Strategic Assessment of Waste Management Solutions Using a Three-Stage MCDM Framework for a Clean Province

Atiwat Nanphang and Pongchanun Luangpaiboon*

Industrial Statistics and Operational Research Unit (ISO-RU), Department of Industrial Engineering, Faculty of Engineering, Thammasat School of Engineering, Thammasat University, Pathumthani, 12120 Thailand

Email: atiwat.nan@dome.tu.ac.th (A.N.); lpongch@engr.tu.ac.th (P.L.)

*Corresponding author

Manuscript received January 10, 2025; revised April 10, 2025; accepted May 7, 2025; published November 21, 2025

***Abstract*—This study presents a comprehensive Multi-Criteria Decision-Making (MCDM) framework, enhanced by the Taguchi approach, to evaluate and prioritize waste management strategies for accomplishing a "Clean Province" initiative. The research concentrates on critical aspects of environmental sustainability, emphasizing waste management and its impact on ecosystems, public health, and resource conservation. Six essential criteria—source-level waste segregation, reduction of waste generation, efficient collection by local administrative organizations, adherence to academic waste disposal standards, management during epidemics, and effective handling of plastic waste—serve as the foundation for evaluation. Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and Analytical Hierarchy Process (AHP) are all incorporated into the proposed framework. AHP determines the relative significance of criteria, whereas TOPSIS and PROMETHEE rank strategies according to their proximity to ideal solutions and preference flows, respectively. The Taguchi approach, which implements the "smaller-the-better" principle for ranking strategies, further fortifies the analysis's robustness, guaranteeing consistent and dependable evaluations. The results indicate that this framework is effective in identifying the most effective waste management strategies, thereby contributing to the overarching objectives of environmental sustainability and resource efficiency. These results emphasize the significance of structured decision-making in addressing solid waste management challenges, which have implications for waste valorization, reuse, and recycling practices. This research emphasizes the integration of waste-to-energy technologies and sustainable approaches to waste reduction, providing policymakers and stakeholders with actionable insights. This study provides a replicable model for improving solid waste management systems, thereby assuring societal well-being and ecological balance, in accordance with the objectives of environmental science and development.**

***Keywords*—waste management strategies, Multi-Criteria Decision-Making (MCDM), Taguchi approach, sustainability, environmental impact, urban and rural waste solutions**

I. Introduction

Effective waste management has become a critical global challenge, exacerbated by rapid urbanization, population growth, and the increasing complexity of modern waste streams. These developments have resulted in unprecedented levels of waste generation, straining existing waste management systems and infrastructure worldwide. Inadequate waste handling and disposal practices contribute to severe environmental issues such as greenhouse gas emissions, land degradation, and water contamination, posing significant risks to public health and ecosystems. Addressing this multifaceted crisis requires innovative, comprehensive waste management strategies that align with sustainable development goals.

In Thailand, the waste management crisis has reached alarming levels due to urbanization and industrialization, prompting the government to develop structured frameworks to address the issue. Notable among these are the Master Plan for Solid Waste Management (2016–2021) and the "Clean Province" initiative, which seek to create sustainable solutions for waste generation, segregation, and disposal. These national strategies emphasize the principles of the 3Rs—Reduce, Reuse, and Recycle—as well as the importance of a circular economy, which transforms waste into valuable resources while minimizing environmental harm.

The "Clean Province" initiative is a flagship program targeting enhanced waste management practices across Thailand's provinces. It integrates efforts at various levels—government agencies, Local Administrative Organizations (LAOs), private sector entities, and community groups—focusing on reducing waste at its source, improving waste collection systems, and promoting scientific disposal methods. A key component of the initiative is addressing hazardous and infectious waste, which poses unique challenges due to its high environmental and health risks. By fostering collaboration among stakeholders and implementing evidence-based practices, the initiative aims to create cleaner and healthier communities while safeguarding natural resources.

Thailand's National Solid Waste Management Master Plan (2016–2021), which was adopted by the Thai Cabinet on May 3, 2016, serves as the foundation for the "Clean Province" initiative. In response to the increasing waste challenges that have resulted from accelerated urbanization, industrialization, and population growth, this Master Plan was developed. It delineates a comprehensive strategic framework that prioritizes the promotion of the 3Rs (Reduce, Reuse, Recycle), a focus on waste minimization at the source, environmentally sound collection and disposal systems, and community involvement in waste management practices. The Plan's objective is to ensure that over 75% of waste is managed in an environmentally appropriate manner and to reduce municipal solid waste generation by a minimum of 7% annually. The "Clean Province" initiative operationalizes these objectives at the provincial level by utilizing localized strategies that are implemented by Local Administrative Organizations (LAOs). Additionally, it emphasizes the alignment of provincial initiatives with national waste policy objectives, which encompasses the promotion of public awareness, the implementation of appropriate hazardous waste management practices, and the integration of waste-to-energy solutions.

The Enhancement and Conservation of National Environmental Quality Act B.E. 2535 (1992) is Thailand's primary environmental law, and it functions as the legislative authority for the initiative. This Act establishes environmental protection measures, such as solid refuse management systems, by empowering the Ministry of Natural Resources and Environment, the Pollution Control Department (PCD), and provincial administrators. It requires the establishment of environmental quality management plans, establishes pollution control standards, and grants government agencies the authority to enforce compliance through inspections, penalties, and reporting mechanisms. Inter-agency collaboration, particularly among the Ministry of Interior, PCD, Department of Health, and LAOs, is required for the implementation of the "Clean Province" initiative. These organizations collaborate on public engagement, technical support, capacity-building, and policy enforcement. The initiative also implements regulatory and financial instruments, including municipal regulations, central grants for waste infrastructure, mandatory refuse segregation rules, and public-private partnerships, to guarantee the systematic execution of its objectives. These legal and institutional mechanisms collectively establish a strong governance framework that bolsters the initiative's objective of establishing sustainable waste management practices throughout the province.

An essential aspect of the "Clean Province" initiative is raising public awareness and empowering communities to actively participate in waste reduction efforts. Educational campaigns, including workshops and training sessions, are designed to instill behavioral changes that encourage waste segregation and promote the use of biodegradable alternatives. These programs aim to shift societal habits, such as reducing reliance on single-use plastics, thereby supporting sustainable lifestyles and contributing to long-term waste management goals.

Infrastructure development is another cornerstone of this initiative. Enhancing the capacity of local waste management systems involves providing accessible waste collection points, segregation bins, and efficient transportation systems for collected waste. The integration of technology and community-driven solutions fosters a collaborative approach, enabling local governments and citizens to work together in managing their waste. This decentralized, community-based approach strengthens the resilience of waste management systems and ensures sustainability.

Despite significant progress, managing hazardous and infectious waste remains a challenge. Such waste requires specialized handling and disposal systems to prevent environmental contamination and public health risks. The initiative addresses these concerns by establishing designated collection points, training personnel in handling hazardous materials, and encouraging partnerships with the private sector to develop safe and efficient disposal methods. This ensures compliance with environmental standards and safeguards community well-being.

To evaluate the effectiveness of these strategies, this study introduces a robust decision-making framework that integrates Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), and the Taguchi approach. This novel three-stage Multi-Criteria Decision-Making (MCDM) approach facilitates a holistic assessment of waste management strategies, enabling policymakers to identify the most efficient and sustainable solutions tailored to specific regional needs.

This study contributes to sustainable waste management by introducing an innovative MCDM framework, offering actionable insights into the implementation of community-driven strategies, and addressing gaps in hazardous and infectious waste management practices. Furthermore, the findings provide a scalable approach that can be adapted to diverse regional contexts, equipping policymakers and practitioners with the tools needed to address global waste challenges effectively. By bridging the gap between research and policy, this study underscores the importance of integrating scientific innovation with practical application to achieve long-term environmental and societal benefits.

