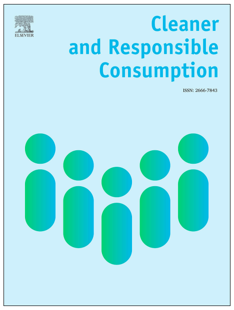


Sustainable Waste Management Strategies for Multilayer Plastic in Indonesia

Mayrianti Annisa Anwar, Suprihatin Suprihatin, Nugroho Adi Sasongko, Mukhamad Najib, Bono Pranoto, Irman Firmansyah, Erni Septiarsi Soekotjo

PII: S2666-7843(25)00005-1

DOI: https://doi.org/10.1016/j.clrc.2025.100254

Reference: CLRC 100254

To appear in: *Cleaner and Responsible Consumption*

Received Date: 26 September 2024

Revised Date: 9 January 2025

Accepted Date: 11 January 2025

Please cite this article as: Anwar, M.A., Suprihatin, S., Sasongko, N.A., Najib, M., Pranoto, B., Firmansyah, I., Soekotjo, E.S., Sustainable Waste Management Strategies for Multilayer Plastic in Indonesia, *Cleaner and Responsible Consumption*, https://doi.org/10.1016/j.clrc.2025.100254.

Sustainable Waste Management Strategies for Multilayer Plastic in Indonesia

Mayrianti Annisa Anwar [a,b] ,*, Suprihatin Suprihatin[c], Nugroho Adi Sasongko[d,e], Mukhamad Najib[f], Bono Pranoto[g], Irman Firmansyah[h], Erni Septiarsi Soekotjo[d]

[a] Natural Resources and Environmental Management, Graduate Study Program, IPB University, Jl. Pajajaran, IPB Baranangsiang Campus, Bogor 16144

[b] Bureau for Legal and Cooperation, Executive Secretariat of National Research and Innovation Agency, Jakarta, Indonesia, 10340

[c] Department of Agroindustrial Technology, Faculty of Agricultural Technology, Bogor Agricultural University (IPB), Kampus IPB Darmaga P.O. Box 220, Bogor, Indonesia

[d] Research Centre for Sustainable Production System and Life Cycle Assessment, National Research, and Innovation Agency (BRIN), Prof BJ Habibie Complex Area, 15314, Banten, Indonesia

[e] Energy Security Graduate Program, Republic of Indonesia Defense University (UNHAN RI), IPSC Sentul Area, 16810, West Java, Indonesia

[f] Faculty of Economics and Management Jl. Agatis, Kampus IPB Darmaga-Bogor – West Java 16680

[g] Research Center for Limnology and Water Resources, National Research and Innovation Agency, Bogor, Indonesia

[h] Head of System Dynamics Centre and Chairman of Indonesian System Dynamics Experts Association

***Corresponding author**.
Email address: anwarannisa@apps.ipb.ac.id (M. A., Anwar)

Credit authorship contribution statement.
Mayrianti Annisa Anwar: Data curation; Formal analysis; Investigation; Methodology; Resources; Validation; Visualisation; Roles/Writing - original draft. **Suprihatin Suprihatin:** Supervision; Validation; Writing - review & editing focusing on the environmental technological aspects. **Mukhamad Najib:** Supervision; Validation; Writing - review & editing focusing on the institutional and policy aspects. **Nugroho Adi Sasongko:** Supervision; Validation; Writing - review & editing; Acquisition of funding, **Bono Pranoto:** Methodology; Resources; Software, Visualisation; Role/Writing, **Irman Firmansyah:** Validation; Writing - review & editing, **Erni Septiarsi Soekotjo:** Data curation; Formal analysis; Investigation: Validation.

Sustainable Waste Management Strategies for Multilayer Plastic in Indonesia

Abstract

Multilayer plastic waste is currently a significant environmental problem in Indonesia, because this waste is classified as difficult to degrade naturally and difficult to recycle. Until now, there has been no effective management strategy for managing this waste. This study utilizes the Multi-Aspect Sustainability Analysis (MSA) framework to assess the sustainability of multilayer plastic waste management in Indonesia, addressing environmental, economic, social, legal, and infrastructure factors. MSA was chosen over other frameworks due to its adaptability to local contexts and its holistic view, making it well-suited to analyze Indonesia's unique waste management challenges. The methodology includes in-depth interviews, scenario planning, and expert panels, integrating qualitative and quantitative insights from various stakeholders. Key goals are to identify priority areas for improvement and develop actionable strategies that enhance recycling effectiveness and align with Extended Producer Responsibility (EPR) policies. Results indicate that advanced recycling technologies, such as chemical recycling, and stronger institutional collaboration are essential. The highest leverage was found in government support, public awareness, and efficient waste infrastructure, which significantly impact sustainability outcomes. This study concludes that policy reforms, technology investments, and stakeholder engagement are critical to building a sustainable waste management system aligned with Indonesia's environmental and economic goals.

Keywords

Sustainability, Multilayer Plastics, Waste Management, Multi-Aspect Sustainability Analysis

1. Introduction

The management of multilayer plastic waste in Indonesia presents significant challenges, primarily due to the absence of a systematic strategy for its handling. This type of waste, composed of various materials like plastic, metal, and paper, is engineered to extend product shelf life (Anwar et al., 2023). However, its difficult-to-decompose nature complicates recycling efforts (Kaiser et al., 2020). Unfortunately, scavengers tend to overlook this waste due to its low economic value, leading to the majority of it ending up in landfills or being incinerated, exacerbating environmental pollution (Green Peace, 2019).

These inadequate waste management practices result in severe negative impacts, accumulating multilayer plastic waste reaching approximately 768,000 tons annually (World Bank, 2021). According to United Nations (2022), plastic production soared from 2 million tonnes in 1950 to 348 million tonnes in 2017, becoming a global industry valued at US$522.6 billion. It is expected to double in capacity by 2040. Consequently, it is crucial for stakeholders, particularly the government as policymakers, to develop effective and sustainable management strategies.

Various initiatives have been undertaken to tackle this issue, including policies to reduce single-use plastics and introduce waste banks. However, the effectiveness of these measures has been limited, especially concerning the implementation of Extended Producer

Responsibility (EPR). EPR is designed to encourage producers to take responsibility for the lifecycle of their products, yet it has not been effectively implemented in Indonesia (Tahar, 2019). Moreover, although promising, existing recycling technologies, such as pyrolysis and solvent-based methods, encounter challenges related to high operational costs and scalability (Zhao et al., 2021).

The existing literature highlights a critical gap in developing management strategies that account for the interconnections among various aspects—environmental, economic, social, technological, and policy, as shown in Fig 1. Many prior studies have concentrated solely on one aspect without investigating their interactions (Firmansyah, 2022). This study aims to bridge that gap by applying the Multi-Aspect Sustainability Analysis (MSA) framework. This framework facilitates a comprehensive evaluation of the sustainability of multilayer plastic waste management by considering these interrelated aspects.

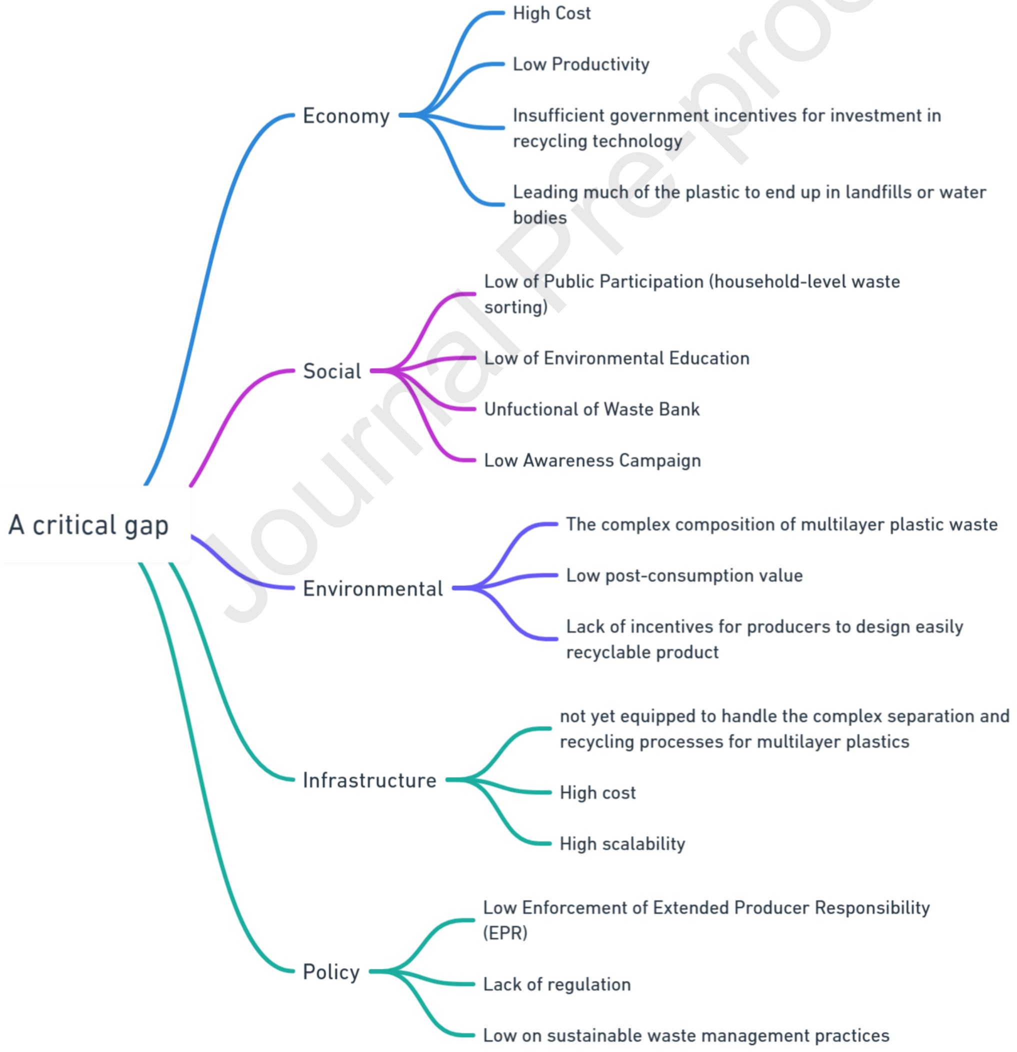


Fig. 1. A critical gap of Multilayer Plastic. Source: (Pitcher & Preikshot, 2001)

This research employs the Multi-Aspect Sustainability Analysis (MSA) framework to evaluate multilayer plastic waste management sustainability in Indonesia. It examines five key areas: environmental, economic, social, legal, and infrastructure, offering a comprehensive view of current practices and improvement scenarios. Unlike previous studies, this research focuses specifically on multilayer plastics, addressing the unique challenges posed by their complex composition (Anwar et al., 2024). It is among the first to recommend practical measures, such as strengthening Extended Producer Responsibility (EPR) and enhancing recycling technologies for multilayer plastics. The study aims to assess the existing state of plastic waste management especially multilayer plastic in Indonesia, identify weaknesses, and provide actionable recommendations, including improved recycling processes, policy reforms, and enhanced institutional cooperation, to foster a more sustainable waste management system aligned with circular economy principles.

2. Literature Review

Multi-Aspect Sustainability Analysis (MSA) has been utilized in several studies in Indonesia based on Multi-Criteria Decision Making (MCDM), exhibiting diverse scopes and limitations. For instance, Juhandi et al., (2024) compared food and non-food plantation agricultural systems, employing MSA alongside Multidimensional Scaling (MDS) to analyze seven sustainability aspects: economic, social, environmental, institutional, technological, marketing, and cultural. While this analysis is comprehensive, it heavily relies on self-reported data collected through interviews and questionnaires, potentially introducing response bias. The findings could be further strengthened by integrating more objective performance indicators.

Similarly, Paulus et al., (2023) focused on freshwater fish aquaculture in Kupang City, utilizing MSA but limiting their analysis to five sustainability aspects: ecology, economy, social, institutional, and infrastructure. While the study provides a detailed examination specific to the aquaculture sector, it faces limitations due to its reliance on subjective inputs from stakeholders and the absence of in-depth future scenario planning. This limitation restricts the analytical capacity to offer long-term insights into aquaculture sustainability.

