Cycle Assessment (LCA) method using a cradle-to-grave approach, as well as the ReCiPe 2016 method, utilizing SimaPro 9.5 software. The analysis covered the stages of raw material procurement, transportation, production, and packaging. Eco-efficiency evaluation was conducted by integrating economic and environmental indicators through Net Present Value (NPV), Eco-Efficiency Index (EEI), Environmental Value Ratio (EVR), and Eco-Efficiency Ratio (EER). The research results indicate that the production stage is the primary environmental critical point that significantly contributes to the categories of global warming, ozone formation, terrestrial acidification, and water consumption due to the use of electricity, LPG, and the direct disposal of raw material waste into the soil. At the packaging stage, one MSME contributes up to approximately 75% to several environmental impact categories due to the use of plastic-based packaging. The eco-efficiency evaluation results indicate that all MSMEfall into the affordable and sustainable category, with EEI values ranging from 2,14 to 2,89 and EER values of 88–99%. MSMEB demonstrated the best eco-efficiency performance with an EEI of 2,89; an EVR of 0,01; and an EER of 99%.

Key words:-
carbon footprint, eco-efficiency, life cycle assessment,

Introduction:-

Jombor Village, Sukoharjo, Indonesia, is a bustling and strategically located area due to its proximity to the Sukoharjo Regency Government, educational institutions, and densely populated residential areas. These conditions create significant economic opportunities for the local community, particularly for MSME owners in the food sector. MSMEs in the food sector contribute 3.94% to the Regional Gross Domestic Product (RGDP) of Sukoharjo Regency, Indonesia (Mahambari, 2024).The food sector SMEs that dominate in Jombor Village, Sukoharjo, Indonesia, are those producing flour-based chicken products. Currently, there are 37 food processing SMEs producing flour-based chicken products. The products include Kentucky-style fried chicken, fried geprek, and grilled geprek.

Production capacity at 37 SMEs in Jombor, Sukoharjo, Indonesia continues to rise in line with high demand in the region. Consumers are predominantly students, employees of institutions operating in the Jombor area, and the local community. This high production volume is directly proportional to increased energy consumption (Meidani and Maryam, 2014) and waste volume (Gholizadeh, 2020).Electricity is used continuously during production activities, such as for freezers, rice cookers, blenders, and fans. The process of frying chicken using gas stoves also contributes to increased carbon emissions (Ali *et al.*, 2024).Previous research indicates that the use of gas stoves can produce 2.98 kg of CO_2 per kg of LPG (Fitri, Putri and Retnawaty, 2020).

Another impact arises during the raw material procurement stage. MSME operators use gasoline-powered vehicles to collect raw materials. MSME operators collect raw materials at Sukoharjo Market, with an average fuel consumption of 0.43 liters per day. Carbon emissions from 1 liter of fuel are equivalent to 2.4 kg of CO_2 (PT PLN Persero, 2024; Saravanakumar and Arunprasad, 2024; Rievaj, Mokrickova and Rievaj, 2016). Thus, a single trip to procure raw materials contributes to the production of 1.032 kg of CO_2. Transportation contributes significantly to the overall carbon footprint of food products (Striebig, Smitts and Morton, 2019; Zhang, 2023).

Electricity consumption, gas usage, and transportation activities at flour-based chicken processing MSMEs operating in Jombor Village generate a significant carbon footprint. All MSMEs operate daily with an average production capacity of 13 kg/day. This high production capacity also contributes to increased (Raj *et al.*, 2025). The waste generated includes 33 kg of dry flour per week, 7 kg of wet flour per week, 25 liters of used cooking oil per week, and wastewater from washing chickens and kitchen equipment

There are two types of flour waste: dry and wet flour waste (Asmoro, 2021).Improper disposal of flour waste can lead to significant greenhouse gas emissions, such as methane (CH_4) and carbon dioxide (CO_2) (Irozi *et al.*, 2022). CH4 has a global warming potential 21–36 times greater than that of CO_2 (Izhar and Xuan, 2021; Siltumens *et al.*, 2023; Alam *et al.*, 2022). Pembuangan The disposal of used cooking oil also causes water contamination, clogging of sewage systems, and soil degradation(Shevchenko *et al.*, 2023), as well as posing health risks if reused (Azmi *et al.*, 2023). Additionally, there is plastic packaging and paper waste from cooking oil because the sales system for flour-based processed chicken MSMEs in Jombor Village predominantly uses a takeout model. Plastic packaging waste has a significant impact on soil and water pollution and harms flora and fauna. Plastic pollutes the biological environment 63% more than paper (Vargas, Mogollón and Rosa Patricia Larios-Francia, 2022).

Food waste is an issue that must be addressed because it relates to food safety and hygiene, as well as environmental sustainability (Walia and Sanders, 2019). If not properly managed, food waste can have economic and social impacts, as well as place undue pressure on natural resources and the environment (Chirsanova and Calcatiniuc, 2021). The food industry plays a crucial role in producing food that is safe for consumers. According to ISO 22000, businesses must ensure the safety and quality of food ingredients all the way through to the finished product (Balashov *et al.*, 2024).Food safety must be addressed from the procurement and production processes (Lestari, Prasetyo and Hartanti, 2023; Pratama, Hartanti and Prasetyo, 2024)through to distribution (Sharif *et al.*, 2024). Material handling, energy use (Nagy and Szabolcs, 2024), and sanitation (Li, 2024)are crucial elements in the food industry (Corigliano and Algieri, 2024).

Statement of the Problem:-

The background of this study is environmental management in flour-based chicken processing MSMEs, which tend to overlook the measurement of overall environmental impacts. MSME operators focus solely on the production stage without considering the entire product life cycle, from raw material procurement and processing to energy use and waste management. This situation leads to potential resource waste and increased carbon emissions (Braun and Rothbart, 2025).

Objectives of the Study:-

This study aims to conduct an environmental impact analysis of all activities carried out by flour-based MSMEs in Jombor. The problem-solving approach in this study employs the Life Cycle Assessment (LCA) method as a tool to identify and measure the environmental impacts of energy use and all operational activities. Life Cycle Assessment (LCA) is highly effective for making quantitative assessments of environmental aspects and the potential impacts generated dihasilkan(Aviso, 2024; Firmansyah, 2018).The results of identifying and measuring environmental impacts through the Life Cycle Assessment (LCA) approach can serve as the basis for formulating more environmentally friendly and sustainable supply chain management strategies for flour-based chicken processing SMEs.

The food industry is currently required to prioritize waste management, compliance with hygiene standards (Muhammad, Zaman and Ariyantoro, 2023),and cost efficiency (Vaez-Ghasemi, Moghaddas and Saen, 2022;Adewale *et al.*, 2024). This is stipulated in Ministry of Industry Regulation No. 39 of 2022 on Green Industry Standards for the Food Industry, which mandates that food processing be conducted in an environmentally friendly and sustainable manner. This regulation is reinforced by Presidential Regulation No. 59 of 2017 on the Achievement of Sustainable Development Goals (SDGs), which encourages Small and Medium Enterprises to contribute to sustainability and environmental management. The demand for an environmentally friendly and sustainable industry aims to reduce carbon emissions (Ramalingam *et al.*, 2025).

The adoption of environmentally unfriendly industrial practices can accelerate environmental degradation and increase operational costs due to resource waste (Espinoza-Castro, Lara-Ramírez and Buele, 2024;Bulan and Anis, 2021). Non-compliance with green industry regulations can lead to difficulties in marketing products, reduced competitiveness (Agarwal *et al.*, 2025; Shi, Xiong and Bu, 2022), and diminished consumer trust among those increasingly concerned about sustainability (Oppong and Bannor, 2022).

Study Gaps:-

Previous studies have been conducted on the measurement of eco-efficiency and environmental impact. A review of these studies indicates that no research has yet analyzed the environmental impact using a comprehensive Life Cycle Assessment, covering the entire process from raw material procurement to packagingin flour-based chicken processing MSMEs. Most research has been conducted on large companies and formal manufacturing industries, such as the palm oil industry (Maisarah and Dian, 2024), the production process of ZA II fertilizer(Dwi and Mirwan, 2023), and the production process of white crystal sugar in Bondowoso(Brilliantina *et al.*, 2023). However, SMEs also contribute to waste generation and carbon emissions, particularly as the number of businesses and production intensity continue to rise, as is currently the case in the flour-based chicken processing industry in Jombor Village. The novelty of this study lies in providing empirical data on environmental impacts based on Life Cycle Assessment (LCA) for flour-based chicken processing SMEs. The results of this study are expected to serve as a basis for decision-making in formulating sustainable environmental management strategies.

Literature Review:-

MSMEs in Food Sector:-

Micro, Small, and Medium Enterprises (MSEMs) in the food sector play a critical role in economic development, employment generation, and food security, particularly in developing countries like Indonesia. MSEMs significantly contribute to GDP and employment in Indonesia, with the food sector being a vital component of this contribution (Lukita *et al.*, 2026; Hasibuan *et al.*, 2026). Growth in production activities among MSMEsin the food sector is often accompanied by increased consumption of raw materials, energy use, and waste generation. These conditions can lead toincreased greenhouse gas emissions, excessive resource consumption, and various other environmental impacts(Sembiring *et al.*, 2025; Jangde, Arjunan and Patanwar, 2025; Kukde *et al.*, 2026).

Sustainable practices are needed to ensure that business growth up with environmental conservation.Innovation is a key driver for the sustainability of MSMEs in the food sector. This includes product and market innovations, as well as adopting sustainable practices like Green Human Resource Management and circular economy principles(Gumbi, Gumbi and Part, 2023; Farao, Bernuzzi and Ronchetti, 2023).Furthermore, the implementation of cleaner production and resource efficiency concepts has been increasingly recognized as an effective strategy for improving economic performance while simultaneously reducing environmental impacts, particularly among food-sector MSMEs.Cleaner production seeks to identify and minimize operational inefficiencies related to the consumption of water, energy, and raw materials, thereby enhancing the efficiency and sustainability of production processes(Ramos *et al.*, 2020). MSMEs can Focus on converting organic waste into valuable by-products like compost or bioenergy(Thazeem *et al.*, 2025).

Food Waste Management:-

Food waste management is a critical global issue with significant environmental, social, and economic implications.The management of raw material waste in small and medium-sized enterprises (SMEs) in the food sector is a critical issue due to its environmental, economic, and social implications. Food SMEs generate significant amounts of solid and liquid waste during production, contributing to pollution and health risks (Bhageria and Vyas, 2023).

SMEs often lack the financial and managerial resources to adopt advanced waste management practices, making them less likely to implement sustainable solutions (Ascenzo *et al.*, 2025). Many SMEs exhibit low levels of awareness and intention regarding waste management, particularly in developing regions (Krzywonos *et al.*, 2025).

SMEs often face financial limitations that hinder the adoption of advanced waste management technologies (Ascenzo *et al.*, 2025). Inconsistent policies and lack of enforcement create challenges for SMEs to comply with sustainable practices (Ascenzo *et al.*, 2025). Inadequate tracking and reporting of waste streams impede effective waste management planning (Loo, Howieson and Jackson, 2026).

Green Supply Management:-
Green Supply Chain Management (GSCM) incorporates environmental considerations into supply chain processes, aiming to reduce negative environmental impacts while achieving sustainable development (Wang, 2024). It involves practices such as eco-design, green purchasing, cleaner production, reverse logistics, and green distribution (Adam and Doumbia, 2025).GSCM implementation can supports competitive advantage, cost savings, and improved brand reputation(Adam and Doumbia, 2025). Collaboration across the supply chain, including suppliers, distributors, and consumers, is essential for successful implementation(Ning *et al.*, 2025).

Green Supply Chain Management (GSCM) is increasingly recognized as a critical strategy for improving environmental sustainability, particularly in Small and Medium Enterprises (SMEs) within the food sector. GSCM practices, such as green marketing, environmental education, and sustainable supplier management, significantly enhance environmental and financial performance. In the previous research, green marketing has been shown to have a strong positive impact on economic, environmental, and social outcomes in SMEs(Chuyen, Trinh and Huy, 2025).GSCM improves operational performance by optimizing resource use, reducing waste, and enhancing supply chain processes(Adawiyah *et al.*, 2015).

Many SMEs struggle with low awareness of GSCM benefits and insufficient support from supply chain partners and policymakers(Mankar *et al.*, 2025). Policies and regulations play a significant role in encouraging GSCM adoption, as seen in food and beverage SMEs in regions like Vietnam(Diep *et al.*, 2022). Proactively adopting green technologies and practices, such as green packaging and recycling, can address key barriers and improve sustainability(Arun *et al.*, 2024).

Life Cycle Assessment:-
Life Cycle Assessment (LCA) is a widely recognized methodology for evaluating the environmental, economic, and social impacts of products, services, or processes throughout their life cycle.LCA focused on environmental impacts, LCA evaluates inputs, outputs, and potential environmental consequences across a product's life cycle, from raw material extraction to disposal(Nikolic *et al.*, 2019).LCA has evolved into Life Cycle Sustainability Assessment (LCSA), integrating the "triple bottom line" of sustainability-environmental, economic, and social dimensions(Corona *et al.*, 2017).This broader framework enables a more holistic evaluation of sustainability impacts(Choe *et al.*, 2024).

Energy systems and industrial processes are prominent areas of LCA application, with a focus on decarbonization strategies and resource efficiency(Ma *et al.*, 2023). High-quality, reliable databases are essential for accurate assessments, but data availability remains a significant barrier(Olsson, Miller and Kneifel, 2024).Developing standardized frameworks for LCSA, including better integration of social and economic dimensions, is a priority(Ma *et al.*, 2023).

Eco-efficiency:-
Eco-efficiency is a critical concept in sustainability, combining economic performance with environmental impact to create more value with less resource use and environmental harm.Eco-efficiency is defined as the efficiency with which natural resources are used to meet human needs while minimizing environmental impact. It is a tool for sustainability analysis, linking economic activities to environmental outcomes(Penny Allen, Christophe Bonazzi, 2017).

