BAREKENG: Journal of Mathematics and Its Applications
December 2025 Volume 19 Issue 4 Page 2861–2876
P-ISSN: 1978-7227 E-ISSN: 2615-3017
https://doi.org/10.30598/barekengvol19no4pp2863-2876

A STEPWISE FRAMEWORK FOR PRIORITIZING BLOCKCHAIN-ENABLED WASTE MANAGEMENT STRATEGIES IN THAILAND USING FUZZY-AHP, FUZZY-PROMETHEE, AND FACTORIAL DESIGN APPROACH

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Article History:

Received: 9th March 2025
Revised: 12th April 2025
Accepted: 10th June 2025
Available online: 1st September 2025

Keywords:

Blockchain Technology;
Design of Experiment;
FPROMETHEE;
Municipal Solid Waste Management;
Sustainable management.

ABSTRACT

Waste management remains a significant challenge in Thailand, as over 27 million tons of waste are produced annually, with over 30% being inadequately managed. The absence of effective waste tracking and monitoring systems further exacerbates the severe environmental issues, such as water contamination, landfill emissions, and public health hazards, that result from this improper handling. This investigation investigates the potential of blockchain technology to improve the efficiency, security, and transparency of waste management processes. A structured decision-making approach is implemented to evaluate blockchain-enabled strategies, which integrates the Fuzzy Analytic Hierarchy Process (FAHP) and the Fuzzy Preference Ranking Organization Method for Enrichment Evaluations (FPROMETHEE). To ascertain the relative significance of the eight critical criteria—operational cost, environmental impact reduction, feasibility, long-term sustainability, revenue generation potential, landfill reduction, cost-effectiveness, and public accessibility—FAHP synthesizes expert opinions under uncertain conditions. Eight critical criteria were assessed. Four blockchain-based waste management strategies were examined: waste tracking systems, recycling incentive programs, waste exchange platforms (WEP), and pay-as-you-throw (PAYT) schemes. These strategies were ranked using the FPROMETHEE method, which ensured a standardized and robust evaluation through an optimization-based normalization procedure. Based on the results, PAYT is the most effective strategy, as it promotes accountability and minimizes landfill dependency by charging households based on waste volume, thereby incentivizing waste reduction at the source. The sensitivity analysis emphasizes WEP as an additional promising approach. PAYT and WEP demonstrate substantial economic viability, ecological impact, and advantages in transparency. The results underline the potential of blockchain to improve stakeholder collaboration, streamline waste management operations, and promote sustainable waste reduction initiatives. This research offers a practical framework for the implementation of blockchain-based waste management solutions to support Thailand's transition toward a circular economy, providing policymakers with valuable insights.

How to cite this article:

A. Tepvarin, P. Luangpaiboon and A. Nanphang., "A STEPWISE FRAMEWORK FOR PRIORITIZING BLOCKCHAIN-ENABLED WASTE MANAGEMENT STRATEGIES IN THAILAND USING FUZZY-AHP, FUZZY-PROMETHEE, AND FACTORIAL DESIGN APPROACH", *BAREKENG: J. Math. & App.*, vol. 19, iss. 4, pp. 2861-2876, December, 2025

Journal homepage: *https://ojs3.unpatti.ac.id/index.php/barekeng/*
Journal e-mail: *barekeng.math@yahoo.com; barekeng.journal@mail.unpatti.ac.id*
Research Article · Open Access

1. INTRODUCTION

Waste management has emerged as a critical environmental and economic concern, particularly in swiftly developing nations like Thailand, where over 27 million tons of waste are produced annually, with over 30% being inadequately managed [1]. This mismanagement results in severe environmental degradation, such as water contamination, hazardous emissions from landfills, and public health hazards [2]. The inefficiencies in Thailand's waste management system result from inadequate monitoring mechanisms, inadequate public participation, and inadequate waste collection and disposal transparency [3]. These concerns underscore the necessity of technology-driven, innovative solutions to improve operational efficiency and encourage sustainable waste management practices [4].

The challenges associated with waste management in Thailand differ significantly between urban centers like Bangkok and rural areas due to variations in population density, infrastructure, and public services. According to the Pollution Control Department of Thailand, Bangkok alone contributed over 10,000 tons per day, accounting for approximately 27.8 million tons of municipal solid waste in 2023. Issues such as inadequate waste segregation, limited recycling infrastructure, and heavy reliance on landfilling cause environmental contamination, greenhouse gas emissions, and public health hazards—problems exacerbated by rapid urbanization and high population density in Bangkok. In contrast, rural areas face limited budgets, a lack of technical expertise, inconsistent waste collection, and a higher proportion of organic waste, necessitating different management strategies. By highlighting these contrasts and integrating recent statistics, this study ensures that the proposed blockchain-enabled solutions are contextually relevant and effectively address Thailand's diverse waste management challenges.

Blockchain technology has emerged as a transformative instrument in waste management, providing decentralized, secure, and transparent data recording systems [5]. Utilizing blockchain technology can considerably enhance waste monitoring, accountability, and resource optimization, reducing fraudulent practices and inefficient waste management. Furthermore, blockchain enables stakeholders to share data in real time, promoting a circular economy and increasing public engagement [6]. Blockchain has been investigated in supply chain monitoring, transparency, and sustainability initiatives; however, its potential in waste management is still unexplored, necessitating additional evaluations of its feasibility and efficacy [7].

A systematic and transparent decision-making framework is essential in Thailand due to the escalating complexity of waste management challenges, particularly the diverse waste compositions across urban and rural regions and the rapid pace of urbanization. The current system often lacks rigorous evaluation of new technologies like blockchain, struggles with inconsistent prioritization of strategies, and inadequately integrates stakeholder perspectives. To address these shortcomings, this study formulates the problem as the need to prioritize blockchain-enabled waste management strategies through a methodology that incorporates both quantitative data and expert judgments under uncertainty, while ensuring the resilience of final rankings.