This paper is organized into five sections to provide a comprehensive analysis of waste management strategies under the "Clean Province" initiative. Section I introduces the research background, objectives, and the significance of effective waste management in addressing global and national challenges. Sections II and III outline LAOs and waste management in the 'clean province' initiative and literature reviews, respectively. Section IV explains the methodologies employed in this study, focusing on the integration of Multi-Criteria Decision-Making (MCDM) techniques, including AHP, TOPSIS, and PROMETHEE, including the Taguchi approach, to evaluate waste management strategies. Section V elaborates on the evaluation criteria and discusses the application of the proposed framework to assess the effectiveness of strategies implemented under the initiative. Section V presents the results and analysis, highlighting the key findings and their implications for sustainable waste management. Finally, Section VI concludes the study by summarizing the insights gained, offering policy recommendations, and suggesting directions for future research to address ongoing and emerging waste management challenges.

II. LAOs and Waste Management

Local Administrative Organizations (LAOs) play a critical role in implementing the "Clean Province" initiative, a comprehensive framework aimed at addressing community-level waste management challenges in Thailand. Recognizing the escalating waste crisis, LAOs are tasked with developing strategies that align with the principles of the 3Rs—Reduce, Reuse, and Recycle—to minimize waste generation and promote sustainable practices. These efforts encompass not only household waste but also hazardous and infectious waste, ensuring public health and environmental protection.

A cornerstone of these strategies is public awareness and community engagement. LAOs actively conduct educational campaigns to inform residents about proper waste segregation, the environmental benefits of recycling, and alternatives to single-use plastics. Initiatives such as workshops, local events, and promotional materials foster a culture of sustainability, encouraging households to adopt waste reduction practices.

By empowering communities with knowledge and tools, LAOs aim to instill long-term behavioral changes that support the initiative's objectives.

Infrastructure enhancement is another critical component. LAOs invest in accessible waste collection points, community sorting stations, and proper disposal facilities. Establishing designated hazardous waste collection sites within villages ensures safe handling and prevents contamination. Additionally, LAOs collaborate with local stakeholders, including waste management enterprises and informal waste collectors, to streamline recycling and disposal processes. Such partnerships enhance the efficiency of waste management systems while creating economic opportunities within the community.

To address hazardous and infectious waste, LAOs implement specialized strategies, such as training programs for personnel and setting up secure waste transport systems to designated disposal sites. These measures comply with national health and environmental standards, mitigating risks to public safety. Furthermore, periodic monitoring and data collection enable LAOs to evaluate the effectiveness of their waste management strategies and make data-driven adjustments to improve outcomes.

LAOs under the "Clean Province" initiative adopt a multi-faceted approach to waste management that integrates public education, infrastructure development, and stakeholder collaboration. By addressing waste challenges at the local level, these organizations not only contribute to national sustainability goals but also create cleaner, healthier communities for future generations. This localized, participatory approach underscores the importance of grassroots efforts in tackling global environmental challenges.

III. Clean Province Initiative

The "Clean Province" initiative's success is contingent upon the coordinated efforts of numerous key stakeholders, in addition to Local Administrative Organizations (LAOs). Legislative authority, regulatory supervision, technical guidance, and financial support are provided by national government agencies, including the Ministry of Natural Resources and Environment, the Pollution Control Department (PCD), and the Ministry of Interior. Through public-private partnerships, the private sector provides infrastructure, technology, and expertise in areas such as recycling, waste-to-energy, and hazardous waste disposal, which are critically important. Communities are mobilized, environmental education campaigns are conducted, and policy reforms are advocated for by non-governmental organizations (NGOs). This multistakeholder collaboration guarantees that waste management governance is not only technically effective but also socially inclusive and adaptable to local requirements.

The "Clean Province" initiative evaluates three key strategies to ensure its success. The first strategy focuses on Promoting Knowledge and Awareness of Waste Management. This includes educational programs such as training and field visits to communities excelling in waste management. It also emphasizes behavioral changes, such as reducing the use of harmful materials like foam and plastic packaging, and promoting biodegradable alternatives. The second strategy is Strengthening Community Capacity for Waste Management, which involves building resilient, community-based waste systems by setting up proper waste collection points and encouraging collective participation. The third strategy, Supporting Participation in Hazardous Waste Management, targets the safe disposal of hazardous materials by establishing designated collection points and engaging government and private sectors in the process.

These strategies are assessed based on six critical criteria. The first is the implementation of the "Separate Before Disposing" campaign to drive community waste management efforts. The second evaluates the reduction and sorting of waste at the source, while the third focuses on the efficiency of midstream waste collection by LAOs. The fourth measures the capacity and correctness of community waste disposal in alignment with academic principles, and the fifth addresses waste management challenges during pandemic situations. The sixth criterion evaluates plastic waste management, emphasizing reduction, reuse, and recycling.

The "Clean Province" initiative is confronted with a number of practical challenges, including regulatory conformance, enforcement, funding, and community engagement. Enforcement is predominantly conducted by provincial environmental offices and local authorities through regular inspections and adherence checks. Penalties are administered under the Enhancement and Conservation of National Environmental Quality Act B.E. 2535 (1992) for non-compliance. Nevertheless, the scope and continuity of waste management interventions may be restricted by the fact that numerous Local Administrative Organizations (LAOs) are subject to budgetary constraints and rely significantly on central government funding. The Pollution Control Department (PCD) and other national agencies offer standardized operating procedures and capacity-building programs to local personnel in order to enhance regulatory compliance. Community engagement is organized through a variety of strategies, such as public education campaigns, partnerships with NGOs and community leaders, and collaboration with institutions. These participatory mechanisms are intended to promote shared responsibility for local waste management practices and to establish long-term behavioral change.

The "Clean Province" initiative is in close alignment with the circular economy framework, the Sustainable Development Goals (SDGs), and Thailand's national environmental policies. At the national level, it supports the objectives of the National Solid Waste Management Master Plan (2016–2021) by promoting environmentally sound technologies, decentralizing waste governance to Local Administrative Organizations (LAOs), and advancing the 3Rs (Reduce, Reuse, Recycle). The initiative contributes to multiple SDGs on a global scale, including SDG 11 (Sustainable Cities and Communities) through the enhancement of urban waste systems, SDG 12 (Responsible Consumption and Production) through the promotion of sustainable consumption and behavioral change, and SDG 13 (Climate Action) through the reduction of landfill emissions through waste diversion and energy recovery. The initiative also embodies the principles of the circular economy by converting waste into valuable resources, incorporating community-level material recovery systems, and promoting the use of biodegradable and recyclable alternatives. This policy alignment guarantees that the initiative not only addresses local waste challenges but also contributes to broader sustainability objectives at the national and global levels.

IV. Literature Review

The literature emphasizes the adaptability of Multi-Criteria Decision-Making (MCDM) methodologies in addressing complex sustainability challenges, particularly in the areas of environmental and waste management. Numerous studies have implemented MCDM techniques, including CILOS, GRA, EDAS, CODAS, and ARAS, in a variety of sectors, including industrial and biomedical waste valorization and water quality assessment. This is consistent with the objectives of this investigation, which is to assess waste management strategies for the "Clean Province" initiative by employing a multi-dimensional decision-making framework.

For example, Das [1] employed the Criterion Impact Loss (CILOS)-based Water Quality Index (WQI) in conjunction with GIS and Artificial Neural Networks (ANN) to evaluate water contamination in the Mahanadi catchment. This illustrates the importance of integrating MCDM with machine learning to identify sources of degradation, thereby promoting sustainable water resource management. Similarly, Meraji *et al.* [2] employed clustering and MCDM methods (COCOSO, EDAS, and GRA) to assess the performance of 168 countries during the COVID-19 pandemic. They specifically included "medical waste" as a distinctive metric. These methods demonstrate a trend toward the incorporation of unconventional variables into public decision-making.

A fuzzy MCDM model was proposed by Chu *et al.* [3] to evaluate medical waste valorization strategies by utilizing ESG metrics, WINGS, and CODAS. ARAS was implemented by Najafi *et al.* [4] to evaluate bioenergy technologies based on criteria such as process temperature and the cost of refuse separation. These studies underscore the importance of economic and environmental trade-offs, but they concentrate on isolated strategy evaluations without ensuring that the results are consistent across a variety of assumptions.