In contrast, Rizieq et al., (2023) applied MSA to assess the sustainability of adopting new rice varieties in West Kalimantan, primarily focusing on the economic dimension. Although the study provides a narrow, in-depth analysis of economic sustainability, it overlooks essential social and environmental factors that could influence the long-term viability of such innovations. This limited focus restricts the broader applicability of its findings compared to other studies.

The contribution of the current research is significant, as it sheds light on the often-overlooked issue of multilayer plastic waste. This type of waste has not received adequate attention across various waste management aspects—including planning, research and development (R&D), implementation, monitoring, and evaluation. It is currently is not explicitly addressed in Indonesian legislation despite its considerable environmental impact.

The MSA approach offers new insights through the holistic integration of five sustainability dimensions: environmental, economic, social, legal, and infrastructure. This methodology differs from prior studies, which typically focus on one or two dimensions, such as environmental impact or economic efficiency in plastic waste management (Zhao et al., 2021). By analyzing all dimensions simultaneously, this research provides a deeper understanding of the interactions among factors influencing the sustainability of multilayer plastic waste management, particularly in developing countries like Indonesia (Firmansyah, 2022). This approach is especially relevant as it considers infrastructure limitations, weaknesses in law enforcement, and low public awareness (Jambeck et al., 2015). Furthermore, the application of MSA enables more comprehensive scenario simulations to evaluate the potential impacts of various interventions, such as Extended Producer Responsibility (EPR) policies, recycling technologies, and inter-agency collaboration (Firmansyah, 2022).

Several strategic actions must be taken to enhance recycling technologies and implement EPR effectively. Strengthening the regulatory framework for EPR should be a primary focus, requiring producers to assume responsibility for their product's lifecycle. Countries like Germany and South Korea have successfully reduced plastic waste through stringent regulations and vigorous enforcement (Plastics Europe, 2022). Economic incentives, such as tax cuts in Sweden, also encourage producers to transition to more environmentally friendly materials (Ellen MacArthur Foundation, 2023). Investment in recycling technology infrastructure, including pyrolysis and enzymatic technologies in Japan, is essential for processing plastic waste more efficiently (Wagner, 2020). Moreover, public education and awareness campaigns, exemplified by the national initiative "Recycle Together" in South Korea, have successfully increased plastic recycling rates (Song & Park, 2024). Collaborative efforts between the public and private sectors, as seen in the circular economy programs in the Netherlands, can further accelerate innovations in plastic waste management (Vanapalli et al., 2021).

Implementing advanced recycling technologies and robust EPR policies will positively impact local communities and economies. Technologies such as pyrolysis and solvent-based methods can generate new job opportunities in the recycling and technology research sectors (Wagner, 2020) These advancements could result in substantial economic benefits in Indonesia, particularly in urban areas. Adopting effective recycling technologies will also mitigate plastic pollution, which frequently contributes to public health issues, such as air pollution from burning plastic waste (Song & Park, 2024). Furthermore, well-implemented EPR policies can stimulate the growth of local industries, especially for small and medium-sized enterprises (SMEs) involved in recycling and material processing, similar to developments observed in Germany (Plastics Europe, 2022). In Indonesia, such policies could foster an economic ecosystem that supports the recycling sector and contributes to local economic sustainability.

The Multi-Aspect Sustainability Analysis (MSA) is a valuable tool for assessing sustainability across various sectors, but it often relies on subjective data collection methods like interviews and focus groups. This limitation could be addressed by incorporating objective measures, such as environmental impact assessments or economic modeling. Additionally, many studies lack long-term scenario analyses, which diminishes the strength of their recommendations. Integrating frameworks like Life Cycle Assessment (LCA) or Material Flow Analysis (MFA) would enhance evaluations, particularly in resource management. At the same time, including future planning and objective performance metrics would improve the credibility and applicability of findings.

The novelty of this research specifically tackles the environmental challenges of multilayer plastic waste, which is prevalent in packaging and poses unique recycling difficulties due to its complex composition. A key innovation is the application of the MSA framework to assess multilayer plastic waste management across environmental, economic, social, legal, and infrastructure dimensions. This targeted approach provides valuable insights into the sustainability of waste management practices in Indonesia, enriching discussions on plastic waste.

3. Methodology

Indonesia faces significant challenges in managing multilayer plastic waste due to its extensive use in packaging and the complexities of recycling these materials. Policies like Presidential Regulation No. 83 of 2018 aim to reduce marine plastic debris by 70% by 2025, but specific measures for multilayer plastics are still lacking. The Extended Producer Responsibility (EPR) policy requires producers to manage their products' entire lifecycle, yet enforcement is weak, leading many companies to neglect sustainable practices (Tahar, 2019).

Initiatives such as the ‘Bali Partnership’ have successfully reduced plastic waste through community-based programs, but multilayer plastics often evade recycling processes, ending up in landfills (Ain et al., 2021). The informal sector plays a crucial role in waste collection and sorting, but its lack of formal integration hinders overall waste management (Aprilia, 2021). Additionally, Indonesia’s waste infrastructure is ill-equipped to handle the complex separation required for multilayer plastics, resulting in low recycling rates.

Policy reforms are recommended to address these challenges. Strengthening EPR compliance with specific recycling targets for multilayer plastics, providing subsidies or tax incentives for companies investing in advanced recycling technologies, and enhancing public-private partnerships could improve sustainability. Stricter labeling regulations for recyclability and integrating the informal sector through capacity-building programs would enhance waste collection and recycling efficiency (Bappenas, 2024; Gunsilius et al., 2011). Furthermore, comprehensive waste audits and data collection were implemented to identify gaps and ensure data-driven regulations.

Multi-Aspect Sustainability Analysis (MSA) was selected for this study due to its distinct advantages over methods like Life Cycle Assessment (LCA) and Material Flow Analysis (MFA). MSA’s multidimensional approach evaluates sustainability holistically by considering five key aspects: environment, economy, social, legal, and infrastructure. This comprehensive perspective is crucial for multilayer plastic waste management, which involves complex challenges across multiple areas. Unlike LCA and MFA, which focus on specific dimensions, MSA encompasses the entire waste management system, integrating factors such as legal frameworks and community involvement, which are vital in Indonesia's context.

Furthermore, MSA is adaptable to local conditions, allowing for adjustments based on Indonesian government policies, infrastructure capabilities, and community engagement, making it more relevant than the rigid frameworks of LCA. Additionally, MSA places a strong emphasis on social and legal aspects, which are often overlooked in LCA or MFA. In Indonesia, community participation and legal policies significantly influence waste management success, and MSA facilitates a thorough assessment of these factors, ultimately providing a more complete understanding of the sustainability of waste management practices.

3.1. Research Design and Approach

Our empirical investigation adopted an exploratory approach to examine the perspectives of academics, businesses, communities, and government regarding barriers to social, economic, environmental, infrastructure, technology, and legal issues affecting multilayer plastic waste management. We utilized in-depth interviews, scenario planning, and an online expert poll (Fig. 2) (Guion, 2006). The semi-structured interviews featured open-ended questions, while scenario planning integrated insights from expert interviews and a literature review to analyze factors like social, ecology, economics, technology, and regulations.

In data collection from April to June 2024, we consulted 18 specialists and experts from various fields that concern multilayer plastic waste management, including academicians, non-government organizations, environmental health, plastic recycling, and the industrial economy, primarily based in Surabaya. Their identities were kept confidential due to data protection protocols. The study employed Multi-Aspect Sustainability Analysis (MSA) using the Rapid Appraisal Process (RAP) design to quickly assess sustainability by evaluating ecological, economic, social, legal, and technological dimensions. Using expert judgment, this design assigns scores to various attributes within these domains, which are then analyzed to visualize sustainability. It offers a rapid, cost-effective approach for regions with limited resources, providing a holistic view of waste management (Pitcher & Preikshot, 2001) principle for efficient decision-making (Firmansyah, 2022). Using archival data, interviews, focus group discussions, and questionnaires, we combined qualitative and quantitative methods to analyze barriers and their interrelations (Nurpagi et al., 2022). Workshops and focus group discussions were also held to triangulate findings and enhance validity.

Fig. 2. Structure of the sequence of methods applied

3.2.Data Collection Methods

Multi-Aspect Sustainability Analysis (MSA) is a powerful tool for assessing sustainability performance across activities, institutions, and companies. This rapid assessment approach utilizes an existing database compiled by experts or respondents meeting specific criteria, allowing for swift evaluations without reanalysis or model redevelopment. The framework integrates data from desk studies and expert judgments using a structured questionnaire model with multiple Likert scale response options. The classification of the indicators in each aspect was based on the concepts of ‘good’ and ‘poor’ (Pitcher & Preikshot, 2001) and the latest with Focus Group Discussions (FGDs) to enrich the result, as shown in Fig. 3.

FGDs offer professional perspectives on the variables being considered, whereas desk studies offer scientifically based factors and indicators from academic sources (Schader et al., 2014). Through in-depth interviews or focus group discussions, expert respondents—typically important players in the field—contribute. Accurate mode value selection is ensured by an odd number of experts.

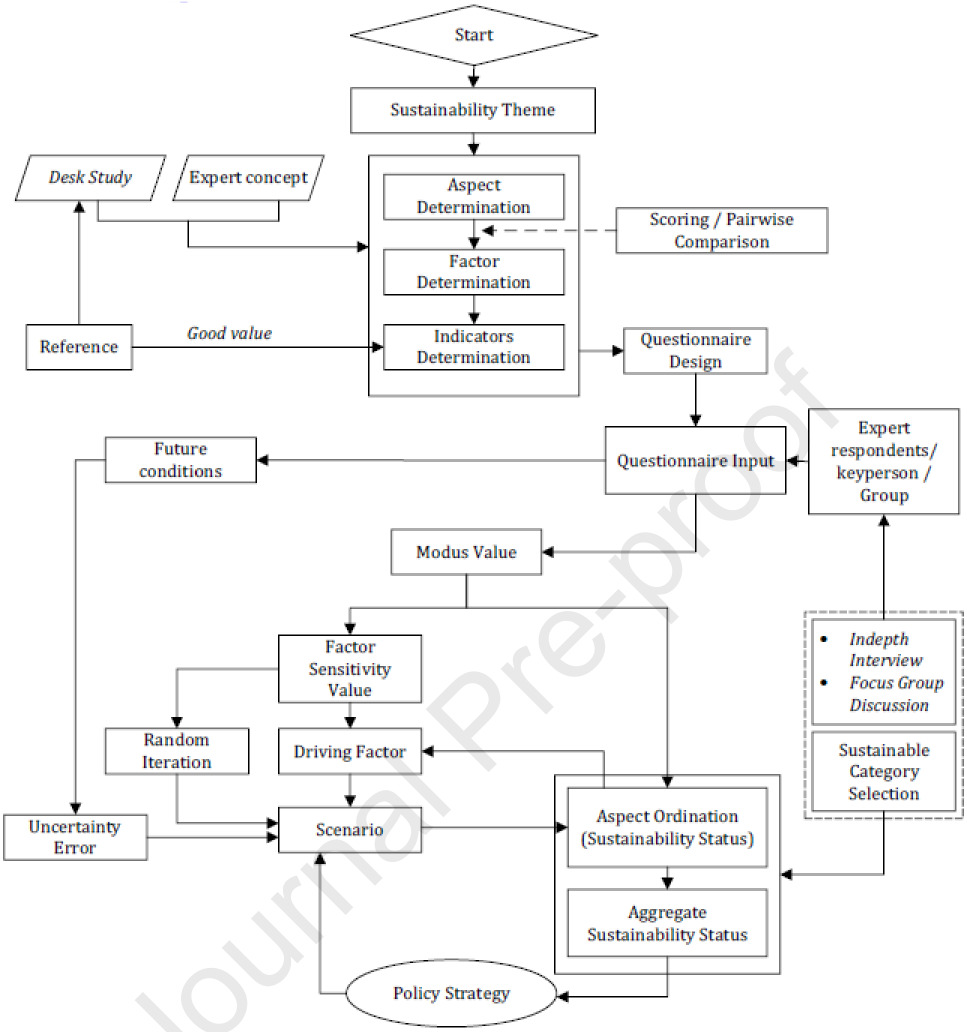


Fig 3. Conceptual framework of the Multi-aspect Sustainability Analysis approach (adapted from (Firmansyah, 2022))

Through the use of expert opinion or real-world scenarios, the MSA method assesses sustainability and produces outputs such as uncertainty error, leverage factors, and status index. These results help policymakers create scenarios and sustainability plans to develop the strategies and policies in social, economic, and environmental factors (Naegler et al., 2021).