The study's objectives are to (1) identify and assess key criteria relevant to waste management in the Thai context, (2) develop and apply an integrated multi-criteria decision-making framework—specifically, Fuzzy-AHP and Fuzzy-PROMETHEE—that handles fuzzy judgments and complex interrelations among criteria, and (3) enhance the robustness of prioritization through a Design of Experiments (DOE) approach. The novelty of this study lies in integrating these advanced methodologies into a single decision-support framework for the first time in Thailand's waste management sector, providing a rigorous, adaptable, and transparent tool that balances expert uncertainties, improves ranking stability, and supports sustainable policy development.

This investigation establishes a structured decision framework for assessing blockchain-enabled waste management strategies. AHP was chosen for this study due to its ability to evaluate and weight multiple criteria using expert judgments through pairwise comparisons. It is particularly beneficial in contexts with limited quantitative data, ensuring that stakeholders' practical priorities are reflected in each criterion's relative importance. PROMETHEE was selected due to its ability to conduct multi-criteria evaluations and generate comprehensive rankings through outranking flows, rendering it particularly effective for comparing intricate waste management strategies in uncertainty. This research provides a decision-support framework that is adaptable, transparent, and robust, which is well-suited to the multifaceted nature of waste management challenges in Thailand due to the integration of AHP and PROMETHEE.

The framework is based on the Fuzzy Analytic Hierarchy Process (FAHP) [8] and the Fuzzy Preference Ranking Organization Method for Enrichment Evaluations (FPROMETHEE) [9]. The investigation concentrates on four blockchain-based waste management strategies: waste tracking systems (WTS), recycling incentive programs (RIP), waste exchange platforms (WEP), and pay-as-you-throw (PAYT) schemes. Transparency and accountability are guaranteed by waste monitoring systems, which monitor waste movement throughout its lifecycle [10]. Recycling incentive programs promote waste reduction by offering blockchain-backed incentives for recycling [11]. The circular economy principles are promoted by waste exchange platforms, which facilitate the trade of recyclable materials between industries and consumers [12]. Waste minimization is promoted by pay-as-you-throw schemes, which employ a variable pricing model in which waste disposal fees are determined by the quantity of refuse produced [13].

In order to prioritize these strategies, eight critical criteria were identified: operational cost, environmental impact reduction, feasibility, long-term sustainability, revenue generation potential, landfill reduction, cost-effectiveness, and public accessibility: [14]. The relative importance of these criteria was determined using the Fuzzy-AHP method, and the blockchain-based strategies were ranked using the FPROMETHEE technique [15]. Additionally, a Design of Experiment (DOE) approach was implemented to evaluate the sensitivity of ranking outcomes in response to various parameter variations, thereby guaranteeing the robustness of the decision-making process [16].

The pay-as-you-throw (PAYT) scheme is the most effective approach, as it substantially reduces waste at its source by providing direct economic incentives for households to reduce waste production [17]. PAYT has been widely acknowledged in global waste management policies as a successful "polluter pays" principle that promotes responsible waste disposal behaviors and reduces landfill dependency [18]. Nevertheless, the waste exchange platform (WEP) also exhibits significant potential, particularly in resource recovery and public engagement, which is achieved through blockchain-powered transaction verification [19]. WEP enables the real-time exchange of materials between industries and consumers, thereby reducing the reliance on basic materials and promoting the principles of a circular economy [20].

In order to evaluate the model's robustness, a sensitivity analysis was conducted using DOE, which involved varying the preference function parameters to evaluate the impact of various weightings on strategy rankings [21]. The experimental design was instrumental in identifying critical factors that substantially impact decision outcomes, guaranteeing that the proposed decision-making framework is adaptable to various waste management contexts [22]. The study emphasizes the potential of blockchain to improve the efficacy of waste management, increase transparency, and facilitate stakeholder collaboration, thereby contributing to Thailand's sustainable development objectives [23].

The following is the structure of this document. A literature review is presented in Section 2, which analyzes extant blockchain applications in waste management and identifies research deficiencies. The research methodology, which encompasses the FAHP and FPROMETHEE frameworks, is elaborated upon in Section 3. The results are discussed in Section 4, which emphasizes the practical implications and evaluation of blockchain-enabled waste management strategies. The study is finally concluded in Section 5, which provides critical insights, limitations, and recommendations for future research [24].

2. RESEARCH METHOD

This study employs structured and explicit methodologies to facilitate decision-making and guarantee reliable outcomes to address the obstacles associated with waste management in Thailand. The objective is to identify the most effective blockchain-based solutions by contrasting strategies and evaluating various criteria. Tools that can accommodate numbers and opinions while accounting for uncertainty are required due to the numerous factors involved. The primary evaluation instruments for this purpose are the FAHP and FPROMETHEE. FAHP is employed to determine the weights for eight critical criteria essential for assessing blockchain-based refuse solutions. These criteria include cost, environmental impact reduction, feasibility, long-term sustainability, revenue generation potential, landfill reduction, cost-effectiveness, and public accessibility.

Expert participation was essential in the development of the FAHP pairwise comparison matrix. A comprehensive and context-specific evaluation of the eight key criteria was guaranteed by the engagement of five experts in industrial engineering, waste management, and environmental policy, each of whom possessed a minimum of five years of relevant experience. To mitigate groupthink and potential biases, each expert independently conducted pairwise comparisons. Reliability in the aggregated fuzzy pairwise matrix was guaranteed by calculating and confirming consistency ratios within acceptable thresholds.

The input data for this study were gathered through official statistics, expert judgment, and literature review. To guarantee relevance to Thailand's waste management context, eight critical criteria were identified for the FAHP procedure through stakeholder consultations and existing studies. Expert participation was indispensable for developing the pairwise comparison matrix employed in FAHP. The evaluation was conducted with five experts in industrial engineering, waste management, and environmental policy. The panel was diverse and knowledgeable, as each expert had at least five years of experience in their respective disciplines. To reduce bias, each expert independently provided pairwise comparisons according to their professional judgment.

The geometric mean method was employed to aggregate the pairwise comparison data of the experts in order to generate a consensus fuzzy pairwise comparison matrix. Consistency ratios were computed to verify the reliability of the aggregated judgments. Additional data, including refuse generation statistics, were obtained from the 2023 annual report of the Pollution Control Department of Thailand. A robust foundation for the application of the integrated FAHP-FPROMETHEE methodology and sensitivity analysis in this study was established through the combination of reliable secondary data and expert assessments.