In the context of industrial performance and sustainable supply chains, Štreimikienė *et al.* [5] used TOPSIS to evaluate automotive reverse logistics, while Bechroune *et al.* [6] employed a GIS-AHP framework to evaluate the suitability of landfill sites in Algeria. In order to evaluate the sustainability of steel products, Depczyński [7] implemented a combination of VIKOR and TOPSIS. The flexibility of MCDM across applications is illustrated in these studies; however, the robustness of rankings under varying decision-making rules is frequently not tested.

Karadayi-Usta [8] implemented a picture fuzzy ORESTE methodology to evaluate textile waste strategies, while Hasankhani *et al.* [9] implemented hybrid MCDM, game theory, and SWOT methodologies to evaluate waste-to-energy alternatives. These studies demonstrate an increasing interest in circular economy strategies; however, they fail to investigate the stability of decision-making across stakeholder preferences, a critical void that our study aims to bridge.

Yi *et al.* [10] integrated LCA, LCC, AHP, and TOPSIS to manage construction waste, while Alvandi Ghiasvand *et al.* [11] utilized IT2F-BWM and hesitancy fuzzy ARAS to evaluate recycling supply chains. Despite their comprehensiveness, these models rely on static expert input without conducting any variability testing. In order to enhance strategic reliability, our methodology implements variant-based decision criteria and the Taguchi method.

SWARA-ARAS and PF-MEREC were implemented by Chaurasiya and Jain [12] to endorse intelligent waste management systems in intelligent cities. Ecco *et al.* [13] conducted a review of MCDM in biowaste applications, underscoring the necessity of integrated methods. Nevertheless, our study is a significant departure from the majority of studies in that it examines the potential for results to change in response to varying expert judgments or decision philosophies.

Salman *et al.* [14] optimized biomass pre-treatment using AHP-TOPSIS, while Theilig *et al.* [15] incorporated AHP, ANP, and LCA for building material sustainability evaluation in the field of construction and energy. Despite their contributions to sustainable design, neither model demonstrated sensitivity to alternative decision environments.

Agrawal *et al.* [16] employed a combination of MLGDM and ISM-DEMATEL to investigate Juran's quality principles in the context of circular economies. GIS and MCDM were combined by Genç *et al.* [17] to assess landfill and waste-to-energy systems. These methodologies prioritize systemic sustainability; however, they do not integrate instruments such as Taguchi to quantify variability in MCDM outcomes.

The ILM index was devised by Rebelato *et al.* [18] to promote sustainability in the leather industry by incorporating LCA and MCDM. Migo-Sumagang *et al.* [19] optimized process systems using BWM and SAW. These works demonstrate the influence of MCDM in the field of engineering; however, they prioritize outcome accuracy over stability across decision frameworks.

The DNMA method was further developed by Al-Barakati and Rani [20] by incorporating intuitionistic fuzzy sets to evaluate healthcare waste. For infrastructure planning, Milojkovic and Prascevic [21] integrated fuzzy AHP and VIKOR. Although they both address uncertainty, they do not statistically validate the resilience of decisions under fluctuating expert input.

Kumar *et al.* [22] proposed N-AHP and N-CoCoSo to assess sustainability in Industry 4.0, while Anjum *et al.* [23] implemented AROMAN in q-rung fuzzy environments for healthcare waste management. These studies emphasize the progress made in computational modeling; however, they frequently lack accessibility for policymakers due to their limited interpretability. Our model addresses this issue by incorporating transparent, structured components.

AHP-MARCOS and fuzzy-TOPSIS were implemented by Yazar *et al.* [24] and Regragui *et al.* [25] to assess the sustainability of hospitals and hazardous refuse. Both frameworks emphasize detailed criteria; however, they do not evaluate the optimality of strategies in the presence of varying risk preferences or assumptions. By employing robustness testing and variant assessment, our model provides a structured and statistically reinforced framework that addresses this lacuna.

Many of the reviewed studies rely on standalone MCDM models without considering the robustness of results across shifting decision contexts or the variability of expert input, despite the methodological diversity. Although methods such as fuzzy AHP, fuzzy TOPSIS, and VIKOR are intended to mitigate imprecision, only a small number of them incorporate statistical quality tools (e.g., Taguchi) to verify the stability of the results. The majority of analyses concentrate on a single optimal result, which may result in the neglect of variations in rankings that arise from alternative assumptions.

This study proposes a hybrid framework that integrates the Taguchi method, a quality engineering tool, with AHP, TOPSIS, and PROMETHEE to evaluate performance variability through Signal-to-Noise ratios. This framework addresses the deficiencies identified in the previous study. The model not only identifies optimal strategies but also guarantees their consistency across risk-averse and risk-neutral conditions by implementing seven variant decision rules (e.g., Wald, Bayes, Hurwicz). Consequently, the proposed framework provides both methodological advancement and real-world applicability in assisting local decision-making regarding refuse management that is consistent with the "Clean Province" initiative.

V. Related Methods

To effectively select the best action plan for achieving the "Clean Province" initiative, systematic and robust methodologies are crucial for informed decision-making. Given the multiple, often conflicting criteria involved, a structured approach is necessary to evaluate and prioritize alternatives effectively. Multi-Criteria Decision Making (MCDM) techniques provide a powerful framework for addressing such complexities, enabling simultaneous assessment of environmental, social, and operational factors. These methods combine qualitative and quantitative data for a comprehensive evaluation, making them ideal for enhancing community waste management strategies.

The Analytic Hierarchy Process (AHP) was employed to determine the criteria weights, offering a structured framework that simplifies complex problems into a hierarchy of criteria. AHP uses pairwise comparisons to establish the relative importance of each criterion, validated through a consistency ratio to ensure reliability. These derived weights serve as inputs for two MCDM techniques: TOPSIS and PROMETHEE.

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) ranks alternatives by identifying those closest to the ideal solution and farthest from the negative ideal, balancing desirable and undesirable outcomes. PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) uses pairwise comparisons to calculate net preference flows, providing intuitive rankings. Together, these methods offer a robust framework for evaluating action plans.

Normalization ensures that the criteria values are comparable across scales. This study applies six normalization rules from "Methods of Variants Assessment" to standardize values for maximizing and minimizing criteria, enhancing comparability and reliability. This comprehensive approach ensures unbiased and consistent evaluation, enabling stakeholders to make well-informed decisions for sustainable waste management.

Normalization is a crucial step in ensuring that the criterion values are comparable across different scales. In this research, six normalization rules from the "Methods of Variants Assessment" are applied to standardize the criteria values. These rules address maximizing and minimizing criteria and ensure that the normalized values are unbiased and consistent. Normalization not only enhances comparability across alternatives but also improves the reliability of the MCDM methods applied in this study.

The six normalization rules and a MCDM employed in this study are as follows: (1) Wald's Rule, which focuses on the worst-case scenario by selecting the maximum value among the minimum scores for each alternative; (2) Savage Criterion, which minimizes potential losses by evaluating maximum relative losses for each alternative; (3) Hurwicz's Rule, which balances pessimistic and optimistic approaches using a confidence coefficient (λ); (4) Laplace's Rule, which assumes all states of nature are equally probable and selects the alternative with the highest average score; (5) Bayes' Rule, which multiplies normalized values by their respective weights to calculate a comprehensive score for each alternative; (6) Hodges-Lehmann Rule, which combines confidence in probability estimates with Wald's and Bayes' approaches using λ to adjust reliance on each method; and (7) Rank Order Centroid (ROC), which provides a simple and efficient method to approximate the importance of criteria by assigning weights based on their rank order. The inclusion of ROC ensures that the importance of the criteria is considered systematically, enhancing the robustness and reliability of the normalization process.

By employing normalization principles to systematically standardize criteria values, this investigation guarantees impartial assessments of alternatives, thereby eliminating biases that may arise from the use of different criteria scales. This essential phase improves the accuracy and fairness of assessments. The framework becomes a robust instrument for selecting optimal action plans by incorporating the Analytic Hierarchy Process (AHP), TOPSIS, PROMETHEE, and the Taguchi approach. The Taguchi approach, which employs the "smaller-the-better" principle and the Signal-to-Noise (SN) ratio, ensures consistency in expert evaluations and minimizes variability, thereby improving the framework's adaptability and dependability for sustainability practices and waste management.