Numerous studies have been carried out to investigate the different facets of sustainability and highlight the significance of interdisciplinary research and sustainable practices to support waste management utilizing Multi-Criteria Decision Making (MCDM) techniques. The importance of strategic planning and policy formulation was highlighted by A. Singh & Sushil, (2017), who used the Total Interpretive Structural Modeling (TISM) technique to discover hierarchical waste management components.

Rousta et al., (2017) advocated for multidisciplinary and context-specific solutions by highlighting the need for infrastructure that integrates both technical and social components through surveys and modeling methodologies. Hellwig et al., (2019) carried out a systematic mapping of the literature and discovered a dearth of study on migrant waste sorting habits, highlighting the crucial role that cultural engagement plays in creating effective policies.

For further insights and a comprehensive breakdown of the methodologies used in evaluating sustainability across multiple aspects, please refer to the supporting information page below, which outlines the specific criteria (S.1.), analytical tools (S.2.), and sustainability aspects applied (S.3.)

4. Result and Discussion

4.1. Environment Aspect

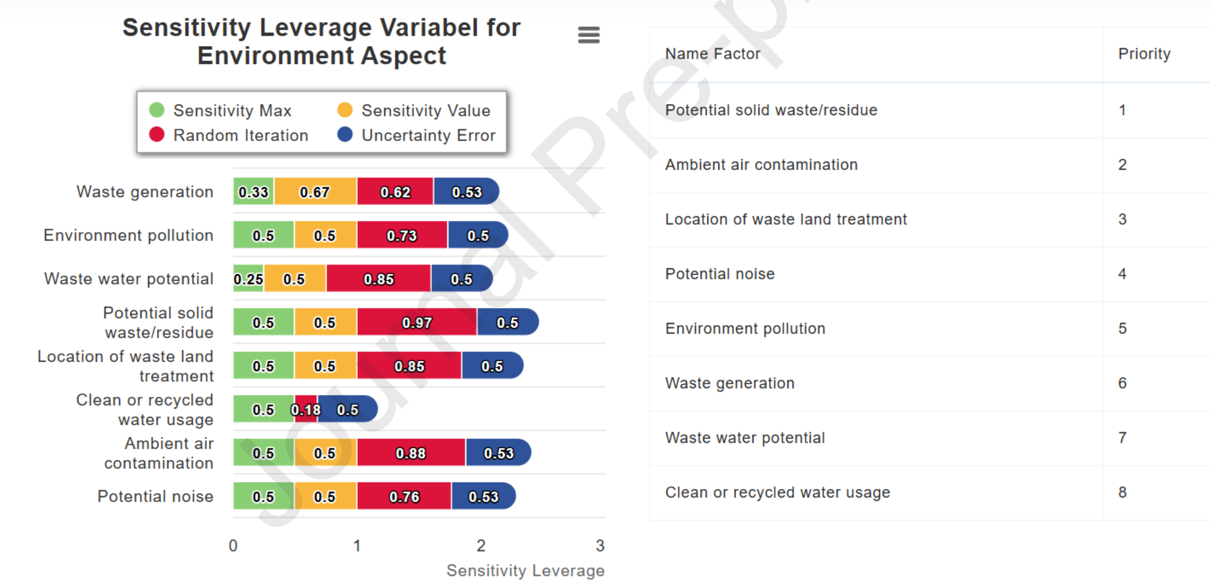
The sensitivity leverage analysis highlights various environmental factors and their relative impact on sustainability outcomes. Each factor's sensitivity is represented by four indicators—Sensitivity Max, Sensitivity Value, Random Iteration, and Uncertainty Error—illustrating the degree of influence these factors have on the overall environmental aspect. The 8 factors that have been analyzed are categorized into 3 levels, as shown in Fig. 4. Three factors are High-priority factors, such as Potential Solid Waste/Residue (Priority 1) and Ambient Air Contamination (Priority 2), demonstrating strong sensitivity values, suggesting that effective management of solid waste and air quality are critical to achieving sustainability goals. These factors substantially impact environmental outcomes, meaning targeted interventions could significantly enhance overall sustainability. Accumulated waste can lead to land and water contamination, greenhouse gas emissions, and difficulties in waste treatment. The high sensitivity of this variable emphasizes the importance of waste reduction and recycling to reduce its environmental impact. Air pollution affects air quality and public health and contributes to climate change and acid rain, impacting both natural ecosystems and urban areas. Reducing air pollution, therefore, could significantly improve environmental sustainability. The Location of Waste Land Treatment (Priority 3) is also a high-impact factor, indicating that optimizing waste treatment locations could further reduce environmental burdens and support sustainable practices. According to Soares et al., (2022) and Soemadijo et al., (2022), the location of waste land treatment for multilayer plastic waste management is crucial because it directly affects plastic waste disposal's environmental, economic, and social impacts.

The importance of this processing land is also because it will support the effectiveness of the recycling process (Cook et al., 2022) and the availability of proper land to mitigate environmental issues and create opportunities for reducing waste (Goyal, 2020), conserving natural resources, and minimizing the environmental impact of plastic waste through the circular economy concept. In addition, there is a need to develop and implement more advanced recycling technologies, such as chemical recycling (Larrain et al., 2021), to improve plastic materials' quality and recycling rate from multi-layered packaging waste. Effective recycling and waste management strategies are essential for decreasing the adverse effects of plastic waste on the environment and advancing a circular economy (Ragossnig & Schneider, 2019).

Moderate-priority factors include Potential Noise (Priority 4) and Environmental Pollution (Priority 5), showing moderate sensitivity values. While these factors are influential, their overall impact on sustainability is less than the top-priority factors. Nonetheless, addressing noise and pollution is essential for minimizing local environmental impacts, and these aspects should still be managed effectively to support broader sustainability objectives.

Lower-priority factors, such as Waste Generation (Priority 6) and Wastewater Potential (Priority 7), show mixed sensitivity. Though relevant, they exert a lesser influence on sustainability outcomes compared to the higher-priority issues. Clean or Recycled Water Usage (Priority 8) has the lowest sensitivity influence, suggesting that, in this analysis, recycled water usage does not significantly affect overall environmental sustainability. While recycling water is beneficial, it may not be the most critical resource allocation area in this context.

This analysis emphasizes the importance of prioritizing solid waste management and air quality control to maximize environmental benefits. Focusing on the highest-impact factors first allows resources to be allocated more efficiently, ensuring that sustainability efforts produce substantial results. This can help create a closed-loop system (El-Halwagy, 2024) where materials are reused rather than discarded. Investing in recycling infrastructure and technologies can create jobs (Gunsilius et al., 2011) and stimulate economic growth (Rozikin & Sofwani, 2023) while promoting sustainable practices (García-Valiñas et al., 2023).



Name Factor	Priority
Potential solid waste/residue	1
Ambient air contamination	2
Location of waste land treatment	3
Potential noise	4
Environment pollution	5
Waste generation	6
Waste water potential	7
Clean or recycled water usage	8

Fig 4. Environmental aspects and their relative impact on sustainability outcomes (Sensitivity Leverage Variable)

This can also help to create a market for recycled plastic products, encouraging more companies to invest in recycling (Franco-García et al., 2019). Preparing standards for materials used in producing multilayer plastics such as polyolefins that can have more value in the recycling process and improving waste management performance through an integrated planning, implementation, monitoring/evaluation, and reporting system is needed.

The sustainability status for the environmental aspect is calculated by plotting performance values along the X and Y axes, each ranging from 0 to 100. The X-axis reflects the current sustainability value, while the Y-axis indicates potential future trends. In this case, the environmental aspect has a current score of 54.13 on the X-axis, placing it within the moderate sustainability category based on the MSA framework, which typically considers scores between 33 and 66 moderate. This suggests that the current environmental performance is adequate but leaves room for improvement, as shown in Fig. 5.

The future trend, represented by the Y-axis value of 48.96, indicates a slight decline in performance if no changes or interventions are made. This decrease suggests that the environmental aspect will likely encounter challenges in maintaining its status, potentially slipping below acceptable sustainability levels. If current practices continue unaddressed, there is a risk that performance will worsen further over time. It is critical to identify the leverage factors driving the anticipated decline and address them proactively. Implementing moderate or optimistic scenario-based strategies can help stabilize or improve future performance. In addition, monitoring the uncertainty error- the degree of deviation between predicted and actual outcomes - will ensure that improvement measures remain aligned with real-world conditions.

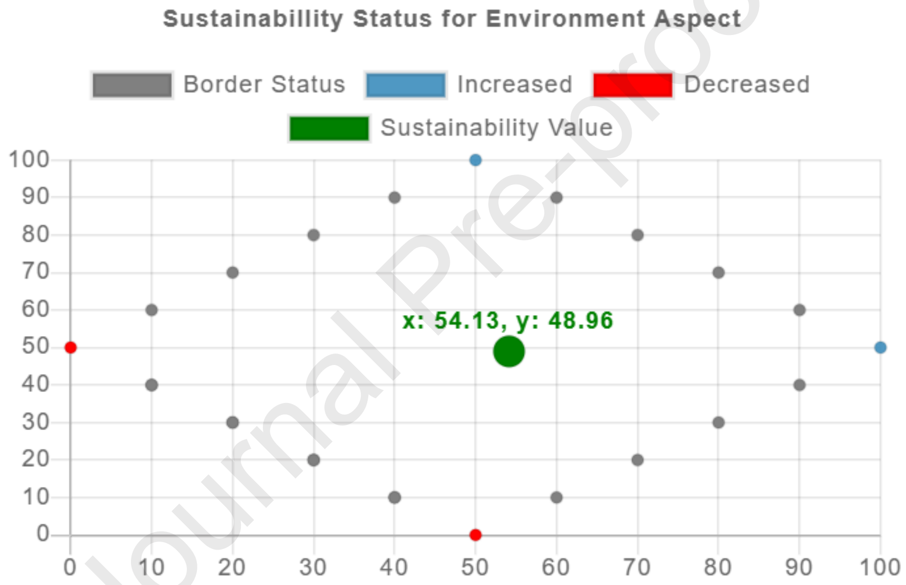


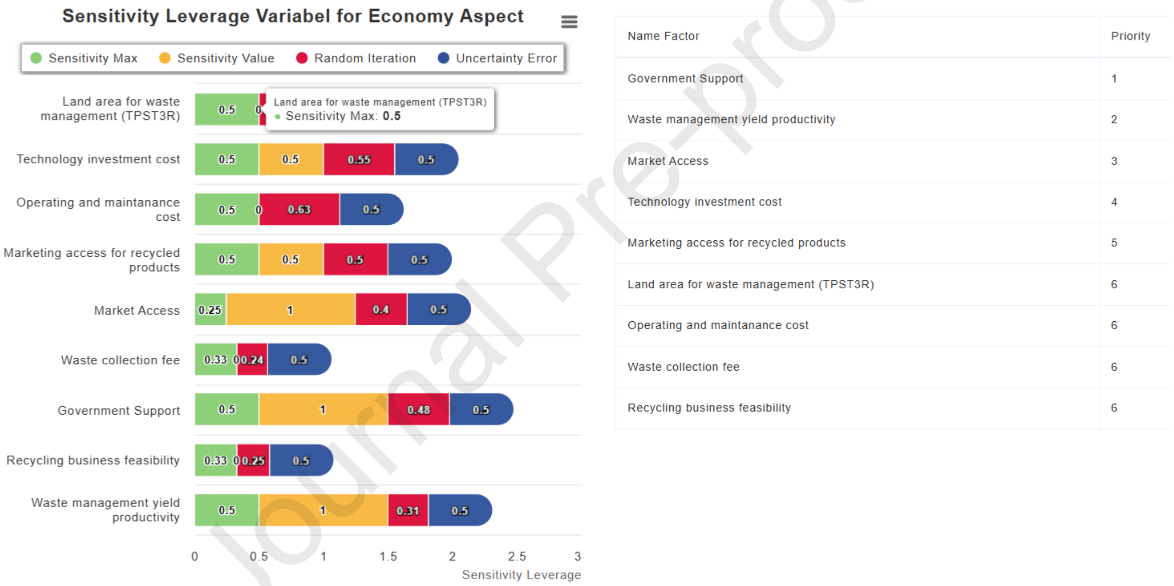
Fig 5. Sustainability Status for Environment Aspect

Environmental aspects currently have a moderate sustainability status, so improvements are still needed in each factor. Stakeholders are advised to pay attention to the leverage factors that affect performance and implement targeted strategies to maintain or improve sustainability. Without such action, the environment's status may continue to decline and jeopardize long-term sustainability goals.