Each waste management strategy's social, economic, and ecological consequences are assessed. Operation Cost (C1) is a metric that evaluates the cost of implementation and maintenance when evaluating a waste management strategy. Revenue Generation Potential (C5) is a metric that concentrates on the economic value that a strategy can generate. Landfill Reduction (C6) is concerned with reducing waste material disposed of in landfills, while Environmental Impact Reduction (C2) concentrates on damage control from a strategy. Long-Term Sustainability (C4) is demonstrated by cost sustainability over an extended period of time without an excessive consumption of resources or significant costs for substantial changes. Although risk assessment (C3) is crucial, it is one of the limitations of being considered feasible due to the impracticality of numerous effective approaches, the absence of technical, financial, or organizational support, and payment.

Moreover, Cost-Effectiveness (C7) is the evaluation of the engagement or interface for the public, ensuring that public money is not squandered by balancing costs with benefits. Public Accessibility (C8) is a related concept. Some of the fundamental strategies include Waste Tracking Systems (S1), which enhance the traceability and accountability of waste by monitoring it throughout its lifecycle; Recycling Incentive Programs (S2), which offer incentives to the public to encourage their participation; Waste Interchange Platforms (S3), which simplify the exchange and reuse of recyclable materials; and Pay-As-You-Throw (S4), which incentivizes responsible disposal practices by charging waste disposal fees based on the volume of waste generated.

This study employs FPROMETHEE on natural data, preserving the original values without scaling. The V-Shape with Indifference Preference function emphasizes significant differences while disregarding minor ones, while the Level Criterion function is employed to examine precipitous shifts in preferences. Two preference functions are employed. These functions are utilized to evaluate the impact of the preference functions on the outcomes, resulting in two distinct evaluations of the natural data. The natural data were analyzed using a Design of Experiment (DOE) approach with a factorial design in this study. It assesses a variety of combinations of p and q values within the preference routines. This phase investigates whether the rankings are consistent across all scenarios or if they fluctuate.

The sensitivity analysis employed a factorial design to examine the impact of preference thresholds (p and q) on the FPROMETHEE rankings; to evaluate the stability of the strategy rankings under various preference circumstances, the parameters were systematically altered across five levels—ranging from 0.55 to 0.75 for p and from 0.25 to 0.45 for q —enabling a structured examination of parameter impacts that facilitated a comprehensive understanding of the model's robustness in diverse decision contexts. The transparency, reproducibility, and scientific rigor of the study are not only enhanced by these methodological enhancements, but they also align with best practices in multi-criteria decision analysis, ensuring that the decision-making framework remains adaptable, interpretable, and robust in response to the complex realities of waste management challenges in Thailand through the integration of systematic sensitivity analysis and expert judgment.

The impact of variations in p and q on the preference functions was investigated in this investigation using a DOE methodology. The research employs a factorial approach to examine all conceivable combinations of p and q. Each scenario evaluates a unique set of values for these two parameters, ensuring that all potential variants are investigated as they appear in the proposed pseudocode (Figure 1). This methodical approach ensures a comprehensive understanding of the robustness and behavior of the preference functions under a diverse range of conditions by evaluating the impact of different parameter combinations on the ranking results.

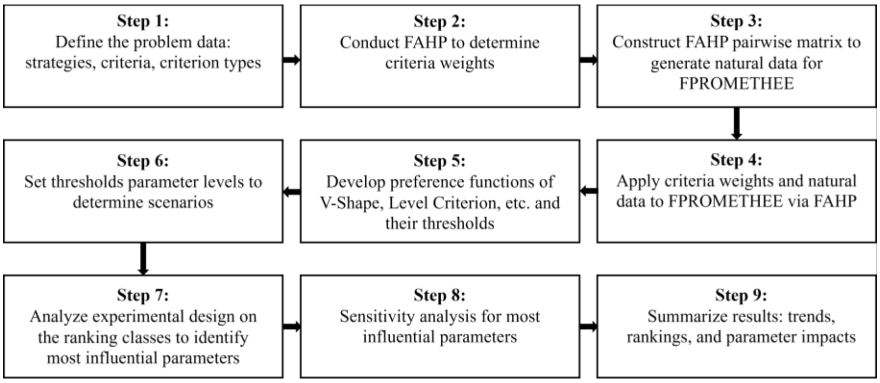


Figure 1. Procedure of A Stepwise Framework

2.1 Fuzzy-Analytical Hierarchy Process (FAHP)

The FAHP procedure [25] begins by establishing a pairwise comparison matrix X, This $n \times n$ matrix captures expert judgments about the relative importance of each criterion, with every entry x_{ij} denoting how much more important criterion i is compared to criterion j. Constructing this matrix systematically ensures that the decision problem is well-defined and that the relationships among all criteria are considered. Once the pairwise matrix is formed, the reciprocal of any fuzzy number (l, m, u) in the matrix is computed using Equation (1). This ensures consistency in cases where the direction of comparison is reversed (i.e., comparing i to j instead of j to i). By applying this conversion, the matrix remains consistent even when the comparison is inverted, preserving the integrity of the fuzzy logic approach.

$$X^{-1} = (l, m, u)^{-1} = \left(\frac{1}{u}, \frac{1}{m}, \frac{1}{l}\right). \tag{1}$$

The fuzzy geometric value in Equation (2) synthesizes the overall significance of each criterion after the matrix entries are assigned and reciprocals are taken into consideration. In this case, the lower, middle, and upper bounds of all fuzzy numbers within a single row are multiplied separately, and the n^{th} root is subsequently obtained, where n is the number of criteria. The expert judgments for each criterion are condensed into a singular ambiguous value in this computation. Consequently, decision-makers can accurately represent the aggregated perception of a criterion's significance, which is a reflection of both the certainty and uncertainty of expert inputs. Equation (3) is employed to derive the fuzzy weights W_i for each criterion, which are based on the fuzzy geometric values.