The novelty of this study is the integration of AHP, TOPSIS, and PROMETHEE with the Taguchi approach to improve the reliability and robustness of expert-based evaluations, despite the fact that these techniques are well-established MCDM techniques. The Taguchi method, which employs the "smaller-the-better" principle and the Signal-to-Noise (SN) ratio, assists in the reduction of variability and inconsistency in expert judgments across a variety of decision scenarios. This statistical reinforcement enables the evaluation of solution stability under various decision rules and mitigates the impact of subjective bias. The study contributes a structured enhancement to conventional MCDM applications within the environmental sustainability context by incorporating this method into the decision-making framework, which results in a more resilient and data-driven evaluation of waste management strategies.

Multi-Criteria Decision-Making (MCDM) methods are indispensable for managing intricate decision-making scenarios that involve conflicting criteria. These methods offer a structured approach to the evaluation of alternatives, which involves the balance of environmental, social, and operational factors. This research employs MCDM techniques to rank action plans for the "Clean Province" initiative, thereby ensuring alignment with sustainability objectives and enhancing precision and reliability through the Taguchi approach.

Although AHP, TOPSIS, and PROMETHEE are frequently employed in multi-criteria decision-making, this study provides a methodological contribution by incorporating these techniques into a comprehensive framework that is further enhanced by the Taguchi approach. Traditional MCDM models frequently generate rankings that are derived from expert evaluations; however, they fail to consider the inherent uncertainty and variability of human judgments. The Taguchi method is implemented as a statistical reinforcement instrument to circumvent this constraint, enabling the computation of Signal-to-Noise (SN) ratios. The study enhances the reliability of the strategy selection process by identifying solutions that demonstrate the highest consistency across multiple expert opinions through the application of the "smaller-the-better" criterion.

Additionally, the framework is fortified by the integration of numerous variant assessment rules, including Wald's Rule, Bayes' Rule, Hurwicz's Criterion, Laplace's Rule, Savage Criterion, Hodges-Lehmann, and Rank Order Centroid (ROC). These principles facilitate a more comprehensive examination of the decision space than the traditional MCDM rankings, as they reflect a variety of risk preferences and decision philosophies. The Taguchi approach is employed to rank strategies under each rule and to analyze the dispersion of results, which increases the confidence of decision-makers in the selected option. For instance, the practical value of this integration in policy scenarios that necessitate both optimality and stability is underscored by the robustness of Strategy 1 across these variants.

Consequently, the significance of this study is not limited to the implementation of AHP, TOPSIS, and PROMETHEE; rather, it is the strategic integration of the Taguchi method as a robustness evaluator, a method that is not frequently employed in the evaluation of waste management strategies. This hybrid framework provides a more reliable foundation for sustainable policy design by resolving variability in expert inputs and simulating diverse decision conditions. It is especially pertinent in intricate governance contexts, such as the "Clean Province" initiative, where the success of implementation is contingent upon adaptability, stakeholder consensus, and consistency.

A. Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP), which was devised by Saaty in 1977, is a widely used methodology for the resolution of intricate multi-criteria decision problems. In the context of this research, AHP is employed to ascertain the relative importance weights of the criteria (Measure) that will be employed to assess the efficacy of action plans in attaining the objectives of the "Clean Province" initiative. These criteria encompass measures such as the appropriate disposal of hazardous and plastic waste, efficient waste collection, and source-level waste segregation. AHP allows stakeholders to quantify the relative significance of these criteria in relation to the overarching objective of identifying the most effective action plan by breaking down the issue into pairwise comparisons.

Consistency verification, hierarchy formation, pairwise comparisons, and criteria weight calculation comprise the AHP procedure. The goal is at the top of a hierarchy, followed by the criteria and sub-criteria levels. The aim is to select the best action plan. The criteria are compared pairwise using Saaty's fundamental scale, which ranges from 1 (equal importance) to 9 (severe importance), based on expert judgments. The weights are determined using the eigenvector procedure, which guarantees the assessments' consistency and robustness. These weights are subsequently employed as inputs for the subsequent evaluation of the action plans using TOPSIS and PROMETHEE. This foundation is used to rank the action plans based on their alignment with the criteria.

The objective and criteria are established at the outset of the process, with the primary objective of selecting the most appropriate action plan for the "Clean Province" initiative. The initiative's objectives are in alignment with six criteria that have been identified through expert judgment. This ensures that the evaluation takes into account the critical aspects of effective community waste management.

The decision-making process is subsequently optimized through the establishment of a hierarchical framework. The hierarchy is structured with the objective of selecting the most effective action plan at the top, followed by six criteria that represent the fundamental components of effective waste management. This structure facilitates systematic and transparent pairwise comparisons by breaking down the decision-making process into manageable levels.

A decision matrix is generated in the third stage by conducting pairwise comparisons of the criteria. Saaty's numerical scale (1 to 9) is employed by experts to denote the relative significance of one criterion in comparison to another. The resulting matrix guarantees a consistent and logical representation of expert judgments by setting diagonal elements to 1 (indicating equal importance) and reciprocal values for reverse preferences.

The matrix is subsequently normalized to determine the criteria weights. The normalized values are averaged across rows to generate relative weights that sum to 1.00, ensuring consistency and comparability. Each element is divided by the sum of its column.

The matrix's reliability is ultimately guaranteed by consistency verification. Based on the number of elements (n) in each matrix (Criteria), the consistency ratio (CR) is determined by comparing the consistency index (CI) to a random index (RI), and λ_{max} is the largest eigenvalue of the consistency vector. The CR must be less than 10% in order to be considered acceptable. The matrix is revised to enhance coherence if the CR surpasses this threshold. Criteria weights are guaranteed to be reliable and accurate through this systematic approach, which provides a solid foundation for subsequent analysis.

$$CR = \frac{CI}{RI}; \text{must have} < 10\% \tag{1}$$

$$CI = \frac{\lambda_{max} - 1}{n - 1} \tag{2}$$

B. TOPSIS (Technique for Order Preference by Similarity to Ideal Solution)

In this study, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is utilized to rank action plans for the "Clean Province" initiative. This method facilitates the selection of the most effective plan by identifying alternatives that are closest to the positive ideal solution (PIS) and farthest from the negative ideal solution (NIS). The evaluation is conducted based on six key criteria (measures) using the following systematic steps.

The process begins with collecting expert evaluations for the three proposed action plans. These evaluations are aligned with the six predefined criteria, forming the basis for quantitative assessment. Next, a decision matrix of the performance score of the i alternative on the j criterion is constructed. This matrix is crucial for quantifying the performance of all alternatives across all criteria.

To ensure comparability, the performance values in the decision matrix are normalized. This step eliminates the impact of differing units across the criteria. The normalized matrix (r_{ij}) is calculated using a standard formula, scaling all criteria values between 0 and 1. Subsequently, the normalized values are weighted by applying the AHP criteria weights (ω_j). The weighted normalized decision matrix (v_{ij}) is then created to reflect the significance of each criterion in the evaluation process.

The next step involves identifying the positive ideal solution (PIS, A^+) and the negative ideal solution (NIS, A^-) for each criterion. These are determined as the maximum and minimum values in the weighted normalized matrix, respectively.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad (3)$$

$$v_{ij} = \omega_j \times r_{ij} \quad (4)$$

$$A^+ = \{v_{1j}, v_{2j}, \dots, v_{ij}\} = \{\max v_{1j}\ for\ \forall\ j \in n\} \quad (5)$$

$$A^- = \{v_{1j}, v_{2j}, \dots, v_{ij}\} = \{\min v_{1j}\ for\ \forall\ j \in n\} \quad (6)$$

$$D_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - A_j^+)^2} \quad (7)$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - A_j^-)^2}. \quad (8)$$

$$RC_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (9)$$

Following this, the Euclidean distances of each alternative from the PIS (D_i^+) and NIS (D_i^-) are calculated. These distances measure how close or far an alternative is from the ideal solutions. Finally, the relative closeness (RC) of each alternative to the PIS is computed. The RC score quantifies the suitability of each alternative, enabling the ranking of action plans based on their proximity to the ideal solution. The alternative with the highest RC_i value is selected as the most suitable action plan. This systematic application of TOPSIS ensures a robust and transparent framework for evaluating and selecting the most effective waste management strategy for the "Clean Province" initiative.

C. Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE)

The PROMETHEE is an MCDM approach that is capable of evaluating and ranking alternatives based on a variety of conflicting criteria. It is the preferred option in a variety of domains, including resource allocation, environmental management, and project selection, due to its ease of use and flexibility. PROMETHEE is especially advantageous when decision-makers are required to evaluate both qualitative and quantitative criteria, as it effectively incorporates weights and preference functions to reflect their priorities and preferences.

PROMETHEE quantifies the degree of preference for one alternative over another by defining preference functions for each criterion. Six standard preference functions, including the usual, U-shape, and Gaussian criteria, are frequently employed, enabling customization to conform to the decision context. These functions facilitate the calculation of aggregated preference indices, which account for the relative importance of criteria and the variations in performance between alternatives.

PROMETHEE proceeds in a sequential manner, beginning with the assignment of AHP weights (ω_j) to criteria to indicate their significance in the decision-making process. For each criterion, a preference function ($P_j(d_{ik})$) is defined to determine the difference between the performance of the *i* and the *k* alternative on the *j* criterion (d_{ik}). Subsequently, the aggregated preference index ($\pi(a_i, a_k)$) is computed for each pair of all *m* alternatives, which serves as a comparative performance indicator.

The positive ($\phi^+(a_i)$) and negative ($\phi^-(a_i)$) outranking flows of the *i* alternative are determined from these indices, which indicate the extent to which an alternative is outranked or underranked by others. The net flow score ($\phi(a_i)$) is determined by the discrepancy between these flows and is used to rank alternatives, and a higher net flow score indicates better performance.

$$d_{ij} = f_j(a_i) - f_j(a_k) \quad (10)$$

$$\pi(a_i, a_k) = \sum_{j=1}^{n} \omega_j P_j(d_{ij}) \quad (11)$$

$$\phi^+(a_i) = \frac{1}{m-1} \sum_{k \neq i} \pi(a_i, a_k) \quad (12)$$

$$\phi^-(a_i) = \frac{1}{m-1} \sum_{k \neq i} \pi(a_k, a_i) \quad (13)$$

$$\phi(a_i) = \phi^+(a_i) - \phi^-(a_i) \quad (14)$$

PROMETHEE offers comprehensive rankings (PROMETHEE II) and partial rankings (PROMETHEE I). The former allows for a certain degree of incomparability among alternatives, whereas the latter provides a comprehensive arrangement. Supplementary visualization tools enhance the ability of decision-makers to analyze results and evaluate trade-offs. Intricate decision-making challenges are addressed by PROMETHEE's structured yet adaptable approach, which provides a transparent and comprehensible framework.

D. Taguchi Approach (TA)

The TA is a dependable engineering optimization technique that is frequently implemented to enhance the quality of products and the efficiency of processes. This method, which was developed by Dr. Genichi Taguchi, emphasizes the application of statistical principles to the design of experiments that systematically examine the effects of multiple factors and their interactions on a specific outcome. The TA contrasts with conventional optimization methods in that it emphasizes the process's robustness against external disturbances and noise factors in order to reduce variability and achieve consistent performance.

The TA employs a systematic approach to optimize parameters through orthogonal arrays, which substantially reduces the number of experimental trials required to study multiple variables. The method is able to effectively identify the optimal combination of input parameters with a minimum number of experiments, thereby saving time and resources. This is made possible by the arrays. It also introduces the Signal-to-Noise (SN) ratio, a metric that is intended to quantify the robustness and consistency of performance. The method divides optimization problems into three primary categories: nominal-is-best, smaller-is-better, and larger-is-better. This classification is consistent with a variety of industrial objectives, including precision, cost reduction, and efficiency enhancement. The "smaller-the-better (STB)" criterion is employed in this study to determine the rank (R) of the *i* alternatives from all *E* experts.

$$SN_{STB}(i) = -10\log_{10}\left[\frac{1}{E}\sum_{e=1}^{E} R_{ie}^{2}\right] \quad (15)$$

VI. Result and Discussion

This research assesses three waste management alternatives for the "Clean Province" campaign utilizing a comprehensive three-stage Multi-Criteria Decision-Making (MCDM) framework. The framework incorporates the Analytic Hierarchy Process (AHP), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE). The study employs Taguchi's optimization method and seven distinct decision-making evaluations to enhance the assessment. This thorough methodology guarantees a meticulous and flexible evaluation of strategies according to six established criteria: source waste segregation, waste reduction, waste collection efficiency, adherence to academic disposal standards, waste management during pandemics, and plastic waste management.

This study was conducted on Local Administrative Organizations (LAOs) in one of the northern provinces of Thailand to illustrate the practical applicability of the proposed framework. Data were gathered through consultations with local officials and waste management practitioners to guarantee that the criteria, strategies, and expert judgments accurately represented the realities of on-the-ground waste management operations. The study provides a contextualized evaluation of the integrated AHP–TOPSIS–PROMETHEE–Taguchi framework's ability to facilitate local decision-making by utilizing actual stakeholder input and implementing the model within an existing administrative structure. The model's real-world efficacy in guiding sustainable waste management strategies is initially validated by this provincial-level case, despite the fact that broader implementation across multiple regions remains an opportunity for future research.

The initial phase utilizes AHP to rank the six criteria, guaranteeing systematic and coherent weight distributions. Criterion 1 (waste segregation at the source) was determined to be the most significant factor, assigned a weight of 0.439422, whilst Criterion 6 (plastic waste management) was the least priority, with a weight of 0.048631. A Consistency Ratio (CR) under 0.1 confirmed the trustworthiness of these weights. The weights were subsequently applied to the TOPSIS and PROMETHEE analyses (Table 1).

Table 1. AHP criteria weights

Criteria	Weights
C1: Waste Segregation at Source	0.439422
C2: Waste Reduction	0.220942
C3: Waste Collection Efficiency	0.130153
C4: Academic-Compliant Disposal	0.104987
C5: Pandemic Waste Management	0.055865
C6: Plastic Waste Management	0.048631

Employing the AHP-derived weights, TOPSIS evaluated the three techniques according to their closeness to ideal solutions (Pi values). Strategy 1 (Promoting Knowledge and Awareness) regularly ranked as the highest-performing option, with a Pi value of 0.774732, signifying its substantial congruence with the criteria's aims. Strategy 2 (Strengthening Community Capacity) achieved a score of 0.597214, indicating a balanced performance, but Strategy 3 (Supporting Participation in Hazardous Waste Management) secured third place with a score of 0.301605.

These findings highlight the efficacy of Strategy 1 in advancing public education and behavioral modifications as essential elements of sustainable waste management. The rankings underscore the strategic benefit of tackling waste at its origin while prioritizing the spread of information. The worst score of Strategy 3 indicates its restricted efficacy in tackling the wider community and infrastructure concerns assessed in this analysis.

The PROMETHEE approach, with AHP weights, confirmed the superiority of Strategy 1, attributing it the highest net flow score ($\varphi(Si) = 0.278$). Strategy 2 was placed second with $\varphi(Si) = -0.095$, while Strategy 3 was ranked third with $\varphi(Si) = -0.183$. The alignment between TOPSIS and PROMETHEE outcomes enhances the credibility of the results, designating Strategy 1 as the most efficacious method for advancing sustainable waste management practices.

The study utilized seven distinct decision-making rules to enhance the analysis based on the initial findings: Wald's Rule (WA), Savage Criterion (SA), Hurwicz's Rule (HU), Laplace's Rule (LA), Bayes's Rule (BA), Hodges-Lehmann Rule (HL), and Rank Order Centroid (ROC). Each rule embodies distinct decision-making preferences, ranging from risk aversion to probabilistic and optimistic methodologies, providing detailed insights into the efficacy of the techniques.