4.2. Economic Aspect

Fig 6. provides a chart that offers insights into the sensitivity leverage variables for the economic aspect. It evaluates key economic sustainability factors, focusing on sensitivity max value, sensitivity value, random iteration, and uncertainty error. These metrics highlight the most impactful factors and guide the prioritization of interventions to improve economic performance effectively. This analysis helps policymakers focus on critical areas needing attention or improvement, guiding targeted strategies to enhance economic sustainability (Abdullah & Abedin, 2024).

Government support is the most critical factor at the top priority list, designated as Priority 1. A high sensitivity leverage value nearing 1 indicates that any change in government involvement—such as policies, funding, or incentives—will substantially affect economic sustainability. Governments play a vital role in developing markets (Shah et al., 2019) for recycled materials by implementing policies that encourage using recycled content in manufacturing. Investments in waste management (Van de Klundert & Anschutz, 2001) and infrastructure (Yiğitcanlar & Dur, 2017) ensure that waste is collected, transported, and processed effectively, reducing improper disposal. International cooperation (Samarasinghe et al., 2021) facilitated by governments helps set global standards and best practices for managing plastic waste sustainably. Furthermore, government policies (Roy et al., 2022) aimed at environmental protection to ensure that recycling processes minimize ecological impact.



Name Factor	Priority
Government Support	1
Waste management yield productivity	2
Market Access	3
Technology investment cost	4
Marketing access for recycled products	5
Land area for waste management (TPST3R)	6
Operating and maintanance cost	6
Waste collection fee	6
Recycling business feasibility	6

Fig. 6. Economic aspects and their relative impact on sustainability outcomes (Sensitivity Leverage Variable)

Waste Management Yield Productivity is closely followed in importance and is ranked as Priority 2. Its sensitivity value of 1 signifies that optimizing the productivity of waste management efforts is essential to improving the economic aspect. Any fluctuation in these two factors could significantly impact sustainability outcomes, making them immediate targets for action. Market Access, categorized as Priority 3, also plays a significant role, but its impact is slightly less critical than government support and yield productivity. Enhancing market access would still be beneficial, especially for sectors linked to waste recycling and green technology. Technology Investment Cost, ranked as Priority 4, suggests that reducing the financial burden of technology adoption would moderately enhance sustainability. However, it does not require as urgent intervention as the top priorities. Similarly, Marketing Access for Recycled Products holds Priority 5, indicating the importance of expanding market opportunities for recycled materials to drive economic performance.

Several other factors share Priority 6, suggesting they are less critical but relevant to overall sustainability. These include Land Area for Waste Management (TPST3R), Operating and Maintenance Costs, Waste Collection Fees, and Recycling Business Feasibility. While these elements contribute to the economic aspect, their relatively low sensitivity values indicate that changes in these areas may not generate as immediate or significant an impact as higher-priority factors. Financial support (Qureshi et al., 2020; Soemadijo et al., 2022), funding and incentives make it feasible for companies to invest in advanced recycling technologies and infrastructure. Public awareness campaigns (R. Kumar et al., 2021; Kurniawan et al., 2023), supported by government resources, educate citizens on the importance of recycling multilayer plastics, increase participation rates, and reduce contamination.

The chart highlights the need to prioritize efforts on Government Support and Waste Management Yield Productivity to achieve meaningful improvements in economic sustainability. Focused interventions in market access and technology investment would further enhance economic outcomes, albeit with slightly less urgency. Addressing uncertainties and variability in waste collection fees and operating costs will also ensure long-term economic stability and efficient resource allocation and refine policy interventions through scenario planning (S. Kumar et al., 2021), ensuring continuous monitoring and policy adjustments (R. Kumar et al., 2021; Kurniawan et al., 2023; Potting et al., 2018) to address potential declines and leverage positive changes. Government support is crucial for managing multilayer plastic waste due to several critical factors besides waste management, such as yield productivity and market access for recycled products. Government regulations create a structured framework that mandates proper recycling and handling of these plastics, ensuring consistent practices

The Sustainability Status for Economy Aspect shows a detailed analysis of the current economic performance and its future potential Fig. 7. The x-axis measures the current sustainability status, where a higher value signifies better financial performance. At the same time, the y-axis reflects the potential for future improvement, with values above 50 indicating a positive trajectory and values below 50 suggesting possible decline. The green marker at (55.56, 50) represents a key sustainability value, indicating that the current economic condition is moderately sustainable, slightly above the midpoint on the x-axis. This suggests that while the economy is stable, it has not reached optimal performance. The y-axis value of 50 implies a neutral outlook, meaning that without significant intervention, the economic status will likely remain stable without substantial improvement or deterioration.

The chart also highlights several critical indicators. A blue marker at (50, 100) shows an area of solid improvement, reflecting positive progress in at least one economic aspect. However, red markers, such as those at (50, 0), signal areas where performance declines, demanding immediate policy intervention to prevent further setbacks. Most indicators are represented by gray markers, indicating that many aspects of the economy are neutral or stagnant, with minimal change or progress.

From a strategic perspective, the MSA framework recommends prioritizing areas marked in red, as they pose the most significant risk of decline. Indicators near the green sustainability value should also be monitored to maintain stability and not regress. The blue marker represents a well-performing area that aligns with Group I of the MSA framework, meaning it should continue to be supported to sustain progress. The chart reflects a moderate economic performance with stable but unremarkable future potential. Strategic interventions should address declining indicators and leverage neutral aspects to enhance sustainability. By following these recommendations using the priority factor, the economy can move toward more sustainable growth and improved performance over time.

Fig. 7. Sustainability Status for Economy Aspect

4.3. Social Aspect

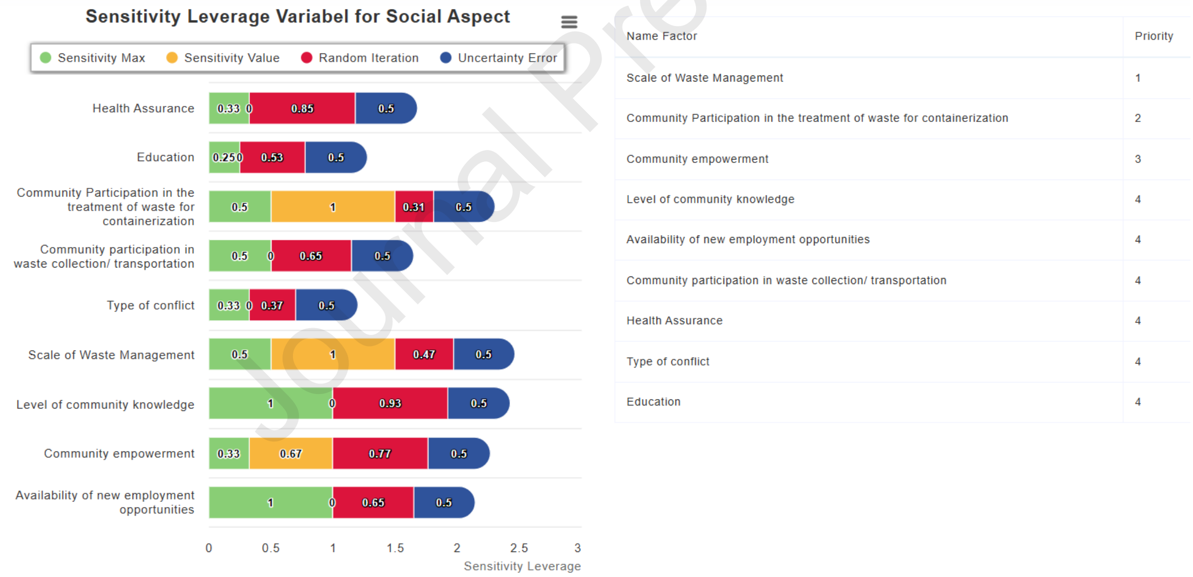
Sensitivity Leverage Variable for Social Aspect illustrates the sensitivity analysis of various social sustainability factors, assessing each based on Sensitivity Max, Sensitivity Value, Random Iteration, and Uncertainty Error. This breakdown helps identify the most influential factors on social sustainability and guides policy prioritization.

Based on the analysis of the leverage factors that emerged from the 9 factors analyzed, it only consists of 2 factors: top priority is Scale of Waste Management, Community Participation in the treatment of waste for containerization, and Community Empowerment. These factors are critical leverage points, meaning their changes would significantly impact social sustainability, making them ideal candidates for policy intervention. Additionally, factors like Community Empowerment, Level of Community Knowledge, and Availability of New Employment Opportunities display high sensitivity values, suggesting they are influential, though less critical than the top two priorities.

Among these, the Level of Community Knowledge shows a maximum sensitivity value of 1, indicating a strong and direct influence on social outcomes. However, it has been assigned a lower priority level (4), possibly due to other higher-impact factors or the complexity of intervening effectively in this area. Similarly, the Availability of New Employment Opportunities and Community Empowerment also reach a sensitivity max of 1 but exhibit some variability in impact, as indicated by random iteration values, suggesting that their precise effects may vary in different scenarios.

Factors with higher uncertainty, like Health Assurance and Education, have notable uncertainty errors. These factors might experience variable outcomes under different conditions, indicating that policy actions should be cautious to account for potential fluctuations. For instance, Type of Conflict demonstrates moderate sensitivity with considerable uncertainty, which, while not an immediate priority, suggests it should be monitored closely.

The scale of Waste Management and Community Participation in Waste Treatment should be the immediate focus for social sustainability strategies, as they have high sensitivity and low uncertainty, making them reliable leverage points. Factors like Community Knowledge and New Employment Opportunities hold the potential for long-term impact but require flexibility to accommodate their uncertainty. High-uncertainty factors like Health Assurance and Education should be approached cautiously, potentially through pilot initiatives, to manage the risk of unpredictable outcomes. This analysis underscores the value of a targeted approach to social sustainability, concentrating on high-impact areas while carefully managing factors with variability, as shown in Fig 8.



Name Factor	Priority
Scale of Waste Management	1
Community Participation in the treatment of waste for containerization	2
Community empowerment	3
Level of community knowledge	4
Availability of new employment opportunities	4
Community participation in waste collection/ transportation	4
Health Assurance	4
Type of conflict	4
Education	4

Fig. 8 Social aspects and their relative impact on sustainability outcomes (Sensitivity Leverage Variable)

The aspects that greatly influence the sustainability of multilayer plastic waste management are the scale of waste management (the highest priority), community participation in waste treatment for containerization, and community empowerment (Laguador et al., 2013). This is important because the determination of the scale carried out by the community will determine the amount and processing available. The waste treatment from home is expected to be done because it will reduce waste going to landfills (Hahladakis et al., 2020).

The complex problem is that the waste disposal process (Amin et al., 2023; Leng et al., 2018) is still mixed and directly managed in the final disposal. The process of sorting and processing waste from home is fundamental, so waste can be divided according to its type to reduce the effect of greenhouse gas emissions and pollution (Tan et al., 2023). These operations also create stable markets for recycled materials by providing a consistent supply and encouraging using recycled content in new products. Additionally, they can invest in public education (Aprilia, 2021; Kakadellis et al., 2021; Torres-Pereda et al., 2020) to increase awareness and participation in recycling programs. In this social aspect, it is also necessary to increase community participation in implementing three independent concepts (recycling, reuse for packaging, and the need for energy recovery), increase capacity building on multilayer plastic, and expand community participation in the waste management system.