$$r_i = ((l_1 l_2 \dots l_n)^{\frac{1}{n}}, (m_1 m_2 \dots m_n)^{\frac{1}{n}}, (u_1 u_2 \dots u_n)^{\frac{1}{n}}). \tag{2}$$

$$W_i = r_i * (r_1, r_2, r_3, \dots, r_n)^{-1}. \tag{3}$$

In essence, the fuzzy geometric value of each criterion is normalized against the sum of all fuzzy geometric values in the matrix. This method standardizes the criteria to ensure that the final set of fuzzy weights collectively reflects the relative importance of each aspect of the decision problem as perceived by experts. The result is a more precise understanding of which criteria may be given greater weight in the overall assessment. Defuzzification is implemented by Equation (4) to generate a singular crisp weight from each fuzzy weight.

$$w_i = \left(\frac{l + m + u}{3}\right). \tag{4}$$

The center of area (or centroid) method is commonly employed, converting the triangular fuzzy number (l, m, u) into one representative value. By averaging its lower, middle, and upper bounds, the inherent subjectivity in expert judgments is still respected, but the result is more interpretable for subsequent ranking and comparison tasks. A normalization step is implemented to generate the normalized weight (Nw_i) in accordance with **Equation (5)** when the sum of the defuzzified weights surpasses 1. Each weight is divided by the sum of all weights, ensuring they collectively sum to exactly 1. This step maintains consistency across the criteria and provides a clear basis for decision-making, as stakeholders can readily interpret how each criterion's weight contributes to the overall priority structure.

$$Nw_i = \frac{w_i}{\sum_i w_i}. \tag{5}$$

2.2 Fuzzy-PROMETHEE

FPROMETHEE is a decision-making method combining fuzzy logic with the traditional PROMETHEE approach **[26]**, making it great for handling uncertainty and subjective opinions. By using fuzzy numbers, this method captures expert opinions more accurately, especially when evaluating strategies based on criteria like cost, environmental impact, and sustainability. The process begins with the construction of a fuzzy decision matrix, where fuzzy numbers are used to represent the performance of each strategy under each criterion. These fuzzy numbers, expressed as triangular fuzzy numbers (TFN) with three parameters—the lower bound (l), the most likely value (m), and the upper bound (u), capture the imprecision inherent in expert evaluations, ensuring a flexible approach to handling uncertainties.

Once the matrix is constructed, the fuzzy numbers are converted into crisp values through defuzzification using the centroid method, which calculates the weighted average of parameters l, m, and u (**Equation (4)**). These crisp values (r_{ij}) then serve as the foundation for evaluating the strategies against the criteria, maintaining consistency and interpretability while preparing the data for the subsequent application of preference functions. The decision matrix must be normalized before applying the preference function, with different approaches used for beneficial criteria (**Equation (6)**) and non-beneficial criteria (**Equation (7)**). For beneficial criteria, where higher values are preferred, normalization ensures that values are scaled proportionally to their maximum. For non-beneficial criteria, where lower values are better, normalization adjusts the values so that lower performance is reflected accordingly.

$$R_{ij} = \frac{[r_{ij} - min(r_{ij})]}{[max\ (r_{ij}) - min(r_{ij})]}, \tag{6}$$

$$R_{ij} = \frac{[max\ (r_{ij}) - r_{ij}]}{[max\ (r_{ij}) - min(r_{ij})]}. \tag{7}$$

The V-Shape with Indifference Preference function (VF) is designed to quantify the degree of preference between strategies based on their performance differences. This function introduces an indifference threshold (q) and a strict preference threshold (p), which determines when one strategy is significantly better than another. For any two strategies, the preference value $p(d)$ is calculated as **Equation (8)**.

$$p(d) = \begin{cases} 0, if\ d \le q \\ \frac{d-q}{p-q}, if\ q < d \le p \\ 1, if\ d > p. \end{cases} \tag{8}$$

Here, d represents the difference in performance between two strategies. This function is particularly useful when minor differences ($d \le q$) can be ignored, while larger differences ($d > q$) are progressively emphasized as d approaches or exceeds p. The Level Criterion Preference function (LF) determines the degree of preference between strategies by introducing a step-like structure in the preference values. The function is calculated by **Equation (9)**.

$$p(d) = \begin{cases} 0, if\ d \le 0 \\ \frac{1}{2}, if\ q < d \le p \\ 1, if\ d > p. \end{cases} \tag{9}$$

This structure creates distinct shifts in preference, making it particularly useful in scenarios where sudden changes in preference are important. Unlike the gradual approach of the VF, this method emphasizes abrupt transitions, making it suitable for criteria where clear thresholds must define preferences. The aggregated preference index $\pi(T_i, T_k)$ calculates how much one strategy (T_i) is preferred over another (T_k) by combining the preference values across all criteria. It is computed as **Equation (10)**.

$$\pi(T_i, T_k) = \sum_{j=1}^{n} P_j(T_i, T_k) \cdot w_j, \forall T_i, T_k \in T \text{ and } i \neq k. \tag{10}$$

where $\pi(T_i, T_k)$ is Aggregated preference index for strategy T_i over T_k,

w_j is Weight of criterion j,

$P_j(T_i, T_k)$ is Preference function showing how much T_i prefers to T_k with respect to c_j .

The step above is applied to the natural data, focusing on how the preference indices are impacted by the evaluation process. After computing the aggregated preference indices, the outranking flows are calculated to summarize each strategy's overall performance. **Equation (11)** and **Equation (12)** give the positive and negative outranking flows. The net outranking flow $\emptyset(T_i)$ provides the final ranking by combining the positive and negative outranking flows as **Equation (13)**. The net outranking flow score represents the overall preference for each strategy, where higher values indicate better performance. By calculating the net flows for natural data, this research evaluates the rankings to ensure a thorough comparison of strategies while maintaining consistency in the evaluation process.

$$\emptyset^+(T_i) = \frac{1}{m-1} \sum_{k=1}^{m} \pi(T_i, T_k), \tag{11}$$

$$\emptyset^-(T_i) = \frac{1}{m-1} \sum_{k=1}^{m} \pi(T_k, T_i). \tag{12}$$

$$\emptyset(T_i) = \emptyset^+(T_i) - \emptyset^-(T_i), \forall_i \in \{1, \dots, m\} \tag{13}$$

2.3 Design of Experiment: Factorial Design Approach

This research used a factorial design approach [27] to examine the influence of preference parameters on ranks within the FPROMETHEE framework. This approach offers a methodical framework to explore many elements' separate and collective impacts. The factorial design organizes the evaluation into various scenarios based on varying p and q values, ensuring that all conceivable combinations are addressed for a comprehensive and structured study. This methodology is essential to our research since it guarantees a thorough investigation of how variations in preference characteristics (p and q) affect the ranks of strategies. The factorial design carefully assesses all potential combinations, decreasing the danger of neglecting significant interactions or trends. It enables us to ascertain whether these criteria substantially influence individually or collectively, providing enhanced insights into the decision-making process.