Three normalization groups were utilized to standardize the criterion values. Van Delft and Nijkamp's normalization standardized all values to the [0–1] interval, but Weitendorf's normalization incorporated zeros and ones. Jüttler's and Körth's normalization facilitated wider ranges, encompassing negative values. This systematic normalization guarantees resilient and adaptable analysis, accommodating various data distributions and decision inclinations.

Strategy 1 consistently outperformed the other strategies in the majority of scenarios, with Pi values ranging from 0.611 to 1.000, as evidenced by the AHP-Weighted TOPSIS results across seven decision variants. The exception was the Savage Criterion (SA), where Strategy 1 achieved the lowest score of 0.000 (Table 2 and Fig. 1). Conversely, Strategy 3, which is typically the least effective among the majority of variants, achieved a score of 1.000 under SA, emphasizing its sole advantage in reducing the utmost regret. Strategy 1 obtained a perfect score of 1.000 under Wald's Rule (WA), which validated its robustness in worst-case decision-making. In the same vein, it demonstrated exceptional performance when subjected to Hurwicz's Rule (HU) (0.878) and Laplace's Rule (LA) (0.919), which are designed to balance optimism and risk. Strategy 1 demonstrated consistent performance under ambiguity, as evidenced by its high scores of 0.919 and 0.887 in probabilistic models such as Bayes's Rule (BA) and Hodges-Lehmann (HL). At the same time, Strategy 2 maintained a consistent second position in the majority of variants, with scores ranging from 0.278 to 0.771. Strategy 3, despite its effectiveness under SA, generally ranked lowest in other contexts (as low as 0.111), which further bolstered the overall dominance and resilience of Strategy 1 in multi-scenario decision-making.

Table 2. AHP-Weighted TOPSIS results across variants

Variants	Strategy 1 Scores	Strategy 2 Scores	Strategy 3 Scores
Wald's Rule (WA)	1.000	0.771	0.389
Savage Criterion (SA)	0.000	0.375	1.000
Hurwicz's Rule (HU)	0.878	0.677	0.342
Laplace's Rule (LA)	0.919	0.660	0.228
Bayes's Rule (BA)	0.919	0.660	0.228
Hodges-Lehmann Rule (HL)	0.887	0.644	0.182
Rank Order Centroid (ROC)	0.611	0.278	0.111

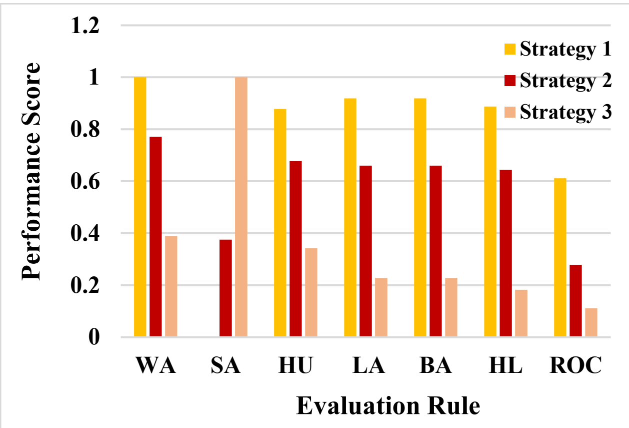

Fig. 1. AHP-Weighted TOPSIS performance scores of the three strategies under different evaluation rules.

In particular, Strategy 1 exhibits consistently superior performance under decision rules that balance optimism and pessimism, as evidenced by the AHP-Weighted PROMETHEE results across seven decision variants (Table 3). The strongest performance in worst-case scenarios was reinforced by Strategy 1, which achieved the maximum net flow score of 1.000 under Wald's Rule (WA). The high net flows observed under Hurwicz's Rule (HU) (0.902), Laplace's Rule (LA) and Bayes's Rule (BA) (both 0.934), and Hodges-Lehmann Rule (HL) (0.908) suggest a high degree of robustness and consistency in the face of uncertainty and probabilistic conditions. Nevertheless, Strategy 1 was relegated to the lowest rung of the Savage Criterion (SA) with a net flow of 0.000, whereas Strategy 3 was the top performer in that scenario with a score of 1.000, indicating a preference for minimizing the utmost regret. The performance of Strategy 2 was moderate and fluctuating across variants, with net flows ranging from -0.308 to 0.808. Although it secured the second rank under SA and ROC, it consistently lagged behind Strategy 1 in the majority of decision conditions. These findings bolster the strategic dominance and stability of Strategy 1 from a variety of decision-making perspectives.

Table 3. AHP-Weighted PROMETHEE results across variants

Variants	Strategy 1 Net Flow	Strategy 2 Net Flow	Strategy 3 Net Flow
Wald's Rule (WA)	1.000	0.192	0.000
Savage Criterion (SA)	0.000	0.808	1.000
Hurwicz's Rule (HU)	0.902	-0.308	-0.594
Laplace's Rule (LA)	0.934	-0.141	-0.396
Bayes's Rule (BA)	0.934	-0.141	-0.396
Hodges-Lehmann Rule (HL)	0.908	-0.168	-0.317
Rank Order Centroid (ROC)	0.611	0.278	0.111

Essential Insights and Pragmatic Implications The findings consistently indicate that Strategy 1 (Promoting Knowledge and Awareness on Waste Management) is the most successful option across all methodologies and variant evaluations. Its focus on public education and awareness initiatives establishes it as a fundamental component of sustainable waste management strategies. Strategy 2 exhibited a balanced performance, especially in fostering community engagement and infrastructural advancement. Strategy 3 necessitates specific enhancements to rectify its deficiencies in extensive community involvement and waste management protocols.

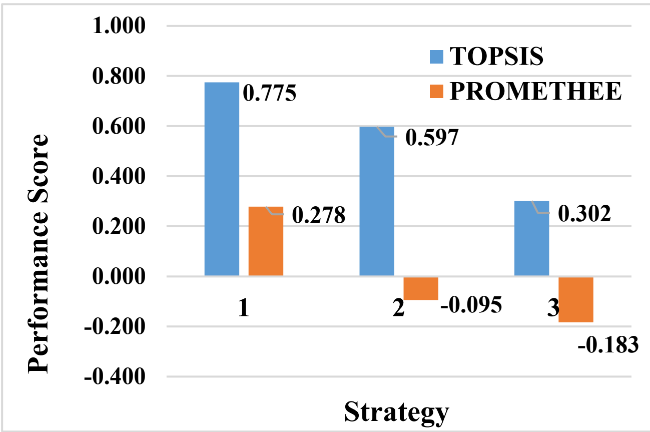

Fig. 2. Evaluating the performance metrics of the strategies with AHP-Weighted TOPSIS and PROMETHEE methodologies.

Fig. 2 illustrates the differences between the AHP-Weighted TOPSIS and AHP-Weighted PROMETHEE methods, which are characterized by their evaluative mechanisms and the interpretation of performance scores. AHP-Weighted TOPSIS emphasizes the nearness of each alternative to an ideal solution, resulting in positive and comparatively high scores for all strategies. Strategy 1 achieved the highest score (0.775), followed by Strategy 2 (0.597) and Strategy 3 (0.302). On the other hand, PROMETHEE implements a pairwise outranking methodology that assesses the net preference flow of each strategy in comparison to the others. The resulting values can be both positive and negative, indicating the degree to which one strategy is preferred over another, in addition to its absolute performance. Strategy 1 maintains its lead with a PROMETHEE score of 0.278, as demonstrated. Conversely, Strategy 2 and Strategy 3 demonstrate negative net flows of -0.095 and -0.183, respectively, indicative of their relative inferiority when contrasted pairwise to the top-ranking alternative.

The selection among these strategies is contingent upon decision-making priorities: TOPSIS is advantageous for prioritizing options according to their proximity to an optimal solution, offering distinct performance differentiation. PROMETHEE is more appropriate for intricate decision-making that requires pairwise comparisons and relative preferences, providing enhanced understanding of trade-offs and comparative advantages among solutions.