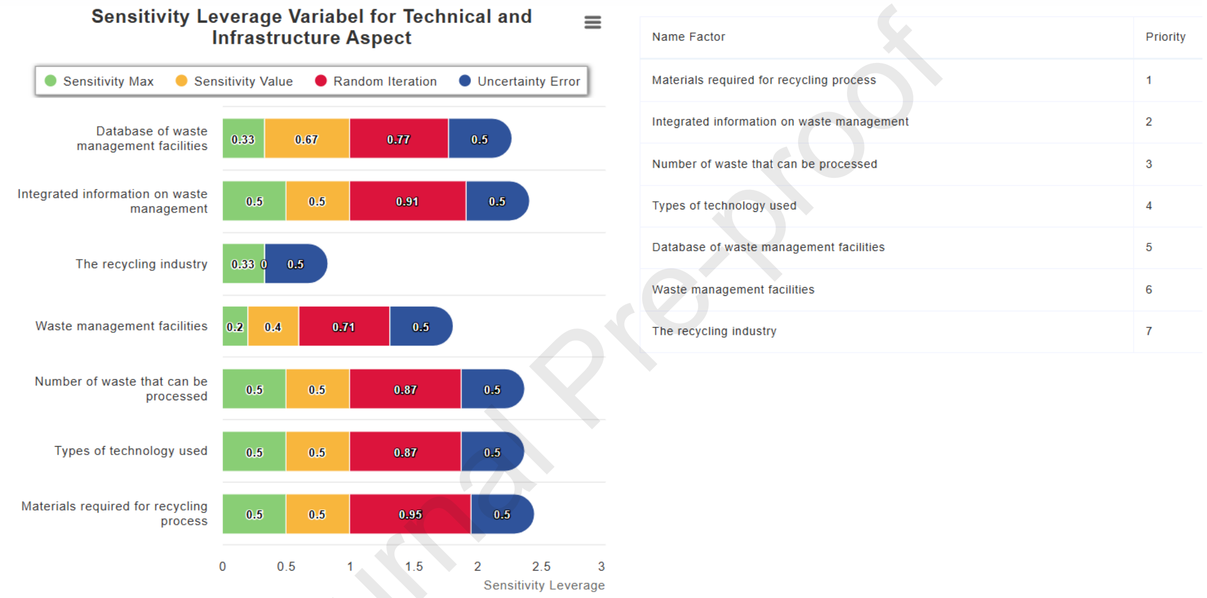
As shown in Fig. 9, that the overall social aspect is seen in the green dot with coordinates (70.33, 50) representing the overall sustainability score for the social aspect. This value reflects an aggregate measure of social sustainability, with an X-axis position of approximately 70.33 and a Y-axis position of 50. The relatively high X-value indicates a moderately positive overall social sustainability score. However, the Y-value being at the midpoint (50) may indicate that there is still room for improvement to achieve optimal sustainability.

Fig. 9 Sustainability Status for Social Aspect

To improve the sustainability status, efforts should focus on shifting the red (decreased) indicators back toward a neutral or positive position and continuing to support the blue (increased) indicators. Additionally, indicators in gray (border status) should be prioritized for regular monitoring, as they have the potential to tip either positively or negatively with small changes. A strategy aimed at stabilizing or enhancing these indicators would likely strengthen the social aspect's sustainability status.

4.4. Technical and Infrastructure

Based on the analysis of the leverage factors that emerged from the 7 factors analyzed, it only consists of 2 factors: integrated information on waste management and types of technology used, as shown in Fig. 10. Sensitivity Leverage Variable for Technical and Infrastructure Aspect chart analyzes the impact of various factors on sustainability within the technical and infrastructure domains, evaluating each factor based on Sensitivity Max, Sensitivity Value, Random Iteration, and Uncertainty Error. The factor with the highest priority is the Materials Required for the Recycling Process (Priority 1), indicating its critical role in sustainability efforts. Although it has a substantial sensitivity max of 0.5, it also shows high levels of random iteration and uncertainty, suggesting that its impact on sustainability may fluctuate in different scenarios. Similarly, Integrated Information on Waste Management (Priority 2) is crucial due to the importance of data integration in waste management, though it also exhibits variability that requires careful management.



Name Factor	Priority
Materials required for recycling process	1
Integrated information on waste management	2
Number of waste that can be processed	3
Types of technology used	4
Database of waste management facilities	5
Waste management facilities	6
The recycling industry	7

Fig. 10. Technical and Infrastructure aspects and their relative impact on sustainability outcomes
(Sensitivity Leverage Variable)

Integrated information on waste management (Amali et al., 2024; Hestin et al., 2017; Kurniawan et al., 2023) is crucial for effectively managing multilayer plastic waste for several reasons besides materials required for the recycling process (Su et al., 2021), types of technology used (Mwanza & Mbohwa, 2019), and the amount of waste (Takenaka et al., 2017) that can be processed. It enhances coordination among stakeholders, including waste collectors, recyclers, and regulatory bodies, ensuring efficient collection, sorting, and processing. Accurate data and monitoring (Jagath et al., 2019) enable tracking of waste from production to disposal, identifying areas for improvement (Lopez-Aguilar et al., 2022) and leading to better waste management strategies (Gala et al., 2020). Policymakers benefit from comprehensive data, formulating targeted regulations and policies. Resource optimization (Arena et al., 2023) is achieved by understanding the waste management landscape and ensuring that financial (Gunsilius et al., 2011), technological, and human resources are used effectively (Asadollahi et al., 2022).

Other moderately prioritized factors, like the Number of Waste that can be Processed (Priority 3) and Types of Technology Used (Priority 4), are also influential in maintaining sustainability, with sensitivity max values of 0.5 and considerable random iteration and uncertainty values. Their importance highlights the need for adaptable technology and adequate processing capacity to ensure efficient waste management. Database of Waste Management Facilities (Priority 5) plays a supportive role, influencing infrastructure sustainability through reliable data access.

Lower-priority factors, such as Waste Management Facilities (Priority 6) and The Recycling Industry (Priority 7), have lower sensitivity max values (0.2 and 0.33, respectively), suggesting that while they are essential, they have a less direct impact on driving sustainability compared to higher-priority factors. However, the random and uncertainty values associated with these factors indicate that stable operational processes are still needed to prevent unexpected impacts on sustainability.

Prioritizing high-impact factors such as materials for recycling and integrated information systems, while accounting for their variability, can significantly improve sustainability in technical and infrastructure domains. Investing in adaptable technology and expanding waste processing capacity will further enhance resilience. While lower-priority factors may have a less direct effect, maintaining their stability is essential for supporting overall sustainability goals in this aspect.

Such as public awareness and engagement (Galluccio, 2021) are also enhanced through transparent and accessible information, encouraging active participation (Dilkes-Hoffman et al., 2019) in recycling programs. Integrated information (Amali et al., 2024) fosters innovation by providing insights into current practices and outcomes, driving the development of new technologies (Cruz Sanchez et al., 2020) for more efficient recycling of multilayer plastics. Compliance with regulatory requirements (Maione et al., 2022) is facilitated by detailed records of waste management activities, ensuring adherence to legal standards (Goodman, 2017). Additionally, integrated information allows for a better assessment (Bianchini & Rossi, 2021; Fan et al., 2023) of the environmental impact of waste management practices (Abdullah & Abedin, 2024), enabling the development of strategies to minimize ecological footprints (R. Kumar et al., 2021).

This study also concludes that there is still a need for optimization in the process of collecting and transporting waste; it is necessary to identify waste management technology, strengthening extended producer responsibility (EPR) and corporate social responsibility (CSR) is a priority (Fianda et al., 2021), multilayer plastic management must be appropriate starting from collection, segregation, redesigning, upcycling, downcycling and chemical recycling technology, and the need for Indonesian National Standards (SNI) (Fan et al., 2023) on chemical recycling technology and other technologies to reduce multilayer plastic waste.

The analysis of the technical and infrastructure aspects of sustainability indicates a moderate overall score of 56.14 as shown in Fig 11., reflecting both areas of strength and opportunities for improvement. To enhance sustainability in this domain, a comprehensive, multifaceted strategy is essential.

Investing in sustainable technologies, optimizing processes, and allocating essential resources—such as budget, skilled personnel, and quality materials—can enhance operational performance and effectively tackle key challenges. Continuous improvement programs, including regular audits, benchmarking, and sustainability training, help sustain progress. Additionally, real-time analytics systems can identify early problem signs, enabling timely corrective actions. Approaches like preventive maintenance, scenario planning, and small pilot projects are valuable for stabilizing performance indicators and mitigating risks. An integrated, data-driven strategy that fosters collaboration among technical, operations, and sustainability teams is crucial for establishing measurable targets and monitoring KPIs. Furthermore, seeking external partnerships and certifications, such as ISO 14001 and ISO 50001, can provide specialized expertise and validate a commitment to sustainable practices.

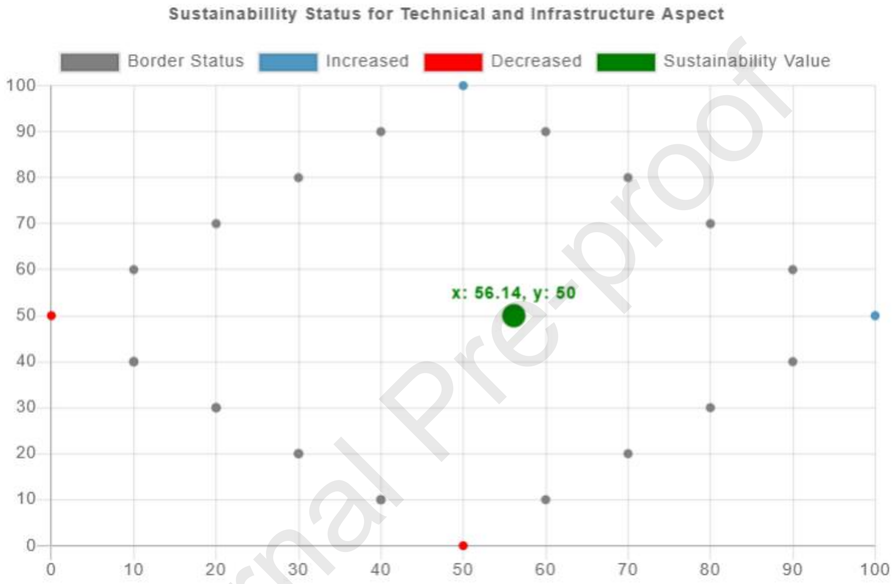


Fig. 11 Sustainability Status for Technical and Infrastructure Aspect

4.5. Law and Institutionalization Aspect

This aspect has a sustainability status of 30.5%, which can be said to be low sustainable. Still, it will be very significant to become even more highly sustainable with an increased value of up to 50%, with the main priority being cooperation with surrounding areas, as shown in Fig 12. In the law and institutionalization aspects, of the 6 factors of the sensitivity leverage variables analyzed, there are 4 main factors based on the priorities determined: cooperation with surrounding areas (priority 1), it's priority ranking indicates that strengthening cooperation with nearby regions is crucial for sustainability, marketing institutions (priority 2), this factor emphasizes the importance of efficient marketing institutions in supporting law and institutionalization. Improving marketing processes or increasing resource allocation for marketing efforts could positively affect sustainability outcomes, extension centers (priority 3), the Extension Centre plays a significant role in the law and institutionalization aspect, Monitoring and possibly expanding the center's functions could yield more consistent outcomes. and law enforcement/enforcement of waste management regulations as shown in Fig 13.

Cooperation (Sztangret, 2020) with neighboring areas is essential for effectively managing coated plastic waste due to several key factors like marketing institutions, extension centers, and law enforcement/implementation (Krämer, 2016) of regulations on waste management (Debnath et al., 2023). It enables the pooling of resources and expertise, leading to more efficient waste management practices by sharing facilities, equipment, and personnel, thus optimizing resource use. This collaboration also allows for economies of scale, making investments in advanced recycling technologies and infrastructure more cost-effective as larger volumes of waste can cover the costs incurred. Implementing consistent waste management standards across the region ensures effective sorting, processing, and recycling of multi-layered plastics, which often require specialized handling (Tesfaye & Kitaw, 2021).

Coordinated campaigns benefit public engagement and education by reaching a wider audience and promoting sustainable behavior. Cooperation also improves crisis management, ensuring a resilient response to natural disasters or contamination events. Finally, regional collaboration generates economic opportunities (Garcia & Robertson, 2017), such as job creation and developing markets for recycled materials, encouraging further investment in waste management infrastructure (Di Foggia & Beccarello, 2022).