3. RESULTS AND DISCUSSION

Five professionals with a minimum of five years of experience in industrial engineering, waste management, and environmental policy were consulted to gather the expert judgment input data. The inputs of each expert were aggregated using the geometric mean method to ensure consistency and reduce bias, and they independently conducted pairwise comparisons of the eight critical criteria. Consistency ratios were computed to verify the reliability of the aggregated matrix. The results of the evaluation of blockchain-enabled waste management strategies using the integrated FAHP and FPROMETHEE framework are presented in this section.

The evaluation of four strategies—Waste Tracking Systems, Recycling Incentive Programs, Waste Exchange Platforms, and Pay-as-You-Throw (PAYT) schemes—is made based on eight criteria: operational cost, environmental impact reduction, feasibility, long-term sustainability, revenue generation potential, landfill reduction, cost-effectiveness, and public accessibility. These criteria guarantee a comprehensive evaluation that considers technical, economic, social, and environmental factors pertinent to Thailand's sustainability objectives. The outcomes are discussed in terms of rankings under varying p (preference threshold) and q (indifference threshold) parameters, emphasizing the sensitivity of the results to these settings. The decision-making framework's robustness is elucidated through sensitivity analysis, identifying the most stable and impactful strategies. The results offer practical suggestions for prioritizing strategies consistent with Thailand's environmental objectives and facilitating the transition to a circular economy.

The local context of Thailand's waste management system further emphasizes the relevance of these findings. In Thailand, policymakers are searching for innovative solutions to long-standing challenges, including landfill overcapacity, limited recycling rates, and public participation divides, in light of the country's accelerated urbanization, increasing waste volumes, and increasing emphasis on circular economy initiatives. The Thai government's "polluter pays" principle and ongoing initiatives to encourage resource recovery and community engagement align with the prioritization of Pay-as-You-Throw and Waste Exchange Platforms strategies. The potential of the proposed decision-making framework to inform national and local waste management planning in support of sustainable development objectives is underscored by these insights, demonstrating its adaptability to Thailand's socio-economic and policy environment.

3.1 Fuzzy Analytic Hierarchy Process (FAHP)

Structured questionnaires were distributed to each expert to collect data for the FAHP pairwise comparisons, enabling them to provide independent judgments on the relative importance of the eight critical criteria. This method guaranteed that expert opinions were formed based on individual professional expertise and reduced the likelihood of groupthink. Consistency ratios were computed to verify the reliability of the aggregated judgments, and the geometric mean method was employed to aggregate the individual responses into a consensus fuzzy pairwise comparison matrix.

For this evaluation, the accuracy of the AHP method is assessed by the Consistency Ratio (CR). The value of CR is 0.0725, which indicates that the CR is less than 10%. In the interim, the expert's assessment is permissible. Upon receiving the experts' assessment of the relative importance of each criterion, convert it to a matrix. The pairwise comparison matrix is converted into a fuzzified pairwise comparison matrix for the reciprocal of any fuzzy number. The fuzzy geometric value in **Equation (2)** synthesizes the aggregate significance of each criterion (**Table 1**). Fuzzy weight (W_i) are obtained from the fuzzy geometric mean, then defuzzified and normalized, yielding final weights (Nw_i) of [0.0270, 0.2341, 0.1288, 0.2494, 0.0996, 0.1463, 0.0630, 0.0519] for [C1, C2, C3, C4, C5, C6, C7, C8].

Table 1. **Fuzzy Geometric Mean Value**

Criteria	C1	C2	…	C8	r_i
C1	(1,1,1)	(1/9,1/8,1/7)		(1/4,1/3,1/2)	(0.22,0.26,0.34)
C2	(7,8,9)	(1,1,1)		(2,3,4)	(1.97,2.39,2.77)
C3	(4,5,6)	(1/6,1/5,1/4)		(2,3,4)	(1.13,1.32,1.49)
C4	(7,8,9)	(1,1,1)	…	(4,5,6)	(2.14,2.55,2.91)
C5	(2,3,4)	(1/4,1/3,1/2)	…	(2,3,4)	(0.84,1.00,1.19)
C6	(4,5,6)	(1,1,1)		(4,5,6)	(1.34,1.50,1.65)
C7	(2,3,4)	(1/4,1/3,1/2)		(1,1,1)	(0.52,0.62,0.77)
C8	(2,3,4)	(1/4,1/3,1/2)		(1,1,1)	(0.41,0.51,0.65)

3.2 Fuzzy PROMETHEE

In this section of the calculated example, only natural data and the VF on the Preference function are presented for the calculation of PROMETHEE. From the evaluation in **Table 2**, the fuzzy values are derived through the FAHP. Once, the fuzzy decision matrix is done. Fuzzy numbers are changed into crispy value. It is computed as **Equation (4)**. Then, do the normalization (**Equation (5)**) before getting into preference function process (**Table 3**). In this study, only C1 is Non-Beneficial Criteria. The others (C2-C8) are Beneficial Criteria.