The radar map presents a multi-dimensional perspective on the performance of each strategy under both TOPSIS and PROMETHEE, uncovering insights that surpass those offered by the bar chart (Fig. 3). It illustrates the relative contributions of each technique, facilitating a more understandable comparison. Strategy 1 prevails in the chart, exhibiting the most extensive and consistent area, indicative of its stable and superior performance across both methodologies. This demonstrates that Strategy 1 satisfactorily fulfills the evaluation requirements, irrespective of the approach employed, highlighting its versatility and dependability.

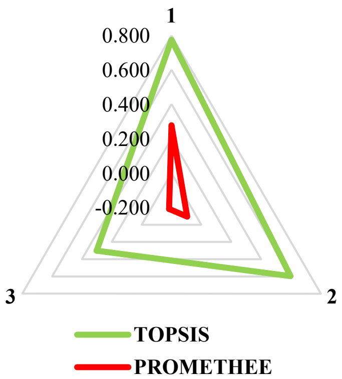

Fig. 3. A performance comparison of the strategies using AHP-Weighted TOPSIS and PROMETHEE.

Conversely, Strategies 2 and 3 exhibit considerably smaller and irregular areas, especially under PROMETHEE, where their scores are markedly condensed. This disparity indicates that PROMETHEE's pairwise comparison methodology imposes greater penalties on these strategies than TOPSIS, which assesses methods according to their closeness to the optimal solution. Strategy 2 demonstrates reasonable agreement with the criteria while underscoring the need for enhancements in infrastructure development and community participation. Strategy 3, characterized by the smallest area, indicates its constrained efficacy, presumably attributable to the resource-intensive demands of hazardous waste management and its restricted scope.

Furthermore, the radar graphic depicts the responsiveness of each approach to strategic performance. PROMETHEE, emphasizing comparative dominance, exposes significant deficiencies in Strategies 2 and 3, but TOPSIS, through its proximity-based assessment, yields comparatively favorable scores. This contrast highlights how the selection of technique influences the perceived efficacy of tactics, providing a more profound comprehension of their strengths and shortcomings.

The radar graphic affirms the supremacy of Strategy 1 while offering a detailed analysis of the problems and areas for enhancement in Strategies 2 and 3. It assists stakeholders in comprehending the performance interpretations of each technique, facilitating more informed judgments in the prioritization and execution of waste management initiatives.

The evaluation of waste management strategies for a clean province is a complex decision-making task that necessitates the application of robust analytical approaches to effectively prioritize alternatives. In order to manage the diverse and conflicting criteria that are present in these assessments, Multi-Criteria Decision-Making (MCDM) techniques are indispensable. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and the Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) are two of the most prominent instruments among these methods. The results of both methods were subjected to the Taguchi Signal-to-Noise (SN) ratio, which emphasizes the "smaller-the-better" criterion, in order to guarantee precise and dependable prioritization. This analysis evaluates the rankings and distinctions between TOPSIS and PROMETHEE in the context of three waste management strategies, emphasizing their respective strengths and contributions to decision-making processes.

In Multi-Criteria Decision-Making (MCDM), the TOPSIS and PROMETHEE methods are both frequently employed. However, they provide distinct methods for assessing alternatives. Both methodologies ranked Strategy 1 as the most favorable in the context of waste management strategies for a clean province. Nevertheless, their methodologies and the resulting insights demonstrate substantial disparities.

Strategy 1 (-4.2597) achieved the highest Signal-to-Noise (SN) value in the TOPSIS evaluation, with Strategy 3 (-9.5424) and Strategy 2 (-10.6695) following closely behind. This suggests that Strategy 1 is close to the optimum solution, as TOPSIS emphasizes the importance of striking a balance between minimizing the distance from the best solution and maximizing the distance from the worst solution. Strategy 1's apparent superiority in terms of overall proximity to the optimal solution is underscored by the broader range of SN values in TOPSIS (-9.5424 to -10.669), which reflects more pronounced distinctions among strategies.

In contrast, PROMETHEE, which utilizes preference flows and pairwise comparisons to rank alternatives, also identified Strategy 1 as the most effective option, with an SN value of -7.2700. Nevertheless, the disparities between the strategies were less pronounced, with Strategy 2 (-9.2082) and Strategy 3 (-9.8528) closely lagging. This is indicative of PROMETHEE's emphasis on the identification of nuanced preferences through preference functions and thresholds, which offer a more detailed assessment of the intensity of preference between alternatives. PROMETHEE's limited range of SN values (-7.27 to -9.85) implies that the strategies are more closely in competition (Fig. 4).

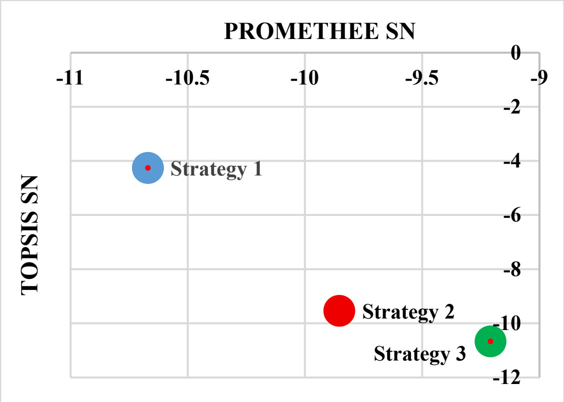

Fig. 4. Relationship between TOPSIS SN and PROMETHEE SN values for the three strategies.

TOPSIS is well-suited for situations in which the balance between criteria is critical, as it provides a straightforward evaluation based on geometric proximity to ideal solutions. Nevertheless, it does not explore the intensity of preference or pairwise comparisons, as PROMETHEE does. PROMETHEE is a valuable instrument for decision-makers who are interested in more detailed interpretations, as it has the capacity to consider subjective preferences and offer insights into the relative strengths of alternatives.

Although both methodologies arrived at the same conclusion regarding the optimal strategy, their distinct methodologies provide complementary insights. PROMETHEE offers a more sophisticated comprehension of preferences, while TOPSIS emphasizes the sharpened distinctions between strategies. Together, they illustrate the significance of employing a variety of MCDM techniques to guarantee comprehensive and resilient decision-making in intricate evaluations, such as the prioritization of waste management strategies.

This study presents a robust, versatile, and context-sensitive evaluation approach by incorporating AHP weights into TOPSIS and PROMETHEE and classifying the results within several decision-making frameworks. The results provide practical recommendations for policymakers and stakeholders, advocating for the prioritizing of public awareness campaigns and strategic investments in community-based waste management projects under the "Clean Province" effort. This strategy not only tackles urgent waste management issues but also corresponds with long-term environmental objectives.

The Taguchi method, AHP, TOPSIS, and PROMETHEE were chosen for this study due to their compatibility with expert-driven, policy-oriented decision-making contexts. AHP is particularly well-suited for the derivation of criteria weights through pairwise comparisons, which enables decision-makers to integrate expert knowledge in a structured and transparent manner. Although both TOPSIS and PROMETHEE are extensively used, they provide complementary perspectives. TOPSIS emphasizes proximity to ideal solutions, while PROMETHEE offers preference-based outranking, which is particularly beneficial when criteria are not readily quantifiable. The robustness of the results was statistically reinforced by incorporating the Taguchi method, which was employed to analyze the variability of rankings across multiple decision scenarios using the Signal-to-Noise ratio. This is a methodological improvement that resolves a prevalent limitation in MCDM research—namely, the susceptibility of rankings to inconsistencies in expert judgment.

In complex decision environments, other methods, such as VIKOR, ELECTRE, fuzzy MCDM, and AI or machine learning models (e.g., neural networks, decision trees), have gained traction. However, they frequently necessitate larger datasets, have higher computational demands, or may lack transparency in terms of decision logic—an important consideration in public policy contexts. Additionally, machine learning models commonly prioritize predictive accuracy over interpretability, rendering them less appropriate for scenarios in which stakeholder engagement and decision justification are essential. That being said, these contemporary methods possess substantial potential, and future research could investigate hybrid frameworks that combine AI-driven insights with interpretable MCDM tools to improve the precision and policy relevance of sustainable waste management decision-making.

Elaborating on the impact of the three strategies on implementation increases the practical significance of the findings. Strategy 1: The promotion of knowledge and awareness regarding waste management, consistently rated top in both AHP-Weighted TOPSIS and PROMETHEE analyses, underscores the significance of public education as a fundamental element of trash management. Executing this strategy includes organizing workshops, awareness campaigns, and outreach initiatives to promote behavioral modifications, including waste segregation and minimizing dependence on single-use plastics. This method establishes a basis for enduring sustainability through the promotion of community awareness. Nonetheless, it necessitates considerable investment in communication resources and collaborations with local organizations to guarantee extensive participation and enduring impact.

Strategy 2: Enhancing Community Capacity for Waste Management and Strategy 3: Facilitating Participation in Hazardous Waste Management, ranked second and third, respectively, provide complementary yet more targeted methodologies. Strategy 2 prioritizes the development of local infrastructure, including garbage collection locations and transit systems, while promoting collective accountability through community-led initiatives. Their success relies on continuous participation and capacity-building initiatives at the grassroots level. Strategy 3 focuses on hazardous and infectious waste, necessitating specialized facilities, technical proficiency, and stringent regulatory adherence. While crucial for mitigating environmental and health hazards, its execution is resource-demanding and may encounter obstacles in the absence of sufficient support. Collectively, these initiatives establish a holistic framework that harmonizes public awareness, infrastructure enhancement, and specialized trash management, facilitating a more efficient and sustainable waste management system within the "Clean Province" project.

VII. Conclusion

By employing a meticulous Multi-Criteria Decision-Making (MCDM) methodology, the "Clean Province" initiative demonstrates a comprehensive approach to waste management by evaluating three fundamental strategies against six established criteria. This study assesses the strategies of Promoting Knowledge and Awareness on Waste

Management, Strengthening Community Capacity for Waste Management, and Supporting Participation in Hazardous Waste Management based on a variety of criteria, including waste segregation, source reduction, collection efficiency, compliance with academic disposal standards, adaptability to pandemics, and plastic waste management. The study identifies actionable pathways to sustainable waste practices through these evaluations.

The synthesis of the Taguchi Signal-to-Noise (SN) approach, the Analytical Hierarchy Process (AHP), TOPSIS, and PROMETHEE guarantees a robust and empirical assessment framework that encompasses social, environmental, and technological aspects. The Taguchi approach, particularly the "smaller-the-better" principle, provides a quantitative foundation for prioritizing waste management strategies based on the performance robustness of multiple experts' evaluations. This approach offers an enhanced layer of analysis. This inclusion enhances the precision of strategy rankings by ensuring that they are in accordance with the technical aspects of waste management and the variability that is inherent in expert judgments.

The findings emphasize the critical role of public education in promoting behavioral changes, the necessity of providing communities with essential infrastructure and resources, and the significance of effective hazardous waste management in protecting the environment and health. This study underscores the importance of minimizing variations and assuring consistency in expert evaluations, which enables more reliable strategy selection by utilizing the Taguchi approach to refine the assessment process. This methodological innovation comprehensively addresses waste concerns, promoting the prioritization of solutions that are tailored to local contexts and informed decision-making.

For the successful implementation of sustainable waste management systems, the findings underscore the importance of collaborative initiatives among government bodies, the private sectors, and communities. Community empowerment remains a critical component of effective waste management, as it fosters increased engagement through initiatives such as refuse segregation campaigns, training programs, and the establishment of waste banks. These initiatives foster long-term collaboration, inclusivity, and shared accountability. The collaborative approach is further refined by the Taguchi-enhanced framework, which guarantees that strategies are not only effective but also resilient in the face of changing conditions.

The research offers policymakers a thorough framework for the development of evidence-based policies. The framework enables the creation of waste management plans that are environmentally responsive, socially inclusive, and technically robust by integrating methodologies such as AHP, TOPSIS, PROMETHEE, and Taguchi. This guarantees that local requirements and preferences are met while simultaneously aligning with overarching sustainability objectives. Additionally, these systems are more adaptable, as they are able to protect public health and environmental standards during disruptions by incorporating criteria that address resilience to crises, such as waste management during pandemics.

The "Clean Province" program is a replicable model that prioritizes community empowerment, multi-stakeholder collaboration, and a criterion-based assessment approach for regions that are confronted with comparable challenges. This framework is more adaptable to a variety of socioeconomic and environmental contexts due to the inclusion of the Taguchi method, which adds an extra layer of reliability. This adaptability increases its effectiveness as a paradigm for the establishment of healthier, cleaner societies on a global scale. The efficacy and reach of waste management systems can be further enhanced by collaborating with private enterprises and utilizing public-private partnerships, particularly in the areas of hazardous waste management and recycling infrastructure.

The integration of sophisticated technologies such as the Internet of Things (IoT) and artificial intelligence (AI) should be further explored in future research to optimize waste management systems. Operational efficiency and cost reduction can be considerably improved by intelligent waste management systems that integrate AI-based route optimization and IoT-enabled sensors. Furthermore, a more thorough assessment of waste management initiatives would be facilitated by the establishment of standardized metrics for long-term sustainability outcomes, including public health benefits, economic impacts, and carbon footprint reduction. By addressing variability and uncertainty in intricate decision-making processes, the robustness of these evaluations can be further enhanced through the implementation of the Taguchi approach in future research.

In summary, the "Clean Province" initiative emphasizes the significance of structured and inclusive waste management strategies that foster sustainable practices, enhance resilience, and empower communities. This study offers a refined framework for addressing the evolving challenges of refuse management by combining the Taguchi approach with MCDM methods. It provides policymakers and practitioners with the resources necessary to cultivate more sustainable, cleaner communities, thereby guaranteeing enduring environmental and societal advantages on a global scale.

Policymakers who are seeking to improve waste management systems under the "Clean Province" initiative and comparable initiatives can benefit from the practical insights provided by the results of this study. Policymakers are encouraged to incorporate public awareness campaigns into formal policy frameworks by allocating dedicated funding, incorporating waste education into school curricula, and partnering with NGOs and community leaders to drive behavioral change, as public awareness campaigns have emerged as the most effective strategy. Additionally, the establishment of performance indicators for outreach effectiveness and the integration of awareness initiatives into local development plans can guarantee accountability and continuity. In this way, policymakers can establish a sustainable foundation for community-driven waste management, thereby aligning local actions with broader environmental objectives and improving the long-term success of waste reduction initiatives by institutionalizing these efforts.

In order to assess the efficacy of the proposed framework in a variety of local governance and waste management contexts, future research could extend its application to multiple provinces or regions. Insights into the long-term impact of specific strategies on waste reduction and community engagement may also be obtained through longitudinal studies. Furthermore, the contemporary decision-making techniques, including fuzzy logic, ELECTRE, VIKOR, and artificial intelligence (AI)-based models, could be incorporated to improve the current framework. In contexts with ambiguous or qualitative data, fuzzy AHP and fuzzy TOPSIS are particularly well-suited for managing uncertainty and linguistic judgments. AI techniques, such as decision trees, neural networks, and ensemble learning, are capable of analyzing large, intricate datasets to identify performance patterns and offer significant predictive power. Future research could investigate hybrid approaches that integrate the interpretability of MCDM with the analytical profundity of AI, thereby enhancing the adaptability and accuracy of strategic waste management planning, despite the fact that such models may be less transparent for direct policymaker use.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

A.N. and P.L. contributed to the data curation of the research design, conceptualization, methodology, software, validation, visualization of the research, analysis of the results, and the writing, review & editing of the manuscript; all authors had approved the final version.

Funding

This work was supported by the research funding from the Faculty of Engineering, Thammasat School of Engineering, Thammasat University: Contract No. 001/2568.

Acknowledgment

The authors thank the referees for their advantageous comments and ideas that have significantly enhanced the substance and arrangement of this contribution.

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