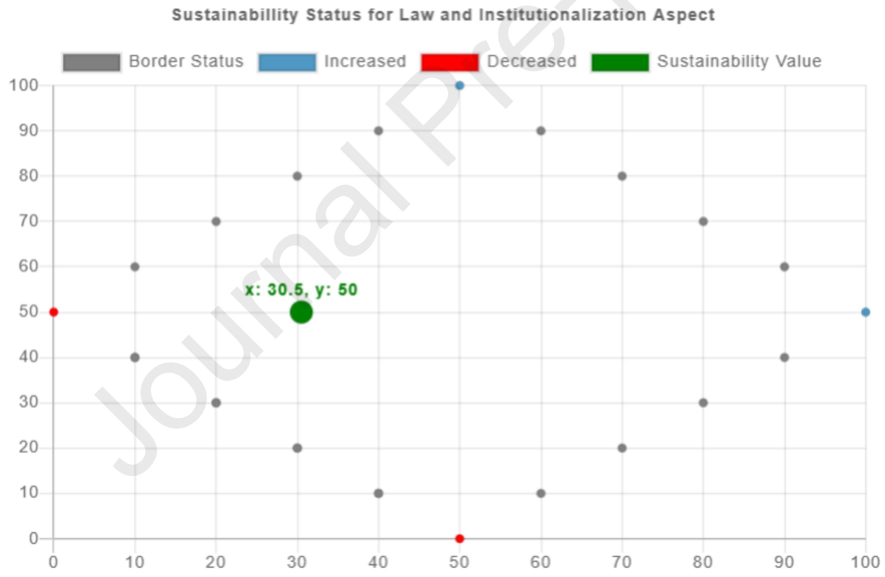
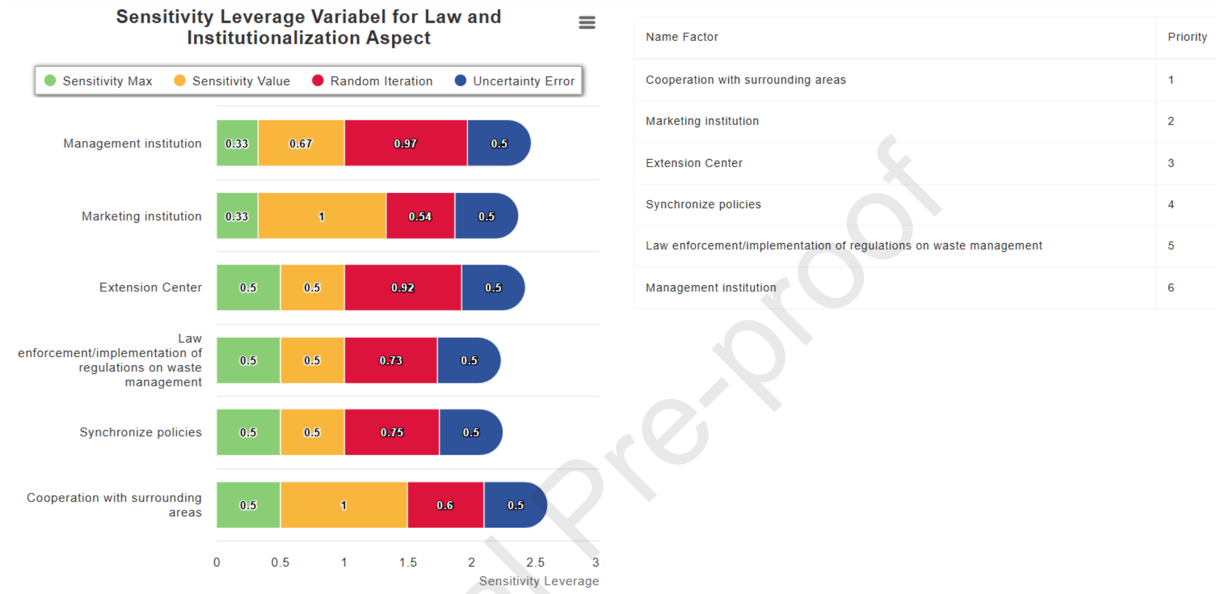


Fig. 12 Sustainability Status for Law and Institutional Aspect

Synchronize Policies (Priority 4), remains essential for ensuring cohesive institutional practices, as indicated by its higher priority rank. Law Enforcement/Implementation of Regulations on Waste Management (Priority 5), effective enforcement and regulatory implementation for waste management is necessary for sustained compliance and adherence to environmental standards. While its sensitivity value is moderate, it's critical for law and institutionalization goals. Management Institution (Priority 6), the management institution's effectiveness in coordinating various institutional tasks still affects overall sustainability. Improvements here could yield incremental benefits.

Improved collection and transport networks result from regional cooperation, reducing carbon footprints and ensuring timely delivery of plastics to recycling facilities. Knowledge exchange and best practices foster innovation, leading to improved methods and technologies for waste management. Regulatory alignment across areas creates an efficient environment, facilitating compliance for businesses and waste management entities. Joint efforts significantly reduce environmental impacts, reducing landfill utilization, pollution, and greenhouse gas emissions.



Name Factor	Priority
Cooperation with surrounding areas	1
Marketing institution	2
Extension Center	3
Synchronize policies	4
Law enforcement/implementation of regulations on waste management	5
Management institution	6

Fig. 13. Law and Institutionalization aspects and their relative impact on sustainability outcomes
(Sensitivity Leverage Variable)

This study recommends the alignment of data-based waste management strategies and policies, the need for inclusive institutions in multilayer plastic management, and the government can issue policies that regulate the overall process and types for all actors in the multilayer plastic waste management sector.

4.6 Sustainability Value of Multilayer Plastic Waste Management Scenarios

The analysis of sustainability across various aspects—Social, Economy, Environment, Technical and Infrastructure, and Law and Institutionalization—reveals distinct outcomes under different scenarios. In the existing condition, the sustainability status varies significantly among aspects, with Social (70.33) and Technical and Infrastructure (56.14) showing relatively higher scores, indicating moderate sustainability. The Economy and Environment aspects score around the mid-50s, suggesting that they are also moderately sustainable, though there is room for improvement. Law and Institutionalization is notably low at 30.5, highlighting a substantial gap in this area that could be crucial for broader sustainability. Overall, the total average sustainability score is 53.33, which classifies the existing condition as Sustainable but with a clear need for improvements, particularly in legal and institutional support.

In the first scenario, which focuses specifically on improving the legal and institutional framework, there are notable gains, especially in Law and Institutionalization, which rises from 30.5 to 63.83. This improvement raises the total average sustainability score to 69.21. Although other aspects experience slight improvements due to the supportive role of stronger institutional frameworks, the Environmental aspect remains stagnant at 54.13. This outcome suggests that while legal and institutional improvements can positively impact sustainability, they may not address ecological issues directly. Nonetheless, the system still remains categorized as Sustainable but now closer to the higher sustainability range.

The second scenario, which involves improvements across all aspects, results in the highest sustainability gains. Here, Social reaches an ideal score of 100, and significant improvements are observed in Economy (80.56), Technical and Infrastructure (70.43), and Law and Institutionalization (80.5). The Environment also sees an increase to 60.38, reflecting that a comprehensive approach to enhancing sustainability can positively impact all aspects, including ecological factors. With a total average sustainability score of 78.37, this scenario achieves a Very Sustainable classification, indicating that a holistic improvement strategy yields the most balanced and sustainable outcomes across all domains are presented in Table 1.

According to the results from the table, second scenario is the best scenario to make improvement in all aspect. Trough this scenario, all aspect will improve sustainable value into very sustainable conditions.

Table 1. Status and sustainability value of existing conditions and scenarios

No.	Aspect	Existing	1st Scenario: Law and Institutionalization Improvement	2nd Scenario: All aspect improvement
1	Social	70.33	92.56	100
2	Economy	55.56	72.22	80.56
3	Environment	54.13	54.13	60.38
4	Technical and Infrastructure	56.14	63.29	70.43
5	Law and Institutionalization	30.5	63.83	80.5
Total Average		53.33	69.21	78.37
Status Sustainability		Sustainable	Sustainable	Very Sustainable

The kite diagram in Fig. 14 also illustrates each facet's sustainability index value of plastic multilayer waste management. The diagram illustrates that several features are classified under the sustainable status category, as shown by the red line. Enhancements must be implemented across all areas to elevate the sustainability value through improvement scenarios. The orange lines represent realistic improvement scenarios (scenario 1) for each element, whereas the blue lines represent idealistic improvement scenarios (scenario 2) for each aspect. As previously explained, the two most influential elements were chosen from the given situations for each component.

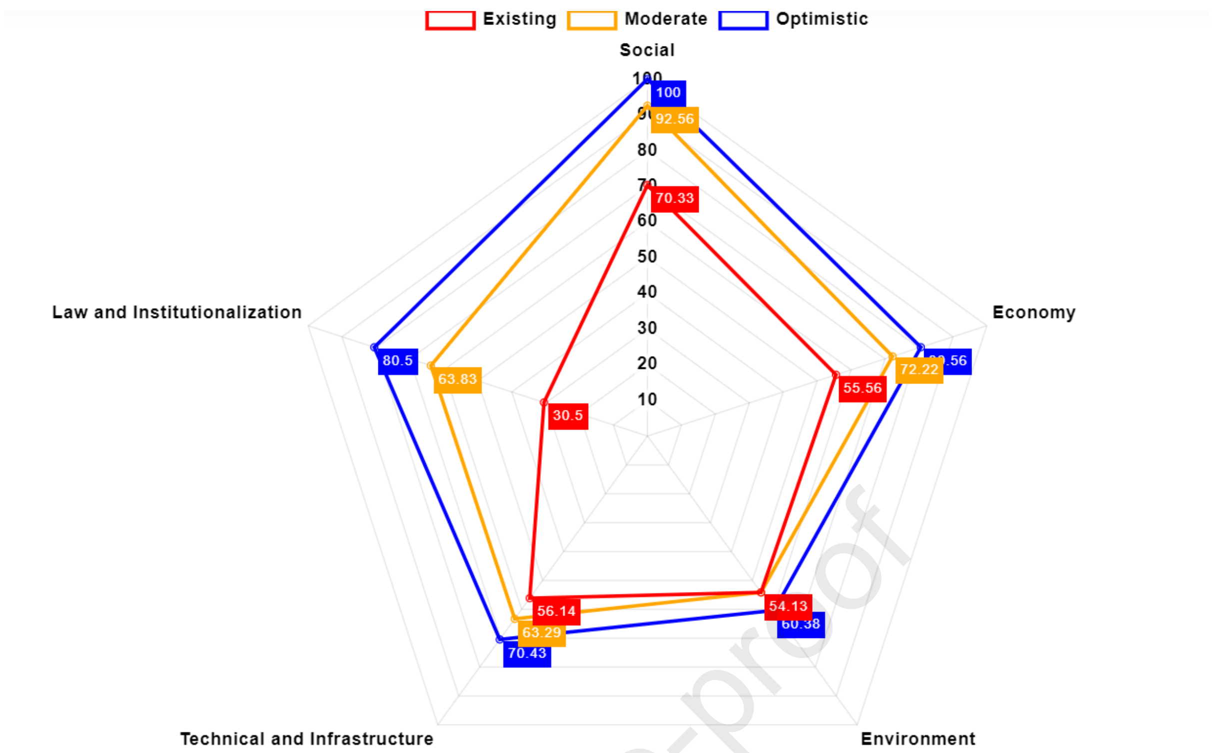


Fig. 14. The kite diagram of index and sustainability status waste management multilayer plastic

The kite diagram visually the framework's emphasis on scenario-based planning. While the Moderate scenario achieves some gains, primarily through institutional improvements, the Optimistic scenario demonstrates that comprehensive improvements across all aspects yield the most balanced and sustainable outcomes. This chart reinforces the idea that addressing all aspects simultaneously is essential for achieving very high sustainability across the board.

5. Conclusion

Multilayer plastic waste management in Indonesia faces significant environmental, economic, social, legal, and infrastructural challenges. The complex composition of these plastics, coupled with inadequate policies and infrastructure, has limited the effectiveness of current waste management efforts. Despite adopting Extended Producer Responsibility (EPR) policies and recycling technologies, the growing crisis demands more comprehensive and sustainable solutions.

Using the Multi-Aspect Sustainability Analysis (MSA) framework, this study identified critical strategies for improvement. Advanced recycling technologies, such as chemical recycling, and stronger institutional collaboration are essential. Public awareness and community participation also play a pivotal role in fostering sustainable practices. Addressing environmental pollution, increasing government support for recycling infrastructure, empowering communities, and integrating advanced waste management technologies are vital steps. Strengthening legal frameworks and fostering interregional cooperation are necessary to create a cohesive waste management system.