Table 2. Fuzzy Decision Matrix for PROMETHEE

Fuzzy Weight	0.0270	0.2341	…	0.0519
Criteria/Strategy	C1	C2	…	C8
S1	(0.110,0.182,0.280)	(0.049,0.067,0.099)		(0.035,0.042,0.052)
S2	(0.453,0.633,0.877)	(0.102,0.151,0.235)	…	(0.299,0.380,0.473)
S3	(0.070,0.116,0.198)	(0.288,0.391,0.521)	…	(0.107,0.143,0.199)
S4	(0.046,0.068,0.114)	(0.288,0.391,0.521)		(0.366,0.435,0.515)

Table 3. Normalization for Beneficial and Non-Beneficial Criteria

Fuzzy Weight	0.0270	0.2341	0.1288	0.2494	0.0996	0.1463	0.0630	0.0519
Criteria/Strategy	C1	C2	C3	C4	C5	C6	C7	C8
S1	0.876	0.000	0.000	1.000	0.000	0.000	0.000	0.135
S2	1.000	0.277	0.403	0.000	0.552	0.411	0.171	0.000
S3	0.000	1.000	1.000	0.176	1.000	0.411	0.818	1.000
S4	0.579	1.000	0.000	0.624	0.106	1.000	1.000	0.081

The performance difference between the two strategies is represented by d after normalization, as illustrated in Table 4. The VF can be calculated for the preference function using Equation (8) by the initial scenario presented in Table 5. The aggregated preference index or $\pi(T_i, T_k)$ is calculated continuously (Table 6). The outranking flows are computed to summarize the overall performance of each strategy after the aggregated preference indices have been determined. Equation (11) and Equation (12) are employed to determine the positive and negative outranking flows. This is an illustration of positive and negative outranking flow for $i = 1$ (Table 7). The final ranking is represented by the net outranking flow (Table 8), which is the sum of the positive and negative outranking flows, as illustrated in Equation (13).

Table 4. Difference Between Two Strategies

Fuzzy Weight	0.0270	0.2341	0.1288	⋮	⋮	0.1463	0.0630	0.0519
Criteria/Difference	C1	C2	C3	…	…	C6	C7	C8
d(S1-S2)	-0.124	-0.277	-0.403			-0.411	-0.171	0.135
d(S1-S3)	0.876	-1.000	-1.000			-0.411	-0.818	-0.865
d(S1-S4)	0.297	-1.000	0.000	…	…	-1.000	-1.000	0.054
d(S2-S1)	0.124	0.277	0.403			0.411	0.171	-0.135
d(S2-S3)	1.000	-0.723	-0.597			0.000	-0.648	-1.000
…		…					…	
…		…					…	
d(S4-S2)	-0.421	0.723	-0.403	…	…	0.589	0.829	0.081
d(S4-S3)	0.579	0.000	-1.000			0.589	0.182	-0.919

Table 5. Preference Function Between Two Strategies

Fuzzy Weight	0.0270	0.2341	0.1288	⋮	⋮	0.1463	0.0630	0.0519
Criteria/Preference	C1	C2	C3	…	…	C6	C7	C8
$P_j(T_{S1}, T_{S2})$	0.000	0.000	0.000			0.000	0.000	0.000
$P_j(T_{S1}, T_{S3})$	1.000	0.000	0.000			0.000	0.000	0.000
$P_j(T_{S1}, T_{S4})$	0.000	0.000	0.000	…	…	0.000	0.000	0.000
$P_j(T_{S2}, T_{S1})$	0.000	0.000	0.022			0.072	0.000	0.000
$P_j(T_{S2}, T_{S3})$	1.000	0.000	0.000			0.000	0.000	0.000
…		…					…	
…		…					…	
$P_j(T_{S4}, T_{S2})$	0.000	1.000	0.000	…	…	1.000	1.000	0.000
$P_j(T_{S4}, T_{S3})$	1.000	0.000	0.000			1.000	0.000	0.000

Table 6. The Aggregated Preference Index Between Two Strategies

0.0270	…	0.0519	Fuzzy Weight
C1	…	C8	Criteria
$P_j(T_i, T_k) \cdot w_j$			$\pi(T_i, T_k)$
$P_1(T_{S1}, T_{S2}) \cdot w_1$	…	$P_8(T_{S1}, T_{S2}) \cdot w_8$	$\pi(T_{S1}, T_{S2})$
$0.000 \cdot 0.0270$	…	$0.000 \cdot 0.0519$	0.249
$P_1(T_{S1}, T_{S3}) \cdot w_1$	…	$P_8(T_{S1}, T_{S3}) \cdot w_8$	$\pi(T_{S1}, T_{S3})$
$1.000 \cdot 0.0270$	…	$0.000 \cdot 0.0519$	0.276
$P_1(T_{S1}, T_{S4}) \cdot w_1$	…	$P_8(T_{S1}, T_{S4}) \cdot w_8$	$\pi(T_{S1}, T_{S4})$
$0.000 \cdot 0.0270$	…	$0.000 \cdot 0.0519$	0.000
$P_1(T_{S2}, T_{S1}) \cdot w_1$	…	$P_8(T_{S2}, T_{S1}) \cdot w_8$	$\pi(T_{S2}, T_{S1})$
$0.000 \cdot 0.0270$	…	$0.000 \cdot 0.0519$	0.113
	…		
	…		
$P_1(T_{S4}, T_{S2}) \cdot w_1$	…	$P_8(T_{S4}, T_{S2}) \cdot w_8$	$\pi(T_{S4}, T_{S2})$
$0.000 \cdot 0.0270$	…	$0.000 \cdot 0.0519$	0.693
$P_1(T_{S4}, T_{S3}) \cdot w_1$	…	$P_8(T_{S4}, T_{S3}) \cdot w_8$	$\pi(T_{S4}, T_{S3})$
$1.000 \cdot 0.0270$	…	$0.000 \cdot 0.0519$	0.254

$$\emptyset^+(T_i) = \frac{1}{4-1}\sum_{k=1}^{4}\pi(T_i, T_k)$$

$$\emptyset^+(T_{S1}) = \frac{1}{4-1}[(0.249 + 0.276 + 0.000)]$$

$$\emptyset^-(T_i) = \frac{1}{4-1}\sum_{k=1}^{4}\pi(T_k, T_i)$$

$$\emptyset^-(T_{S1}) = \frac{1}{4-1}[(0.113 + 0.588 + 0.443)]$$

Table 7. The Positive and Negative Outranking Flow

$\pi(T_i, T_k)$	$\pi(T_{S1})$	$\pi(T_{S2})$	$\pi(T_{S3})$	$\pi(T_{S4})$	$\emptyset^+(T_i)$
$\pi(T_{S1})$	-	0.249	0.276	0.000	0.175
$\pi(T_{S2})$	0.113	-	0.027	0.037	0.059
$\pi(T_{S3})$	0.588	0.510	-	0.280	0.459
$\pi(T_{S4})$	0.443	0.693	0.254	-	0.463
$\emptyset^-(T_i)$	0.381	0.484	0.186	0.106	-