Eco-efficiency is often measured using indicators that assess economic (e.g. cost, profit) and environmental (e.g. emissions, resource use) dimensions. These indicators can be applied at company, product, or process levels(Gotze, Pecas and Richter, 2019).Many studies integrate LCA to evaluate eco-efficiency, considering environmental impacts across a product's life cycle(Souza *et al.*, 2021;Wichai-utcha *et al.*, 2019;Gotze, Pecas and Richter, 2019).

The lack of standardized methods for integrating economic and environmental metrics complicates broader adoption(Gotze, Pecas and Richter, 2019).Eco-efficiency varies significantly across regions and industries, influenced by local development modes and resource availability (Huang *et al.*, 2018). Traditional eco-efficiency assessments are relative and may not align with planetary boundaries. New frameworks aim to address this gap by linking impacts to Earth's carrying capacity(Usman *et al.*, 2023).

Eco-efficiency is a versatile and evolving tool for promoting sustainability across various sectors. While its application has grown significantly, challenges like standardization, regional disparities, and alignment with absolute sustainability goals remain. Future research should focus on refining methodologies, integrating broader sustainability metrics, and exploring innovative applications in emerging industries.

Method:-

The subject of this study is the flour-based chicken processing system at MSMEs in Jombor Village, Sukoharjo, Indonesia. Author selected 10 SMEs as the subjects of this study, covering everything from raw material procurement and the production process to packaging. This study utilizes primary data obtained through direct field observations, as well as a literature review to gather supporting information, such as emission factors, material characteristics, and eco-efficiency indicators.

The scope of this study is cradle-to-grave approach, which encompasses the entire product life cycle, starting from raw material extraction (cradle), continuing through the production process, and ending with waste disposal (grave) (Park, Lee and Won, 2024). The method applied is Life Cycle Assessment (LCA), integrated with eco-efficiency to evaluate the overall life cycle across all stages.The analysis was conducted using SimaPro 9.5.0 software. The research flowchart is presented in Figure 1.

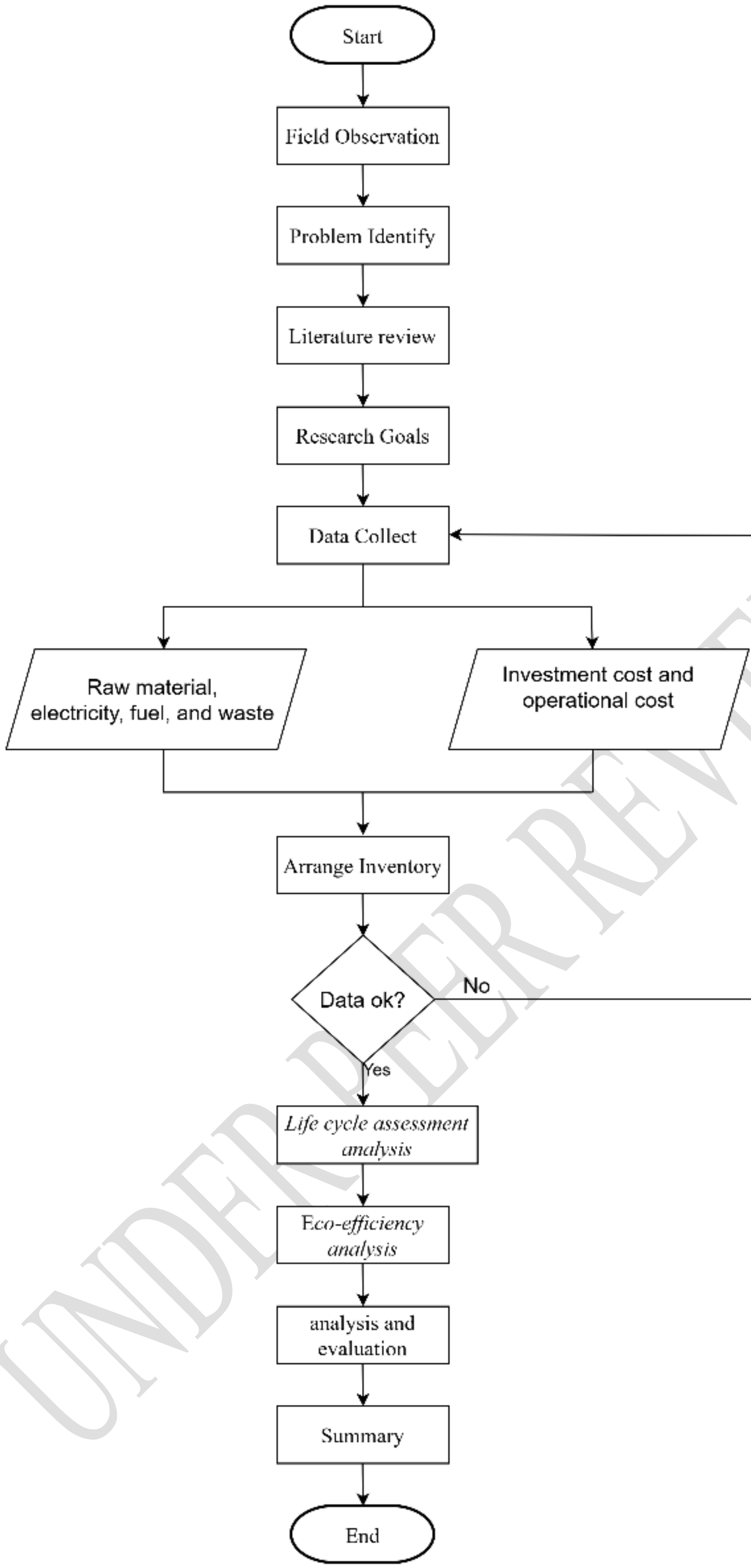

Figure 1. Research Flowchart

The next step after the LCA is to conduct an eco-efficiency analysis. Step in calculating eco-efficiency analysis there are:

a. Net Present Value, is the difference between the present value of the investment and future net cash flows (Drozdowski and Dziekański, 2022). This value is influenced by production costs and product sales (Ningrum, Yulia and Wahidhani, 2024).

N	:	Investment calculation year
Ft	:	*Cashflow* in the - year
i	:	*interest rate*
I_0	:	Investment on 0year

b. Benefit Cost Ratio to compare revenue after deducting expenses

PW	:	*Present Worth*
EUAB	:	*Equivalent Uniform Annual Benefit*
EUAC	:	*Equivalent Uniform Annual Cost*

c. Eco-EfficienyIndek (EEI), to determine the affordability and sustainability of the production process at flour-based chicken processing MSMEs. The eco-efficiency calculation involves the following (Mahastuti, 2017):
   1) EEI > 1 = affordable & sustainability.
   2) EEI = 0~1 = affordable, but not sustainability.
   3) EEI < 0 = not affordable & not sustainability.

Step for calculating the *Eco-Efficiency Index* (EEI):

d. Eco-costs Value Ratio (EVR), measuring economic and environmental efficiency by comparing eco-costs with net value.

$$EVR = \frac{Eco - Cost}{Net\ Value}$$

A low value indicates high efficiency, while a high value indicates the need for a more sustainable design.

e. Eco-Efficiency Ratio (EER), to determine the eco-cost-to-net-present-value ratio. $EER = (1 - EVR) x\ 100\%$

Result:-

Life Cycle Transportation:-

An analysis of the transportation stage was conducted to identify the contribution of raw material distribution, as the majority of MSMEs in the Jombor, Sukoharjo area purchase their raw materials at traditional markets. Transportation is a key aspect of supply chain management because it involves the use of petroleum-based fuels in vehicles. The life cycle assessment approach, using Software 9.5.0 with the ReCiPe 2016 method, is useful for evaluating the extent to which energy use contributes to environmental impacts.

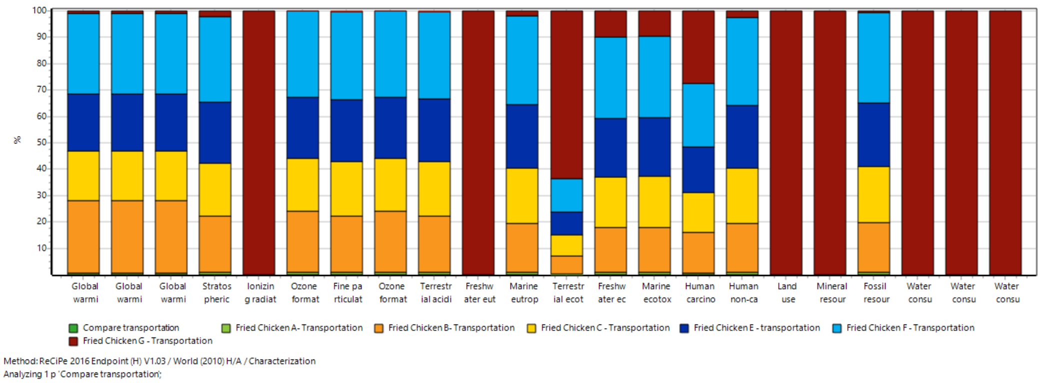

Figure 2. Impact assessment from transportation aspect

Figure 2 illustrates the contribution of environmental impacts across all MSMEs. The figure shows variations in environmental burden characteristics across each category of environmental impact. MSME A contributes to increases in global warming, ozone formation, fine particulate matter formation, and terrestrial acidification. This means that the largest source of emissions stems from a combination of energy-related activities.

Global warming can raise the Earth's average temperature. This finding is supported by a study in Pakistan, which indicates that transportation activities, such as freight transport and logistics significantly contribute to carbon emissions. A 10% increase in transportation activities by MSMEs results in a 5% rise in CO_2 emissions (Adeel *et al.*, 2025). SMEs in Jombor, Sukoharjo face challenges in optimizing logistics due to small-volume, high-frequency purchases. This increases fuel consumption and carbon emissions (Moutaoukil *et al.*, 2014).

Transportation activities contribute significantly to ozone (O_3) formation through the emission of volatile organic compounds (VOCs) and nitrogen oxides (NO_x), which are precursors to ozone. On-road vehicle emissions are identified as a major source of ozone and particulate matter, with light-duty trucks and buses contributing significantly to ozone-related health impacts (Anenberg *et al.*, 2021). Road transport is consistently identified as a significant contributor to PM2.5 emissions in urban areas. Emissions stem from vehicle exhaust, brake wear, tire wear, and resuspended road dust (Askariyeh *et al.*, 2020). PM2.5 from transportation has severe health implications, including respiratory and cardiovascular issues, as it penetrates deeply into the lungs (Camatini *et al.*, 2016).

Life Cycle Production:-

The analysis of the production stage is used to identify energy consumption, raw material usage, and the amount of waste generated. Most MSMEs in the Jombor, Sukoharjo area use fans during operations, freezers for 24 hours, and other electronic devices. The life cycle assessment approach using Software 9.5.0 with the ReCiPe 2016 method is useful for evaluating the contribution of energy use to environmental impacts. The analysis results can identify environmental hotspots during the production stage, thereby enabling the formulation of improvement strategies focused on resource efficiency and the application of cleaner production principles. The analysis results are presented in Figure 3.

Method: ReCiPe 2016 Endpoint (H) V1.03 / World (2010) H/A / Characterization
Analyzing 1 p 'Compare production';

Figure 3. impact assessment from production aspect

Based on the results of the Life Cycle Assessment (LCA) using the ReCiPe 2016 Endpoint (H) method, it was found that the production stage is the primary source of environmental impact. All of these production activities contribute to environmental impacts across various categories, including global warming, ozone formation, terrestrial acidification, and water consumption.

The contribution of production activities to these environmental impacts indicates that the use of raw materials, energy consumption, water use, as well as emissions and waste generation during the production process play a significant role in determining a product's environmental performance. In the global warming category, energy consumption during the production process is the primary cause of environmental impact. Production activities and energy consumption account for approximately 76% of total global greenhouse gas emissions (Kiviluoma *et al.*, 2022). Global warming from the production aspect in the Jombor SMEs results from the use of electricity and fuel, particularly the use of LPG. The combustion of these fuels produces CO_2, methane (CH_4), and nitrous oxide (N_2O) emissions that contribute to climate change(Dutta, 2021). Additionally, 60% of SMEs dispose of flour waste directly into the soil, which can affect soil chemistry(Zhang *et al.*, 2025).

These findings identify the production stage as an environmental hotspot in the product life cycle. Therefore, environmental improvement strategies should focus on this stage by increasing energy efficiency, reducing the consumption of raw materials and water, utilizing more environmentally friendly energy sources, and applying the principles of cleaner production. These efforts are expected to reduce the environmental impact across various categories while improving the overall sustainability performance of the production system.

Life Cycle Packaging:-

The packaging stage is a crucial part of a product's life cycle. However, the use of packaging materials contributes to increased environmental impact, particularly in terms of the volume of solid waste generated. Most SMEs in the Jombor area of Sukoharjo use plastic packaging for takeout food. A life cycle assessment approach using Software 9.5.0 with the ReCiPe 2016 method is useful for evaluating the contribution of various types of packaging used to different categories of environmental impact. This evaluation aims to identify more environmentally friendly packaging alternatives and support the implementation of sustainability principles in the supply chain. The analysis results are presented in Figure 4.

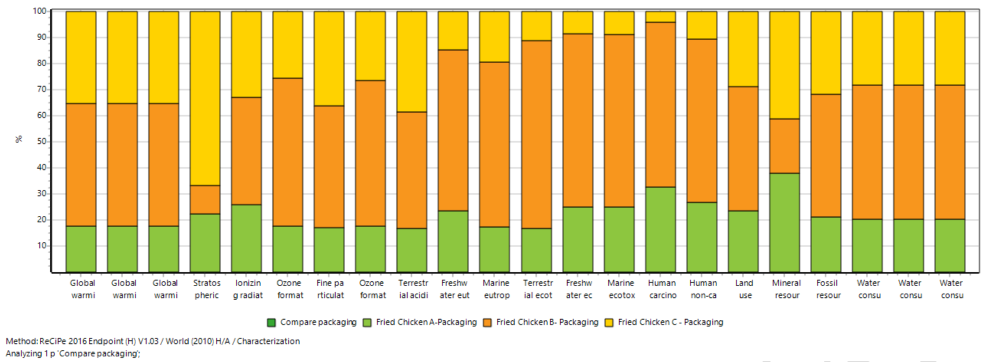

Figure 4. impact assessment from packaging aspect

This study sampled 10 MSMEs in the Jombor area of Sukoharjo. As shown in Figure 4, the results of the environmental impact characterization during the packaging stage indicate that Fried Chicken B is the primary contributor in most environmental impact categories, accounting for approximately 75%. Fried Chicken B's contribution to the global warming category is relatively high, at approximately 45% to 65%, indicating that the packaging materials used have a greater environmental impact intensity compared to other MSME.

Meanwhile, Fried Chicken A has the lowest environmental impact contribution, at 30% in most categories. These results indicate that environmental impacts during the packaging stage are significantly influenced by the type and quantity of packaging materials used. Therefore, improvement efforts should be focused on Fried Chicken B through reducing packaging material usage and selecting more environmentally friendly materials to lower the resulting environmental burden.

Eco-efficiency:-

An eco-efficiency evaluation was conducted to assess the balance between economic performance and environmental impact across each MSMEs. This approach integrates economic indicatorsspecifically Net Present Value (NPV)with environmental indicators represented by the Eco-Efficiency Index (EEI), Environmental Value Ratio (EVR), and Eco-Efficiency Ratio (EER). This analysis aims to determine the extent to which MSMEcontribute to generating optimal economic value while minimizing the resulting environmental impacts. Consequently, each MSMEcan be classified into sustainability categories, specifically the affordable and sustainable category.

Table 1. Eco-efficiency

MSME	Eco-efficiency				Indicator
	NPV	EEI	EVR	EER	
A	9750	2,14	0,12	88%	affordable, sustainable
B	9750	2,89	0,01	99%	affordable, sustainable
C	5250	2,60	0,05	95%	affordable, sustainable
D	5250	2,60	0,05	95%	affordable, sustainable
E	5250	2,18	0,12	88%	affordable, sustainable
F	5250	2,18	0,12	88%	affordable, sustainable
G	9750	2,64	0,05	95%	affordable, sustainable
H	9750	2,64	0,05	95%	affordable, sustainable
I	9000	2,68	0,04	96%	affordable, sustainable
J	9000	2,44	0,08	92%	affordable, sustainable

Based on the results of the eco-efficiency evaluation, all MSMEs fall into the affordable and sustainable category, indicating that each MSME is capable of generating positive economic value while keeping environmental impacts at a relatively low level. This is demonstrated by a positive Net Present Value (NPV) ranging from 5,250 to 9.750, an Eco-Efficiency Index (EEI) above 2 and an Eco-Efficiency Ratio (EER) ranging from 88% to 99%. These conditions indicate that all MSMEs have achieved a good balance between economic performance and environmental performance, thereby supporting the application of sustainability principles in their operational activities.

MSME B demonstrated the best eco-efficiency performance with an EEI of 2,89; an EVR of 0,01; and an EER of 99%. These values indicate that MSME B is capable of generating high economic value with the relatively lowest environmental impact compared to other MSME. Additionally, MSME G, H, and I also demonstrate excellent performance with EEI values ranging from 2,64 to 2,68 and EER values of 95-96%, indicating relatively optimal resource efficiency and environmental management.

Meanwhile, MSME A, E, and F have relatively lower eco-efficiency values compared to other MSME, with EEI values ranging from 2,14 to 2,18; an EVR of 0,12, and an EER of 88%. Although they still fall within the sustainable category, these values indicate that these three MSME generate a relatively greater environmental impact for every unit of economic value produced. Therefore, there remains an opportunity to improve environmental efficiency through the optimization of resource use, waste reduction, and the adoption of more environmentally friendly technologies or materials.

MSME C and D exhibit similar eco-efficiency characteristics with an EEI of 2,60; an EVR of 0,05; and an EER of 95%. Although they have lower NPV values compared to some other MSME, both MSME are still able to maintain a good balance between economic and environmental performance. Similarly, MSME J demonstrates fairly good performance with an EEI value of 2,44 and an EER of 92%, indicating an adequate level of sustainability although there is still room for improving environmental efficiency.

Conclusion:-

This study demonstrates that the application of Life Cycle Assessment (LCA) integrated with eco-efficiency can provide an analysis of the environmental and economic performance of flour-based chicken processing MSMEs in Jombor Village, Sukoharjo. The LCA analysis results indicate that the production stage is an environmental hotspot, contributing the most to the impact categories of global warming, ozone formation, terrestrial acidification, and water consumption. These impacts are primarily caused by the use of electricity, LPG, water consumption, and waste generation during the production process. Additionally, transportation activities and the use of plastic packaging also contribute to increased environmental burdens across several impact categories.

The results of the environmental impact characterization indicate variations in contributions among MSME. During the packaging stage, MSME B was the largest contributor in most environmental impact categories, accounting for approximately 75%, while MSME A had the lowest contribution, at less than 30% in most categories. The eco-efficiency evaluation indicates that MSME B has the best eco-efficiency performance with an EEI value of 2,89; an EVR of 0,01 and an EER of 99%, demonstrating the ability to generate high economic value with relatively low environmental impacts. The results of this study underscore the importance of implementing Green Supply Chain Management, energy efficiency, the use of more environmentally friendly packaging materials, and the adoption of cleaner production to enhance the sustainability of SMEs while strengthening business competitiveness in the long term.

References:-

1. Adam, A.A. and Doumbia, M.O. (2025) ‘Contemporary Issues in Supply Chain Management and Logistics: The Role of Green Supply Chain Management in Public Health Facilities’, in *Contemporary Issues in Supply Chain Management •*. Available at: https://doi.org/10.1201/9781779643612.
2. Adawiyah, W.R. *et al.* (2015) ‘Green supply chain management and its impact on construction sector Small and Medium Enterprises (SMEs) performance: A case of Indonesia’, *International Business Management*, pp. 4–6. Available at: https://doi.org/10.3923/ibm.2015.1018.1024.
3. Adeel, M. *et al.* (2025) ‘The Nonlinear Dynamics of CO 2 Emissions in Pakistan : A Comprehensive Analysis of Transportation , Electricity Consumption , and Foreign Direct Investment’, *Sustainability*, pp. 1–26.
4. Adewale, T.T. *et al.* (2024) ‘Integrating sustainability and cost-effectiveness in food and FMCG supply chains : A comprehensive model Integrating sustainability and cost-effectiveness in food and FMCG supply chains : A comprehensive model’, *Comprehensive Research and Reviews Journal* [Preprint], (September). Available at: https://doi.org/10.57219/crrj.2024.2.1.0029.
5. Agarwal, S. *et al.* (2025) ‘Redefining marketing strategies through sustainability : Influencing consumer behavior in the circular economy : A systematic review and future research roadmap’, *Cleaner and Responsible Consumption*, 18(June), p. 100298. Available at: https://doi.org/10.1016/j.clrc.2025.100298.
6. Alam, A. *et al.* (2022) ‘APPLICATION OF LANDGEM MATHEMATICAL MODEL FOR THE ESTIMATION OF GAS EMISSIONS FROM CONTAMINATED SITES . A CASE STUDY OF A DUMPING SITE IN LAHORE , PAKISTAN’, *Environment Protection Engineering*, 48(1). Available at: https://doi.org/10.37190/epe220105.
7. Ali, M. *et al.* (2024) ‘Kontribusi Transisi Energi pada Sektor Rumah Tangga untuk Mencapai Target Netral Karbon di Indonesia’, *Jurnal Rekayasa Teknologi Nusa Putra*, 10(1), pp. 31–37.
8. Anenberg, S.C. *et al.* (2021) ‘Mortality-based damages per ton due to the on- road mobile sector in the Northeastern and Mid- Atlantic U . S . by region , vehicle class and precursor Mortality-based damages per ton due to the on-road mobile sector in the Northeastern and Mid-Atlantic U’, *Environmental Research*, 16.
9. Arun *et al.* (2024) ‘Barriers to Sustainable Supply Chain Management in Food Processors MSME : A Total Interpretive Structural Modeling Approach’, in *ICT for Intelligent Systems*, pp. 359–370.
10. Ascenzo, F.D. *et al.* (2025) ‘The Evaluation of Corporate Sustainability Strategies in Italy : Challenges and Opportunity of Recycled Packaging’, *Sustainability*, 17.
11. Askariyeh, M.H. *et al.* (2020) ‘Near-Road Tra ffi c-Related Air Pollution : Resuspended PM 2 . 5 from Highways and Arterials’, *International Journal of Environmental Research and Public Health*, 17.
12. Asmoro, N.W. (2021) ‘Review Karakteristik dan Sifat Tepung Singkong Termodifikasi (Mocaf) dan Manfaatnya pada Produk Pangan [Characteristics and Properties of Modified Cassava Flour (Mocaf) and Its Benefits in Food Products] Pendahuluan’, *Journal of Food and Agricultural Product*, 1(1), pp. 34–43.
13. Aviso, K.B. (2024) *Overview of LCA—History, Concept, and Methodology*. Available at: https://doi.org/10.1016/B978-0-323-90386-8.00113-3.
14. Azmi *et al.* (2023) ‘View of The Assessment of Environmental Impact of the Chicken Meat Agroindustry in Indonesia’.
15. Balashov, B. *et al.* (2024) ‘ANALYSIS OF INDUSTRIAL FOOD PRODUCTION SYSTEMS TO ENSURE FOOD SAFETY AND QUALITY’, *Bulletin of Shakarim University Technical Sciences*, 15(1), pp. 37–48. Available at: https://doi.org/10.53360/2788-7995-2024-3(15)-24.
16. Bhageria, S. and Vyas, S. (2023) ‘A study of environmental-friendly practices by food processing SMEs’, in *AIP Conference Proceedings*.
17. Braun, A. and Rothbart, M. (2025) ‘Sustainable Design of Automotive Batteries’, in *Advanced Automotive Battery Conference*.
18. Brilliantina, A. *et al.* (2023) ‘Penerapan Life Cycle Assessment (LCA) Untuk Mengurangi Dampak Lingkungan Pada Proses Produksi Gula Kristal Putih Di Bondowoso Aulia’, *Jurnal Sains dan Terapan*, 2(1).
19. Camatini, M. *et al.* (2016) *Impact of the Airborne Particulate Matter onthe Human Health*. Wiley Online Library. Available at: https://doi.org/10.1289/ehp.10767.
20. Chirsanova, A. and Calcatiniuc, D. (2021) ‘the Impact of Food Waste and Ways To Minimize It’, *Journal of Social Sciences*, IV(1)(March). Available at: https://doi.org/10.52326/jss.utm.2021.4(1).15.
21. Choe, C. *et al.* (2024) ‘ScienceDirect Life cycle sustainability assessment for sustainable energy future : A short review on opportunity and challenge’, *Green and Sustainable Chemistry*, 50, p. 100974. Available at: https://doi.org/10.1016/j.cogsc.2024.100974.
22. Chuyen, T.T., Trinh, P.T.X. and Huy, T.T. (2025) ‘Green supply chain and sustainable development performance : evidence from the agricultural sector in the Mekong Delta’, *International Scientific Journal*

about Logistics, 12, pp. 739–753.

23. Corigliano, O. and Algieri, A. (2024) ‘A comprehensive investigation on energy consumptions, impacts, and challenges of the food industry’, *Energy Conversion and Management: X*, 23(July), p. 100661. Available at: https://doi.org/10.1016/j.ecmx.2024.100661.
24. Corona, B. *et al.* (2017) *Social Life Cycle Assessment of a Concentrated Solar Power Plant in Spain*. Available at: https://doi.org/10.1111/jiec.12541.
25. Diep, T. *et al.* (2022) ‘Uncertain Supply Chain Management The moderating role export and firm size on the relationship between green supply chain management and operational performance’, *Uncertain Supply Chain Management*, 10, pp. 1161–1174. Available at: https://doi.org/10.5267/j.uscm.2022.8.011.
26. Drozdowski, G. and Dziekański, P. (2022) ‘Net Present Value (Npv) As a Reinforcement of the Decision-Making Process in Terms of Investment Selection’, *Market Infrastructure*, (66), pp. 2–5. Available at: https://doi.org/10.32843/infrastruct66-7.
27. Dutta, A. (2021) ‘Energy Conservation and Its Impact on Climate Change’, in *Environmental Management: Issues and Concerns in Developing Countries*, pp. 139–150.
28. Dwi, S.A. and Mirwan, M. (2023) ‘Analisis Life Cycle Assessment (LCA) pada Proses Produksi Pupuk ZA II Menggunakan Metode Recipe 2016’, *Jurnal Sains dan Teknologi*, 2(3), pp. 620–632. Available at: https://doi.org/10.55123/insologi.v2i3.2074.
29. Espinoza-Castro, F., Lara-Ramírez, A. and Buele, J. (2024) ‘Environmental Sustainability in Industrial Operations : A Comprehensive Review’, in *IEEE Eighth Ecuador Technical Chapters Meeting (ETCM)*. Available at: https://doi.org/10.1109/ETCM63562.2024.10746185.
30. Farao, C., Bernuzzi, C. and Ronchetti, C. (2023) ‘The Crucial Role of Green Soft Skills and Leadership for Sustainability : A Case Study of an Italian Small and Medium Enterprise Operating in the Food Sector’, *Sustainability*, 15.
31. Firmansyah, M.A. (2018) *Perilaku Konsumen*. Publisher: Deepublish, Yogyakarta. Available at: 10.1016/b978-0-12-824315-2.00735-1.
32. Fitri, Y., Putri, A.N. and Retnawaty, S.F. (2020) ‘Estimasi Emisi CO 2 Dari Sektor Rumah Tangga Di Kota Pekanbaru’, *Jurnal Sins dan Kesehatan*, 11(1).
33. Gholizadeh, Y. (2020) ‘Younes Gholizadeh Causality Relationship between Energy Consumption and Economic Growth in the European Union Countries Economics and Econometrics Research Institute EERI’, *Economics and Econometrics Research Institute* [Preprint].
34. Gotze, U., Pecas, P. and Richter, F. (2019) ‘Design for Eco efficiency- a system of indicators and their application to the case of moulds for injection moulding’, *Procedia Manufacturing*, 33, pp. 304–311. Available at: https://doi.org/10.1016/j.promfg.2019.04.037.
35. Gumbi, N., Gumbi, L. and Part, H.T. (2023) ‘Mobile Cloud Based Enterprise Resource Planning Systems for Small Medium and Micro Enterprises : A Systematic Literature Review’, in *Communications in Computer and Information Science ((CCIS,volume*, pp. 46–69.
36. Hasibuan, R. *et al.* (2026) ‘Human resource management and its impact on employee performance in MSMEs-SLR’, *Frontier in Sustainability*, (February), pp. 1–10. Available at: https://doi.org/10.3389/frsus.2026.1764507.
37. Huang, J. *et al.* (2018) ‘Composite eco-e ffi ciency indicators for China based on data envelopment analysis’, *Ecological Indicators*, 85(November 2017), pp. 674–697. Available at: https://doi.org/10.1016/j.ecolind.2017.10.040.
38. Irozi, M.F.I. *et al.* (2022) ‘The Contribution of Polluter Pays Principle (PPP) Approach on Environmental Pollution Reduction and Health Risk for Municipal Solid Waste (MSW)’, in *Environmental Management and Sustainable Development*.
39. Izhar, T.N.T. and Xuan, L.P. (2021) ‘The estimation of greenhouse gas emission in leachate treatment plant and its carbon credit revenue The estimation of greenhouse gas emission in leachate treatment plant and its carbon credit revenue’, in *IOP Conference Series: Earth and Environmental Science*. Available at: https://doi.org/10.1088/1755-1315/646/1/012067.
40. Jangde, P.K., Arjunan, T.V. and Patanwar, P. (2025) *Energy Utilisation in Food Processing Industries*. 1st edn. CRC Press.
41. Kiviluoma, J. *et al.* (2022) ‘Flexibility From the Electrification of Energy : How Heating , Transport , and Industries Can Support a 100 % Sustainable Energy System’, in *IEEE Power and Energy Magazine*. Available at: https://doi.org/10.1109/MPE.2022.3167576.
42. Krzywonos, M. *et al.* (2025) ‘Best Practices in Food Waste Recovery’, in *Encyclopedia of Agriculture and Food Systems* •. Available at: https://doi.org/10.1016/B978-0-443-15976-3.00137-9.

43. Kukde, R.B. *et al.* (2026) *3D-Printing Technology in Food Waste Valorization with Economic Feasibility*. 1st edn. CRC Press.
44. Lestari, M.S., Prasetyo, R. and Hartanti, S. (2023) 'Analysis and Design of Work Systems using Hazard Analysis and Critical Control Points (HACCP) Standards at Mr. Sarbani's Tempe Jombor Sukoharjo', *JURNAL Al-AZHAR INDONESIA SERI SAINS DAN TEKNOLOGI*, 8(3), p. 205. Available at: https://doi.org/10.36722/sst.v8i3.1692.
45. Li, F. (2024) 'Challenges and Opportunities for Sustainable Supply Chain Management', *Frontiers in Business, Economics and Management*, 15(1).
46. Loo, L., Howieson, J. and Jackson, E.L. (2026) 'A strategic framework and business tools for reducing pre-retail food waste – A practical application for food SMEs', *Cleaner Waste Systems*, 14(May), p. 100525. Available at: https://doi.org/10.1016/j.clwas.2026.100525.
47. Lukita, C. *et al.* (2026) 'Maturity Level Measurement Model of MSMEs for Sustainable Economic Growth', *APTISI Transactions on Technopreneurship (ATT)*, 8(2), pp. 434–442.
48. Ma, S. *et al.* (2023) 'Exploring the Research Frontier of Life Cycle Sustainability Assessment-A Systematic Literature Review of Applied Bibliometric Analysis', *Chemical Engineering Transactions*, 106(May), pp. 547–552. Available at: https://doi.org/10.3303/CET23106092.
49. Mahambari, M. (2024) *Produk Domestik Regional Bruto Kabupaten Sukoharjo Menurut Lapangan Usaha*. Badan Pusat Statistik Kabupaten Sukoharjo. Available at: http://scioteca.caf.com/bitstream/handle/123456789/1091/RED2017-Eng-8ene.pdf?sequence=12&isAllowed=y%0Ahttp://dx.doi.org/10.1016/j.regsciurbeco.2008.06.005%0Ahttps://www.researchgate.net/publication/305320484_SISTEM_PEMBETUNGAN_TERPUSAT_STRATEGI_MELESTARI.
50. Mahastuti, N. (2017) *Analisis Gate to Gate dengan Metode Eco Indicator 99 (H) pada Pengukuran Eko Efisiensi di Industri Kecil (Studi Kasus: IKM Tahu Kampung Purwogondo, Kecamatan Kartasura, Sukoharjo)*. Universitas Muhammadiyah Surakarta.
51. Maisarah and Dian, R. (2024) 'Metode Life Cycle Assessment (LCA) dalam Penilaian Dampak Lingkungan Industri Kelapa Sawit untuk Kelapa Sawit Berkelanjutan', *Jurnal Pertanian Berkelanjutan*, 2.
52. Mankar, V.A. *et al.* (2025) 'A Study of Drivers and Barriers of Green Supply Chain Management Practices in the Context of Developing Framework for SMEs', in *Leveraging AI for Innovative Sustainable Energy: Solar, Wind and Green Hydrogen*. Available at: https://doi.org/10.4018/979-8-3373-0045-0.ch001.
53. Meidani, A.A.N. and Maryam, Z. (2014) 'Energy Consumption and real GDP in Iran', *International Journal of Energy Economics and Policy •*, pp. 25–27.
54. Moutaoukil, A. *et al.* (2014) 'A Comparison of Homogeneous and Heterogeneous Vehicle Fleet Size in Green Vehicle Routing Problem', in *IFIP Advances in Information and Communication Technology*, pp. 1–7.
55. Muhammad, D.R.A., Zaman, M.Z. and Ariyantoro, A.R. (2023) 'Sustainable materials and infrastructures for the food industry', *Sustainable Development and Pathways for Food Ecosystems: Integration and Synergies*, (0), pp. 147–182. Available at: https://doi.org/10.1016/B978-0-323-90885-6.00010-7.
56. Nagy, G. and Szabolcs, S. (2024) 'Green logistics : Transforming supply chains for a sustainable future', *Advance Logistics System- Theory and Practice* [Preprint], (October). Available at: https://doi.org/10.32971/als.2024.026.
57. Nikolic, D. *et al.* (2019) 'METHODOLOGY OF LIFE CYCLE SUSTAINABILITY ASSESSMENT', *Quality Festival*, pp. 793–800.
58. Ning, J. *et al.* (2025) 'Does green supply chain management improve corporate sustainability performance ? Evidence from China', *Environmental Impact Assessment Review*, 112(238), p. 107828. Available at: https://doi.org/10.1016/j.eiar.2025.107828.
59. Ningrum, R.R.A., Yulia, I.A. and Wahidhani, E. (2024) 'Effect of Sales, Production Cost and Operating Cost on Net Profit', *Jurnal Ilmiah Akuntansi Kesatuan*, 12(2), pp. 275–284. Available at: https://doi.org/10.37641/jiakes.v12i2.2061.
60. Olsson, J.A., Miller, S.A. and Kneifel, J.D. (2024) 'Resources , Conservation & Recycling A review of current practice for life cycle assessment of cement and concrete', *Resources, Conservation & Recycling*, 206(December 2023), p. 107619. Available at: https://doi.org/10.1016/j.resconrec.2024.107619.
61. Oppong, D. and Bannor, R.K. (2022) 'Bibliometric analysis and systematic review of compliance with agricultural certification standards: evidence from Africa and Asia', *All Life*, 15, pp. 970–999.
62. P, H.S., Bulan, P. and Anis, Q. (2021) 'Circular Initiatives for Industrial Sustainability', in *E3S Web of Conferences 317*, pp. 1–7.
63. Park, D., Lee, H. and Won, W. (2024) 'Unveiling the environmental gains of biodegradable plastics in the

waste treatment phase: A cradle-to-crave life cycle assessment', *Chemical Engineering Journal*, 487(March), p. 150540. Available at: https://doi.org/10.1016/j.cej.2024.150540.

64. Penny Allen, Christophe Bonazzi, D.G. (2017) 'Eco-Efficiency', in *Metaphors for Change*. 1st edn. Routledge, p. 36.
65. Pratama, F.Y., Hartanti, S. and Prasetyo, D.H. (2024) 'Eco-Efficiency dalam Green SCM: PLTSa Sebagai Alternatif Manajemen Sampah dan Sumber Listrik', *JAPTI: Jurnal Aplikasi Ilmu Teknik Industri*, 5(September).
66. PT PLN Persero (2024) 'Adu Emisi Bensin VS Mobil Listrik', *Kumparan Bisnis*. Available at: https://kumparan.com/kumparanbisnis/adu-emisi-bensin-vs-molis-mana-lebih-pekat-22OmLCjq0th/3.
67. Raj, P. *et al.* (2025) 'Innovative Strategies for Sustainable Waste Disposal', in *Leveraging Urban Computing for Sustainable Urban Development ·*. IGI Global.
68. Ramalingam, S. *et al.* (2025) 'Synergies for sustainability : Renewable energy , urban planning , and green industry in carbon emission reduction', *Sustainable Futures*, 10(June), p. 101222. Available at: https://doi.org/10.1016/j.sftr.2025.101222.
69. Ramos, S. *et al.* (2020) '1 - Cleaner production strategies for the food industry', in *The Interaction of Food Industry and Environment*. Academic Press, pp. 1–34.
70. Rievaj, V., Mokrickova, L. and Rievaj, J. (2016) 'Impact of Driiving Techniques on Fuel Consumption', *Communications - Scientific Letters of the University of Žilina* [Preprint].
71. Saravanakumar, L. and Arunprasad, S. (2024) 'Catalytic Converter — An Integrated Approach to Reduce Carbon Dioxide Emission', *SAE Technical Paper Series*, 1.
72. Sembiring, N. *et al.* (2025) 'Redefining food processing : Smart innovations for efficiency and eco-friendly production', in *BIO Web of Conferences*.
73. Sharif, M.K. *et al.* (2024) *Food Secutiry, Food Safety, and Sanitation*, *Wiley Online Library*. Available at: https://doi.org/10.1111/j.1540-6210.2009.02054.x.
74. Shevchenko, A. *et al.* (2023) 'The Use of Wastes from the Flour Mills and Vegetable Processing for the Enrichment of Food Products', in *Bioconversion of Wastes to Value-added Products*.
75. Shi, D., Xiong, G. and Bu, C. (2022) 'The effect of stringent environmental regulation on firms ' TFP- new evidence from a quasi-natural experiment in Chongqing ' s daily penalty policy', *Environmental Science and Pollution Research*, 29, pp. 32065–32081.
76. Siltumens, K. *et al.* (2023) 'Title : INTERACTION BETWEEN METHANE AND CARBON DIOXIDE EMISSIONS USING METHANE-REDUCING', in *Proceedings of 23rd International Multidisciplinary Scientific GeoConference SGEM 2023*. Available at: https://doi.org/10.5593/sgem2023V/4.2/s19.32.
77. Souza, A.M. De *et al.* (2021) 'Application of the desirability function for the development of new composite eco-efficiency indicators for concrete e', *Journal of Building Engineering*, 40(March). Available at: https://doi.org/10.1016/j.jobe.2021.102374.
78. Striebig, B., Smitts, E. and Morton, S. (2019) 'Impact of Transportation on Carbon Dioxide Emissions from Locally vs . Non-locally Sourced Food Refbacks', *Emerging Science Journal*, 3(4), pp. 3–7. Available at: https://doi.org/10.1111/jiec.12371.Food.
79. Thazeem, B. *et al.* (2025) 'Recent Trends in Composting of Food Waste', in *Resource Recycling and Management of Food Waste*, pp. 89–109.
80. Usman, H. *et al.* (2023) 'Evaluating the absolute eco-efficiency of food products : A case study of rice in Pakistan', *Environmental Impact Assessment Review*, 101(December 2022), p. 107119. Available at: https://doi.org/10.1016/j.eiar.2023.107119.
81. Vaez-Ghasemi, M., Moghaddas, Z. and Saen, R.F. (2022) 'Cost efficiency evaluation in sustainable supply chains with marginal surcharge values for harmful environmental factors : a case study in a food industry', *Operational Research, Springer*, 22, pp. 5897–5912.
82. Vargas, N.K.B., Mogollón, M.I.R. and Rosa Patricia Larios-Francia (2022) 'Environmental Impact Assessment of Flexible Food Packaging', *The International Journal of Environmental Sustainability*, 19(1).
83. Walia, B. and Sanders, S. (2019) 'Curbing food waste: A review of recent policy and action in the USA', *Renewable Agriculture and Food Systems*, 34(2), pp. 169–177.
84. Wang, Y. (2024) *Analysis of participating subjects in green supply chain: Supplier selection, distributor characteristics, and consumer behavior*. 1st edn. CRC Press.
85. Wichai-utcha, N. *et al.* (2019) 'Eco efficiency analysis of high density polyethylene resin by integrated life cycle assessment and life cycle cost', *International Journal of Management and Business Research* [Preprint].
86. Zhang, F. (2023) 'Biofuels for transportation Biofuels for transportation', *Journal of Physics: Conference Series* [Preprint]. Available at: https://doi.org/10.1088/1742-6596/2608/1/012049.

87. Zhang, L. *et al.* (2025) 'Science of the Total Environment Heavy metal (loid) s accumulation and human health risk assessment in wheat after long-term application of various urban and rural organic fertilizers', *Science of the Total Environment*, 961(October 2024), p. 178389. Available at: https://doi.org/10.1016/j.scitotenv.2025.178389.