Scenario analysis shows that a holistic approach addressing all dimensions yields the most balanced and impactful results. By adopting advanced technologies, strengthening EPR policies, improving infrastructure, and enhancing collaboration, Indonesia can align its waste management practices with circular economy principles. These measures will reduce environmental impacts, generate economic benefits, and promote social well-being, paving the way for a more sustainable future.

Acknowledgments

We (the authors) would like to express our deepest gratitude to all parties from academician, community, researcher, non-government organization, and private sector who have provided support and funding for the realization of this project and research.

Funding

This study is part of a PhD project supported by the researcher and team. The team worked together to plan the study, gathered and analyzed data, and decide whether to publish and prepare the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Reference

Abdullah, M., & Abedin, M. Z. (2024). Assessment of plastic waste management in Bangladesh: A comprehensive perspective on sorting, production, separation, and recycling. *Results in Surfaces and Interfaces*, *15*(March), 100221. https://doi.org/10.1016/j.rsurfi.2024.100221

Ain, K. Q., Nasri, M. A., Alamsyah, M. N., Pratama, M. D. R., & Kurniawan, T. (2021). Collaborative governance in managing plastic waste in Bali. *IOP Conference Series: Earth and Environmental Science*, *905*(1). https://doi.org/10.1088/1755-1315/905/1/012115

Amali, L. N., Padiku, I. R., & Hunta, A. M. (2024). Development of Integrated Waste Management Information System to Support Sustainable Development. *Jambura Journal of Informatics*, *6*(1), 14–25. https://doi.org/10.37905/jji.v6i1.24659

Amin, N., Aslam, M., khan, Z., Yasin, M., Hossain, S., Shahid, M. K., Inayat, A., Samir, A., Ahmad, R., Murshed, M. N., Khurram, M. S., El Sayed, M. E., & Ghauri, M. (2023). Municipal solid waste treatment for bioenergy and resource production: Potential technologies, techno-economic-environmental aspects and implications of membrane-based recovery. *Chemosphere*, *323*, 138196. https://doi.org/https://doi.org/10.1016/j.chemosphere.2023.138196

Anwar, M. A., Sasongko, N. A., Suprihatin, & Najib, M. (2023). Sustainable plastic packaging waste management strategy based on a circular economy. *IOP Conference Series: Earth and Environmental Science*, *1267*(1). https://doi.org/10.1088/1755-1315/1267/1/012062

Anwar, M. A., Suprihatin, Sasongko, N. A., Najib, M., & Pranoto, B. (2024). Challenges and prospects of multilayer plastic waste management in several countries: A systematic literature review. *Case Studies in Chemical and Environmental Engineering*, *10*(July), 100911. https://doi.org/10.1016/j.cscee.2024.100911

Aprilia, A. (2021). Waste Management in Indonesia and Jakarta: Challenges and Way Forward. *Background Paper 23rd ASEF Summer University ASEF Education Department October 2021*, *October*, 1–18. https://asef.org/wp-content/uploads/2022/01/ASEFSU23_Background-Paper_Waste-Management-in-Indonesia-and-Jakarta.pdf

Arena, U., Parrillo, F., & Ardolino, F. (2023). An LCA answer to the mixed plastics waste dilemma: Energy recovery or chemical recycling? *Waste Management*, *171*, 662–675. https://doi.org/https://doi.org/10.1016/j.wasman.2023.10.011

Asadollahi, A., Tohidi, H., & Shoja, A. (2022). Sustainable waste management scenarios for food packaging materials using SimaPro and WARM. *International Journal of Environmental Science and Technology*, *19*(10), 9479–9494. https://doi.org/10.1007/s13762-022-04327-0

Bappenas. (2024). *National Waste Waste Management Management Reform Reform Emission Reduction In Cities Through Improved Waste Management Project (ERiC-DKTI).*

Bianchini, A., & Rossi, J. (2021). Design, implementation and assessment of a more sustainable model to manage plastic waste at sport events. *Journal of Cleaner Production*, *281*, 125345. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.125345

Cook, E., Velis, C. A., & Cottom, J. W. (2022). Scaling up resource recovery of plastics in the emergent circular economy to prevent plastic pollution: Assessment of risks to health and safety in the Global South. *Waste Management and Research*, *40*(12), 1680–1707. https://doi.org/10.1177/0734242X221105415

Cruz Sanchez, F. A., Boudaoud, H., Camargo, M., & Pearce, J. M. (2020). Plastic recycling in additive manufacturing: A systematic literature review and opportunities for the circular economy. *Journal of Cleaner Production*, *264*, 121602. https://doi.org/10.1016/j.jclepro.2020.121602

Debnath, B., Bari, A. B. M. M., Ali, S. M., Ahmed, T., Ali, I., & Kabir, G. (2023). Modelling the barriers to sustainable waste management in the plastic-manufacturing industry: An emerging economy perspective. *Sustainability Analytics and Modeling*, *3*(March), 100017. https://doi.org/10.1016/j.samod.2023.100017

Di Foggia, G., & Beccarello, M. (2022). Introducing a system operator in the waste management industry by adapting lessons from the energy sector. *Frontiers in Sustainability*, *3*. https://doi.org/10.3389/frsus.2022.984721

Dilkes-Hoffman, L. S., Pratt, S., Laycock, B., Ashworth, P., & Lant, P. A. (2019). Public attitudes towards plastics. *Resources, Conservation and Recycling*, *147*(March), 227–235. https://doi.org/10.1016/j.resconrec.2019.05.005

El-Halwagy, E. (2024). Towards waste management in higher education institute: The case of architecture department (CIC-New Cairo). *Results in Engineering*, *23*(August), 102672. https://doi.org/10.1016/j.rineng.2024.102672

Ellen MacArthur Foundation. (2023). *What is a circular economy? | Ellen MacArthur Foundation*. https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

Fan, Y. V. Y. Van, Čuček, L., Krajnc, D., Klemeš, J. J. J., & Lee, C. T. C. T. (2023). Life cycle assessment of plastic packaging recycling embedded with responsibility distribution as driver for environmental mitigation. *Sustainable Chemistry and Pharmacy*, *31*, 100946. https://doi.org/https://doi.org/10.1016/j.scp.2022.100946

Fianda, A. Y. A., Fandinny, I., Kacaribu, L. N. B., Desyani, N. A., Asyifa, N., & Wijayanti, P. (2021). Eco-friendly packaging: Preferensi dan Kesediaan Membayar Konsumen di Marketplaces. *Jurnal Ilmu Lingkungan*, *20*(1), 147–157. https://doi.org/10.14710/jil.20.1.147-157

Firmansyah, I. (2022). Multiaspect Sustainability Analysis (Theory and Application). *Expert Simulation Program Article*, *1*, 1–14. https://exsimpro.com/wp-content/uploads/2022/09/Multiaspect-Sustainability-Analisys-Exsimpro-Article-2022.pdf

Franco-García, M. L., Carpio-Aguilar, J. C., & Bressers, H. (2019). The Future of Circular Economy and Zero Waste. *Greening of Industry Networks Studies*, *6*, 265–273. https://doi.org/10.1007/978-3-319-92931-6_13

Gala, A., Guerrero, M., & Serra, J. M. (2020). Characterization of Post-Consumer Plastic Film Waste From Mixed MSW in Spain: A Key Point for the Successful Implementation of Sustainable Plastic Waste Management Strategies. *Waste Management*, *111*, 22–33. https://doi.org/10.1016/j.wasman.2020.05.019

Galluccio, M. (2021). Adaptive Decision-Making Process in Crisis Situations. In *Science and Diplomacy* (pp. 9–22). Springer International Publishing. https://doi.org/10.1007/978-3-030-60414-1_2

García-Valiñas, M., Arbués, F., & Balado-Naves, R. (2023). Assessing environmental profiles: An analysis of water consumption and waste recycling habits. *Journal of Environmental Management*, *348*(October). https://doi.org/10.1016/j.jenvman.2023.119247

Garcia, J. M., & Robertson, M. L. (2017). The future of plastics recycling. *Science*, *358*(6365), 870–872. https://www.jstor.org/stable/26400835

Goodman, M. J. (2017). The "natural" vs. "natural flavors" conflict in food labeling: A regulatory viewpoint. *Food and Drug Law Journal*, *72*(1), 78–102. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85038129438&partnerID=40&md5=f24d626acf8cc1713e21c9a902a1127e

Goyal, S. (2020). Reducing Waste in Circular Economy. *Encyclopedia of Renewable and Sustainable Materials: Volume 1-5*, *1–5*, 467–473. https://doi.org/10.1016/B978-0-12-803581-8.11503-6

Green Peace. (2019). Throwing Away the Future : *Throwing Away The Future: How Companies Still Have It Wrong on Plastic Pollution "Solutions''," * 32.

Guion, L. a. (2006). Conducting an In-depth Interview 1. *Boards*, 1–4.

Gunsilius, E., Spies, S., García-Cortés, S., Medina, M., Dias, S., Scheinberg, A., Sabry, W., Abdel-Hady, N., Santos, A.-L. F. dos, & Ruiz, S. (2011). Recovering resources, creating opportunities. Integrating the informal sector into Solid Waste Managment. *Deutsche Gesellschaft Für Internationale Zusammenarbeit (GIZ) GmbH*, 49.

Hahladakis, J. N., Iacovidou, E., & Gerassimidou, S. (2020). Plastic waste in a circular economy. In *Plastic Waste and Recycling*. Elsevier Inc. https://doi.org/10.1016/b978-0-12-817880-5.00019-0

Hellwig, C., Häggblom-Kronlöf, G., Bolton, K., & Rousta, K. (2019). Household Waste Sorting and Engagement in Everyday Life Occupations After Migration—A Scoping Review. *Sustainability*, *11*(17), 4701. https://doi.org/10.3390/su11174701

Hestin, M., Faninger, T., & Milios, L. (2017). *Increased EU Plastics Recycling Targets: Environmental, Economic and Social Impact Assessment Final Report*. *May*.

Jagath, P., Gamaralalage, D., & Onogawa, K. (2019). *Strategies to Reduce Marine Plastic Pollution from Land-based Sources in Low and Middle - Income Countries*. 1–30.

Jambeck, J., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M. E., Andrady, A. L., Narayan, R., & Law, K. L. (2015). Plastic Waste Inputs From Land Into the Ocean. *Science*, *347*(6223), 768–771. https://doi.org/10.1126/science.1260352

Juhandi, D., Darwanto, D. H., Masyhuri, M., Mulyo, J. H., Sasongko, N. A., Susilawati, H. L., Meilin, A., Martini, T., Anda, M., Sasongko, N. A., Octavian, A., & Mumpuni, T. (2024). Land use planning strategies for food versus non-food estate sustainable farming. *Global Journal of Environmental Science and Management*, *10*(3), 1249–1274. https://doi.org/10.22034/gjesm.2024.03.19

Kaiser, K., Schmid, M., Schlummer, M., Lahtela, V., Silwal, S., & Kärki, T. (2020). Re-Processing of Multilayer Plastic Materials as a Part of the Recycling Process: The Features of Processed Multilayer Materials. *Polymers*, *12*(11), 2517. https://doi.org/10.3390/polym12112517

Kakadellis, S., Woods, J., & Harris, Z. M. (2021). Friend or foe: Stakeholder attitudes towards biodegradable plastic packaging in food waste anaerobic digestion. *Resources, Conservation and Recycling*, *169*(October 2020), 105529. https://doi.org/10.1016/j.resconrec.2021.105529

Krämer, L. (2016). Enforcement of Environmental Law. *Enforcement of Environmental Law*, *6*(1), 32–42. https://doi.org/10.4337/9781784718350

Kumar, R., Verma, A., Shome, A., Sinha, R., Sinha, S., Jha, P. K., Kumar, R., Kumar, P., Shubham, Das, S., Sharma, P., & Prasad, P. V. V. (2021). Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions. *Sustainability (Switzerland)*, *13*(17), 1–40. https://doi.org/10.3390/su13179963

Kumar, S., Raut, R. D., Nayal, K., Kraus, S., Yadav, V. S., & Narkhede, B. E. (2021). To identify industry 4.0 and circular economy adoption barriers in the agriculture supply chain by using ISM-ANP. *Journal of Cleaner Production*, *293*, 126023. https://doi.org/10.1016/j.jclepro.2021.126023