Table 8. Net Outranking Flow for S1-S4 for the First Scenario

Strategy	$\emptyset^+(T_i)$	$\emptyset^-(T_i)$	$\emptyset(T_i)$	Ranking
S1	0.175	0.381	-0.206	3
S2	0.059	0.484	-0.425	4
S3	0.459	0.186	0.273	2
S4	0.463	0.106	0.358	1

As shown in **Table 8**, the final ranking of blockchain-based waste management strategies after applying FPROMETHEE is illustrated by the results of this study. The strategies were ranked based on their performance across eight critical criteria: operational cost, environmental impact mitigation, feasibility, long-term sustainability, revenue generation potential, landfill reduction, cost-effectiveness, and public accessibility, using the integrated FAHP and FPROMETHEE methods. Significant performance disparities between the strategies are revealed by the rankings analysis under the parameter values of p = 0.55 and q = 0.40 (**Table 5**-**Table 8**). The Waste Tracking System (S1) was ranked third in the evaluation criteria due to its high costs and management challenges, which necessitated specialized skills and time for implementation. Although it improves transparency, accountability, and waste monitoring, it is less efficient than less expensive alternatives. Nevertheless, this system has enduring utility. The Recycling Incentive Program (S2) was the lowest-ranked program, as it faced increased management challenges due to its high costs and safety restrictions. Even though it encourages public participation and reduces pollution, its overall efficacy is not substantially different from that of methods that do not face these obstacles.

The second-ranked Waste Exchange Platform (S3) effectively reduces landfill waste and encourages participation; however, it encounters technical and user control complexities. While it is cost-effective, it continues to experience challenges with long-term efficacy and necessitates additional personnel to guarantee transparent, secure, and smoothly functioning operations. PAYT system (S4) was the most effective, as it charged based on the volume of refuse disposed of, thereby reducing waste at the source. It promotes responsible disposal and reduces development costs; however, it encounters obstacles in public acceptability, particularly in enforcement and adaptation. Both strategies are highly effective and practicable in the real world. Nevertheless, the journey toward long-term success while simultaneously adhering to safety protocols presents a significant obstacle. Although both strategies possess viable potential, their success is contingent upon factors such as the economic climate, government efficacy, and social structure. Therefore, these strategies will dictate the effectiveness of the measures for these factors.

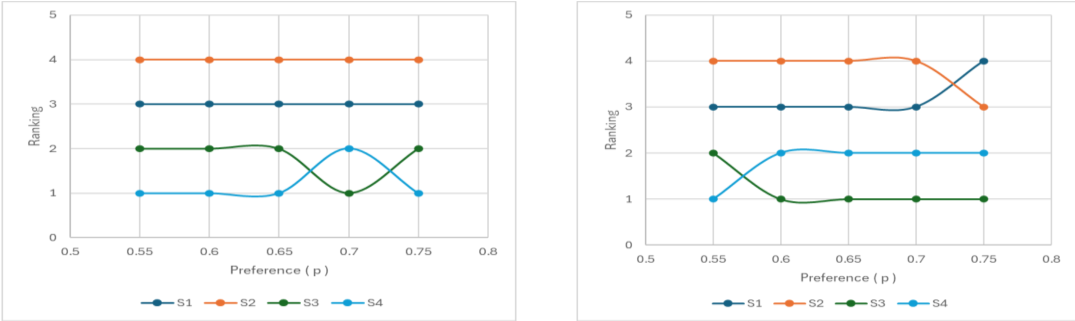
3.3 Design of Experiment (DOE)

The sensitivity analysis in this study utilized a factorial design method to systematically examine the influence of the preference thresholds (p and q) in the FPROMETHEE model on the ranking outcomes of the blockchain-enabled waste management strategies. The factorial design approach enables the simultaneous analysis of multiple parameter levels and their potential interactions, thereby guaranteeing a thorough comprehension of the impact of these threshold variations on the robustness of the decision framework.

The DOE identifies the most influential parameters affecting decision outcomes while providing insights into the stability of rankings under varying parameter settings. The sensitivity analysis of the prioritization process to changes in p and q ensures that the proposed decision-making framework remains both adaptable and reliable across diverse contexts. A total of 25 scenarios were generated to assess the impact of variations in the p (preference threshold) and q (indifference threshold) parameters on the ranking of strategies. The parameters were varied across five selected levels (0.55, 0.60, 0.65, 0.70, 0.75 for p) and (0.25, 0.30, 0.35, 0.40, 0.45 for q). Furthermore, this analysis is a critical foundation for evaluating the resilience of blockchain-enabled waste management strategies in Thailand, ensuring that stakeholders can confidently rely on the decision-making framework regardless of changing conditions or circumstances.

In accordance with the PROMETHEE literature and sensitivity analysis frameworks, the values for the preference threshold (p) and indifference threshold (q) parameters within the V-Shape with Indifference Preference function were determined in this study. The model's sensitivity to changes in these parameters was examined in a balanced and comprehensive manner by selecting a step size of 0.05. The chosen ranges—0.55 to 0.75 for p and 0.25 to 0.45 for q—are consistent with the thresholds that are frequently employed in similar multi-criteria decision-making studies [9]. These studies suggest that moderate and incremental adjustments be made to capture subtle and more significant preference-level changes while avoiding abrupt discontinuities in rankings [2].

Several intriguing patterns and issues regarding the sensitivity of rankings to changes in the parameters p and q are revealed by the VF data that has been provided. One noteworthy finding is that the combination of p and q significantly influences the classification of strategies (S1, S2, S3, S4). For example, strategy S2 initially occupies the second position but ascends to the first position when q = 0.40, and p increases from 0.65 to 0.70. This illustrates the substantial influence of p on preference transitions (Figure 2 (a)). Another significant observation is that the rankings for specific strategies, such as S3 and S4, become constant as the values of p increase from 0.55 to 0.75. This instability implies that the results are less sensitive to incremental changes in the data, as higher p values have no impact for changing preference threshold from 0.55 to 0.75. This sensitivity emphasizes the necessity of meticulous parameter calibration in practical applications of FPROMETHEE that employ the VF.



(a) (b)

Figure 2. VF and LF with Indifference Ranking with Difference Preference Threshold (fixed *q*=0.40) (a) Level Criterion Preference Function, (b) V-Shape with Indifference Preference Function

For LF (Figure 2 (b)), it illustrates how the LF reacts when q is fixed at 0.40 and p ranges from 0.55 to 0.75. At p = 0.55, S4 occupies the top rank, while S2 is at the bottom. S1 and S3 begin in the middle positions, but as p increases, S3 steadily advances and eventually overtakes S4 around p = 0.60. This behavior shows that higher preference thresholds tend to ignore smaller performance gaps, causing more abrupt ranking shifts among the strategies. In contrast, S1 experiences moderate changes, generally hovering around third or fourth place rather than showing drastic rises or falls. S2, which starts off in the lowest position, also makes notable progress as p grows, though it doesn't consistently surpass S3 or S4.

As p increases in the LF (e.g., p = 0.60 or p = 0.75), rankings begin to diverge from the VF due to the LF's tendency to disregard minor differences, leading to broader groupings or shifts in strategy positions. For instance, certain strategies may appear indifferent or swap positions at certain points, whereas the VF maintains more detailed rankings by continuously increasing preference. This distinction highlights that the VF simplifies rankings by applying a clear preference threshold, while the LV remains responsive to performance variations across all preference levels.

In this comparison (Figure 3), S3 and S4 compete closely across different p values, frequently switching rankings in both the VF and LF, indicating that slight adjustments to p can shift the balance between them. Meanwhile, S1 generally remains in third place, occasionally dropping to fourth when p reaches certain thresholds, while S2 typically holds fourth place but sometimes moves up to third as p increases. The radar layout further illustrates that the VF responds continuously to performance differences, whereas the LF can cause abrupt ranking shifts. These findings highlight that while S1 and S2 remain relatively stable, S3 and S4 are highly sensitive to changes in the preference threshold (p).

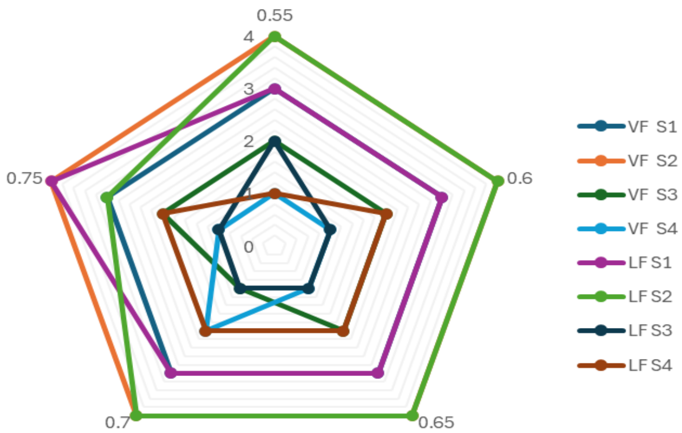


Figure 3. Preference Function Comparison at *q* = 0.40

4. CONCLUSION

This study has limitations, such as its emphasis on Thailand's waste management landscape, which may necessitate contextual adaptation for broader applications, despite its contributions. Blockchain adoption in waste management should be refined through the examination of stakeholder engagement strategies, cost-benefit analyses, and pilot implementations in future research. Furthermore, optimizing automation, real-time monitoring, and predictive analytics for waste reduction could further enhance the integration of blockchain, IoT, and AI. Waste management industries can convert extant inefficiencies into sustainable, transparent, and economically viable solutions that facilitate the transition to a circular economy by capitalizing on blockchain's capabilities. This study highlights the effectiveness of integrating FAHP and FPROMETHEE with factorial design sensitivity analysis to evaluate blockchain-enabled waste management strategies. By assessing four strategies across eight critical criteria, the framework underscores the potential of technologies like PAYT and WEP to enhance transparency, efficiency, and stakeholder collaboration. Our integrated approach goes beyond traditional cost-based models by incorporating expert-derived weights and parameter variability analysis to capture interdependencies and uncertainties in decision-making. This study not only emphasizes the evaluations of blockchain-enabled waste management strategies using FAHP and FPROMETHEE, but also illustrates the value of incorporating these methods with a factorial design sensitivity analysis. Our methodology is distinguished by its capacity to conduct a systematic assessment of the relative significance of numerous criteria and to investigate the impact of various parameter settings (p and q) on the ranking results. In contrast to a conceptual base case that may rely on a simple cost-benefit analysis or single-criterion evaluation, which frequently fails to capture the interdependencies and uncertainties that are inherent in waste management decision-making, our integrated approach offers a more comprehensive and robust evaluation. Implementing these strategies requires collaboration among stakeholders and careful integration with existing systems. Future work should compare blockchain-based and conventional methods, explore hybrid models, and assess scalability in diverse policy environments. Despite challenges, blockchain's potential for traceability, accountability, and data security makes it a promising tool for sustainable waste management in Thailand and beyond.

AUTHOR CONTRIBUTIONS

Aprirak Tepvarin: Conceptualization, Data Curation, Investigation, Methodology, Resources, Software, Visualization. Pongchanun Luangpaiboon: Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Investigation, Methodology, Project Administration, Supervision, Validation, Writing – Original Draft, Writing – Review and Editing. Atiwat Nanphang: Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Investigation, Methodology, Project Administration, Resources, Software, Validation, Visualization, Writing – Original Draft, Writing - Review and Editing. All authors discussed the results and contributed to the final manuscript.

FUNDING STATEMENT

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 Faculty of Engineering, Thammasat School of Engineering, Thammasat University, for funding this research.

CONFLICT OF INTEREST

The authors declare no conflicts of interest to report study.

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