Kurniawan, T. A., Meidiana, C., Dzarfan Othman, M. H., Goh, H. H., & Chew, K. W. (2023). Strengthening waste recycling industry in Malang (Indonesia): Lessons from waste management in the era of Industry 4.0. *Journal of Cleaner Production*, *382*(November 2022), 135296. https://doi.org/10.1016/j.jclepro.2022.135296

Laguador, J. M., Mandigma, L. B., & Agena, E. (2013). Community Extension Service in the Waste Management Practices of Brgy . Wawa Residents in. *SAVAP International*, *4*(4), 141–152. http://www.savap.org.pk/journals/ARInt./Vol.4(4)/2013(4.4-16).pdf

Larrain, M., Van Passel, S., Thomassen, G., Van Gorp, B., Nhu, T. T., Huysveld, S., Van Geem, K. M., De Meester, S., & Billen, P. (2021). Techno-economic assessment of mechanical recycling of challenging post-consumer plastic packaging waste. *Resources, Conservation and Recycling*, *170*(April), 105607. https://doi.org/10.1016/j.resconrec.2021.105607

Leng, Z., Padhan, R. K., & Sreeram, A. (2018). Production of a sustainable paving material through chemical recycling of waste PET into crumb rubber modified asphalt. *Journal of Cleaner Production*, *180*, 682–688. https://doi.org/10.1016/j.jclepro.2018.01.171

Lopez-Aguilar, J. F., Sevigné-Itoiz, E., Maspoch, M. L., & Peña, J. (2022). A realistic material flow analysis for end-of-life plastic packaging management in Spain: Data gaps and suggestions for improvements towards effective recyclability. *Sustainable Production and Consumption*, *31*, 209–219. https://doi.org/https://doi.org/10.1016/j.spc.2022.02.011

Maione, C., Lapko, Y., & Trucco, P. (2022). Towards a circular economy for the plastic packaging sector: Insights from the Italian case. *Sustainable Production and Consumption*, *34*, 78–89. https://doi.org/https://doi.org/10.1016/j.spc.2022.09.002

Mwanza, B. G., & Mbohwa, C. (2019). Technology and plastic recycling: Where are we in Zambia, Africa. *Managing Technology for Inclusive and Sustainable Growth - 28th International Conference for the International Association of Management of Technology, IAMOT 2019*, 964–971.

Naegler, T., Becker, L., Buchgeister, J., Hauser, W., Hottenroth, H., Junne, T., Lehr, U., Scheel, O., Schmidt-Scheele, R., Simon, S., Sutardhio, C., Tietze, I., Ulrich, P.). F.

indéterminée, Viere, T., & Weidlich, A. (2021). Integrated Multidimensional Sustainability Assessment of Energy System Transformation Pathways. *Sustainability*, *13*(9), 5217. https://doi.org/10.3390/su13095217

Nurpagi, E. M., Ekayani, M., & Ismail, A. (2022). Waste generation potential and household's willingness to pay for the management of Community 3R Waste Treatment Facility (TPS 3R) in Babakan Village, Bogor Regency. *Jurnal Pengelolaan Sumberdaya Alam Dan Lingkungan*, *12*(4), 599–608. https://doi.org/10.29244/jpsl.12.4.599-608

Paulus, C. A., Damianus, A., Yahyah, Rayzcha, M. I. H., Eddy, R., & Firmansyah, I. (2023). Multi-Aspect Sustainability Analysis of Freshwater Fish Aquaculture in Kupang City of East Nusa Tenggara Province, Indonesia. *Russian Journal of Agricultural and Socio-Economic Sciences*, *140*(8), 173–186. https://doi.org/10.18551/rjoas.2023-08.18

Pitcher, T. J., & Preikshot, D. (2001). RAPFISH: A rapid appraisal technique to evaluate the sustainability status of fisheries. *Fisheries Research*, *49*(3), 255–270. https://doi.org/10.1016/S0165-7836(00)00205-8

Plastics Europe. (2022). The circular economic for plastics. An European overview. *Plastics - the Facts 2022*, 81. https://plasticseurope.org/knowledge-hub/the-circular-economy-for-plastics-a-european-overview-2/

Potting, J., Hanemaaijer, A., Delahaye, R., Ganzevles, J., Hoekstra, R., & Lijzen, J. (2018). Circular Economy : What We Want To Know and Can Measure. *Planbureau Voor de Leefomgeving (PBL)*, 20.

Qureshi, M. S., Oasmaa, A., Pihkola, H., Deviatkin, I., Tenhunen, A., Mannila, J., Minkkinen, H., Pohjakallio, M., & Laine-Ylijoki, J. (2020). Pyrolysis of plastic waste: Opportunities and challenges. *Journal of Analytical and Applied Pyrolysis*, *152*(March). https://doi.org/10.1016/j.jaap.2020.104804

Ragossnig, A. M., & Schneider, D. R. (2019). Circular economy, recycling and end-of-waste. *Waste Management and Research*, *37*(2), 109–111. https://doi.org/10.1177/0734242X19826776

Rizieq, R., Ekawati, Ellyta, & Bancin, H. D. (2023). Sustainability in adoption of new improved rice variety innovations in West Kalimantan Province: Review of economic aspects. *IOP Conference Series: Earth and Environmental Science*, *1241*(1). https://doi.org/10.1088/1755-1315/1241/1/012047

Rousta, K., Ordóñez, I., Bolton, K., & Dahlén, L. (2017). Support for Designing Waste Sorting Systems: A Mini Review. *Waste Management & Research the Journal for a Sustainable Circular Economy*, *35*(11), 1099–1111. https://doi.org/10.1177/0734242x17726164

Roy, H., Alam, S. R., Bin-Masud, R., Prantika, T. R., Pervez, M. N., Islam, M. S., & Naddeo, V. (2022). A Review on Characteristics, Techniques, and Waste-to-Energy Aspects of Municipal Solid Waste Management: Bangladesh Perspective. *Sustainability (Switzerland)*, *14*(16). https://doi.org/10.3390/su141610265

Rozikin, M., & Sofwani, A. (2023). Joint Collaboration of the Local Government (Regency, City, and Province) for the Successful Development in East Java Of Indonesia. *Journal of Law and Sustainable Development*, *11*(11), e1354. https://doi.org/10.55908/sdgs.v11i11.1354

Samarasinghe, K., Pawan Kumar, S., & Visvanathan, C. (2021). Evaluation of circular economy potential of plastic waste in Sri Lanka. *Environmental Quality Management*, *31*(1), 99–107. https://doi.org/10.1002/tqem.21732

Schader, C., Grenz, J., Meier, M., & Stolze, M. (2014). Scope and Precision of Sustainability Assessment Approaches to Food Systems. *Ecology and Society*, *19*(3). https://doi.org/10.5751/es-06866-190342

Shah, K. U., Niles, K., Ali, S. H., Surroop, D., & Jaggeshar, D. (2019). Plastics waste metabolism in a Petro-Island state: Towards solving a “wicked problem” in trinidad and tobago. *Sustainability (Switzerland)*, *11*(23). https://doi.org/10.3390/su11236580

Singh, A., & Sushil, S. (2017). Developing a Conceptual Framework of Waste Management in the Organizational Context. *Management of Environmental Quality an International Journal*, *28*(6), 786–806. https://doi.org/10.1108/meq-07-2016-0045

Singh, B., & Jana, A. K. (2024). Forecast of agri-residues generation from rice, wheat and oilseed crops in India using machine learning techniques: Exploring strategies for sustainable smart management. *Environmental Research*, *245*, 117993. https://doi.org/https://doi.org/10.1016/j.envres.2023.117993

Soares, C. T. de M., Ek, M., Östmark, E., Gällstedt, M., & Karlsson, S. (2022). Recycling of multi-material multilayer plastic packaging: Current trends and future scenarios. *Resources, Conservation and Recycling*, *176*(June 2021), 105905. https://doi.org/10.1016/j.resconrec.2021.105905

Soemadijo, P., Anindita, F., Trisyanti, D., Akib, R., Abdulkadir, M., Nizardo, N. M., & Rachmawati, R. L. (2022). a Study of Available Technology for Recycling Low Value Plastic in Indonesia. *Journal of Environmental Science and Sustainable Development*, *5*(2), 436–457. https://doi.org/10.7454/jessd.v5i2.1128

Song, U., & Park, H. (2024). Plastic recycling in South Korea: problems, challenges, and policy recommendations in the endemic era. *Journal of Ecology and Environment*, *48*, 1–11. https://doi.org/10.5141/jee.23.083

Su, Q. Z., Vera, P., Nerín, C., Lin, Q. B., & Zhong, H. N. (2021). Safety concerns of recycling postconsumer polyolefins for food contact uses: Regarding (semi-)volatile migrants untargetedly screened. *Resources, Conservation and Recycling*, *167*(December 2020), 105365. https://doi.org/10.1016/j.resconrec.2020.105365

Sztangret, I. B. (2020). The marketing value creation in the waste management sector – multi-conceptual business model. *SHS Web of Conferences*, *73*, 01028. https://doi.org/10.1051/shsconf/20207301028

Tahar, N. (2019). *Peraturan Menteri Lhk Nomor P.75 Tahun 2019 Peta Jalan Pengurangan Sampah Oleh Produsen*. 41.

Takenaka, N., Tominaga, A., Sekiguchi, H., Nakano, R., Takatori, E., & Yao, S. (2017). Creation of advanced recycle process to waste container and packaging plastic - polypropylene sorted recycle plastic case. *Nihon Reoroji Gakkaishi*, *45*(3), 139–143. https://doi.org/10.1678/rheology.45.139

Tan, Q., Yang, L., Wei, F., Chen, Y., & Li, J. (2023). Is reusable packaging an environmentally friendly alternative to the single-use plastic bag? A case study of express delivery packaging in China. *Resources, Conservation and Recycling*, *190*(May 2022), 106863. https://doi.org/10.1016/j.resconrec.2022.106863

Tesfaye, W., & Kitaw, D. (2021). Conceptualizing reverse logistics to plastics recycling system. *Social Responsibility Journal*, *17*(5), 686–702. https://doi.org/10.1108/SRJ-12-2019-0411

Torres-Pereda, P., Parra-Tapia, E., Rodríguez, M. A., Félix-Arellano, E., & Riojas-Rodríguez, H. (2020). Impact of an intervention for reducing waste through educational strategy: A Mexican case study, what works, and why? *Waste Management*, *114*, 183–195. https://doi.org/https://doi.org/10.1016/j.wasman.2020.06.027

United Nations. (2022). Resolution adopted by the United Nations Environment Assembly on 2 March 2022 5/14. *Unep*, 3–6. http://www.who.int/mediacentre/factsheets/fs355/en/.

Van de Klundert, A., & Anschutz, J. (2001). Integrated sustainable waste management - the concept: Tools for decision-makers: Experiences from the Urban Waste Expertise Program. In *Waste*. https://www.ircwash.org/sites/default/files/Klundert-2001-Integrated.pdf

Vanapalli, K. R., Sharma, H. B., Ranjan, V. P., Samal, B., Bhattacharya, J., Dubey, B., & Goel, S. (2021). Challenges and Strategies for Effective Plastic Waste Management During and Post COVID-19 Pandemic. *The Science of the Total Environment*, *750*, 141514. https://doi.org/10.1016/j.scitotenv.2020.141514

Wagner, T. P. (2020). Policy instruments to reduce consumption of expanded polystyrene food service ware in the USA. *Detritus*, *9*(March), 11–26. https://doi.org/10.31025/2611-4135/2020.13903

World Bank. (2021). Plastic Waste Discharges from Rivers and Coastlines in Indonesia. *Plastic Waste Discharges from Rivers and Coastlines in Indonesia*. https://doi.org/10.1596/35607

Yiğitcanlar, T., & Dur, F. (2017). *Developing a Sustainability Assessment Model: The Sustainable Infrastructure, Land-Use, Environment and Transport Model*. 155–176. https://doi.org/10.1201/b19796-12

Zhao, J., Faqiri, H., Ahmad, Z., Emam, W., Yusuf, M., & Sharawy, A. M. (2021). The Lomax-Claim Model: Bivariate Extension and Applications to Financial Data. *Complexity*, *2021*. https://doi.org/10.1155/2021/9993611

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The author is an Editorial Board Member/Editor-in-Chief/Associate Editor/Guest Editor for *[Journal name]* and was not involved in the editorial review or the decision to publish this article.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: