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Evaluating Sustainable Plastic Bag Recycling Using Multi-Criteria Decision Making as a Real-Life Study in Thailand

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Abstract

Thailand generated 27.2 million tons of municipal solid waste in 2024, of which 12% was plastic waste, predominantly single-use plastics. The mismanagement of plastic waste can lead to significant long-term environmental issues, including the release of toxic chemicals through open burning and air pollution, posing risks to human health. Effective and efficient plastic waste collection and recycling are therefore essential to address the reduction and management of plastic waste, as well as to support a low-carbon energy transition. This study assessed three community-driven initiatives by conducting a comparative sustainability assessment of plastic bag recycling under real-life conditions in Thailand using a multi-criteria decision-making framework. The results of the assessment in three municipalities showed that the actual collection rates in all initiatives remained extremely low (0.0014–0.1555%). The highest rankings were observed with recycling initiatives driven by superior collection rates and favorable economic returns. The hindrances to promoting sustainability are found to be due to policy inconsistency, ineffective leadership, and behavioral barriers. The practical collection rates should increase to at least 25% to be more sustainable in terms of economic, social, and environmental aspects compared to those without the recycling initiative. These findings, thus, provide specific targets for improving plastic waste separation and management strategies in all regions facing similar challenges.

Keywords: analytic hierarchy process; greenhouse gas emissions; municipal solid waste; sustainability evaluation; waste management

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1. Introduction

Plastic is a synthetic or semi-synthetic material made from polymers. It is a versatile and durable material that is used in a variety of products and applications. Plastic is lightweight, strong and can be molded into various shapes and sizes. It is also corrosion-resistant and can be made transparent. Global plastic production now exceeds 400 million tons annually and is projected to double by 2050, driven by population growth, urbanization, and economic expansion [1]. Approximately two-thirds of plastic products are single-use items, such as bags, cups, straws, cutlery, and food packaging, with a lifespan of less than one month. Consequently, these products enter the waste stream within a short period of time.

Annual world plastic waste generation has reached 300 million tons, and its cumulative production since the 1950s has exceeded 6.30 billion tons [1,2]. An estimated 80% of this waste is expected to persist in landfills or the natural environment [1]. Plastics such as polyethylene, polypropylene, and polystyrene are highly resistant to natural degradation processes, including biodegradation, photodegradation, hydrolysis, and thermal oxidation, with degradation times often exceeding a decade [2–4]. Inefficient waste management has led to the widespread accumulation of plastic in the environment, contributing significantly to global plastic pollution [2]. Projections indicate that mismanaged plastic waste will exceed 200 million tons by 2060, posing an escalating threat to ecosystems, human health, and socio-economic stability [3].

Over time, plastic fragments persist in terrestrial and aquatic ecosystems, the atmosphere, and even within human bodies [2,3,5]. These particles pose risks to biodiversity and ecosystem functions; for instance, plastic pollution in soils disrupts earthworm activity and microbial communities, leading to reduced reproductive success and lower agricultural productivity [3]. Furthermore, plastics can act as vectors for pathogenic species, thereby amplifying ecological and health risks [4,6]. Beyond environmental impacts, plastic pollution imposes significant social and economic burdens. It contributes to losses in fisheries, tourism, cultural heritage, and recreational industries. For example, plastic debris has caused revenue losses of US$29–37 million in the Korean tourism sector and an estimated US$1.2 billion loss in fisheries across the Asia-Pacific region [6]. In addition, plastics exacerbate climate change by emitting greenhouse gases (GHGs) throughout their life cycle, particularly during production and end-of-life treatment. Notably, approximately 90% of plastic-related GHG emissions arise from the production phase [6]. These environmental, social, and economic consequences highlight the urgent need for effective actions by governments, academic institutions, communities, and industry to mitigate plastic waste and transition toward sustainable plastic management.

Both public (e.g., government agencies, municipalities, local communities, and authorities) and private sectors have implemented strategies to improve plastic waste management beyond conventional practices such as landfilling and incineration. Guided by the waste management hierarchy, the 3Rs (Reduce, Reuse, and Recycle) are the most widely adopted approaches for minimizing plastic waste [7]. Recycling involves collecting and processing plastic into raw materials to produce new products [5]. Numerous international initiatives based on the 3Rs have been launched. For example, "Plastic Free July" is a global campaign that encourages individuals to reduce single-use plastics during July each year [8]. The Global Tourism Plastics Initiative engages the tourism sector in reducing plastic consumption, enhancing plastic waste collection systems, and promoting the use of recycled plastic [9]. Similarly, the Ocean Foundation supports programs such as Blue Resilience, Ocean Science Equity, and Plastics Initiatives, which aim to reduce marine pollution, foster a sustainable blue economy, raise awareness of marine plastic pollution, and promote the redesign of plastic waste into new products [10]. While these initiatives improve awareness and reduce mismanaged plastic, they also highlight the need to evaluate their effectiveness through a long-term sustainability lens.

Sustainability was first defined by the United Nations in 1987 as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [11,12]. Sustainability assessment serves as a decision-support tool that evaluates both the positive and negative impacts across these three dimensions [13–21]. This approach has been applied to projects [22,23], products [24–26], policies [27,28], and waste management systems [20,21,29,30]. In the context of plastic waste management, sustainability can be achieved only when the economic, social, and environmental dimensions are addressed in an integrated manner. Plastic waste management options include landfilling, incineration (with or without energy recovery), recycling, open burning, and open dumping. According to OECD's Global Plastics Outlook 2022, almost 50% went to sanitary landfills, 22% was disposed of in uncontrolled dumpsites and burned in open pits, 19% was incinerated, and 9% of plastic waste is ultimately recycled [31]. Landfilling is the dominant method, handling most of the plastic waste due to its low cost and ease, as reported in Lithuania, Russia and Thailand [29,30,32]. Open burning and dumping are also common, particularly in rural or inadequately serviced areas, though these practices contribute significantly to air pollution and environmental degradation. Recycling is an effective approach for returning plastic waste to the industrial/commercial sector and supporting resource efficiency. Previous studies consistently highlight the advantages of recycling over disposal-based strategies [20,29,30,32–34]. However, few empirical studies quantify the minimum plastic recycling rates required to achieve greater sustainability under real operational conditions. For example, Menikpura et al. (2013) reported that a 24% recycling rate, including paper, plastic, glass, aluminium, and steel, in Nonthaburi province, Thailand, offset the adverse impacts of landfilling, while Samitthiwetcharong et al. (2024) demonstrated economic and environmental gains from increased plastic recycling in Rayong province [32,34]. Nevertheless, these studies do not specifically address plastic bag recycling. To support actionable policy, municipalities require evidence-based targets for minimum collection rates to design feasible and cost-effective plastic bag recycling programs. Overall, sustainability assessment provides valuable guidance for decision-making and facilitates the transition toward more sustainable waste management practices. Furthermore, comparative ranking methods are essential for evaluating and prioritizing alternative plastic waste management options effectively.

Comparing alternatives based on sustainability assessment, ranking methods are commonly employed, for example, decoupling index [30,35], summed rank [36], and multi-criteria decision analysis (MCDA) [37–39]. Among various ranking methodologies, the MCDA has been widely used to evaluate and select optimal alternatives based on multiple criteria [40,41]. A recent review by Ferla et al. (2024), which analyzed 42 articles published between 2010 and 2023, highlighted that the Analytic Hierarchy Process (AHP) is the most frequently used MCDA method [42]. This is mainly because AHP accommodates both qualitative and quantitative criteria, integrates expert opinions, and supports intuitive decision-making, offering advantages over other MCDA methods such as the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Viekriterijumsko Kompromisno Rangiranje (VIKOR), and Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) [42]. The application of AHP in sustainability assessment spans multiple fields, including food, agriculture, and waste management, typically employing an average of 52 indicators, with a median of 19 [37,42,43]. For instance, Le et al. (2023) applied AHP to evaluate municipal solid waste (MSW) treatment technologies in Ho Chi Minh City, Vietnam [37]. They found that waste-to-energy incineration was the most favorable option due to its low land use requirements, waste reduction potential, and energy-recovery benefits [37]. Nonetheless, a notable limitation of AHP lies in its reliance on expert judgment for pairwise comparisons, which may introduce uncertainty due to subjective human reasoning [42]. Moreover, different studies have applied diverse sets of indicators, such as fuel cost, capital cost, GHG emissions, employment, and social acceptance, leading to variability in assessment outcomes [37,44,45].

Nowadays, Thailand has produced a cumulative total of over 235 million tons of plastic products since 2016 [46]. The production of single-use plastic bags, such as polyethylene, polypropylene, and polystyrene, amounted to approximately 1.99 million tons during

2016–2022, with domestic consumption of 1.00 million tons, imports of 0.08 million tons, and exports of 1.07 million tons. The total market value was estimated at 181,364 million baht over this period. With high consumption, Thailand produces plastic waste of around 2–3 million tons per year (12% of total waste generation) since 2016 [47,48]. Only 0.5 million tons per year of them can be collected and circulated back to industries [47]. This is largely because many areas still lack effective plastic waste separation and collection systems at the household level, and only valuable plastics, such as polyethylene terephthalate (PET) bottles, are typically returned to the industrial sector through scrap dealers or junk shops [47]. The remainder of the plastic waste is managed through various methods such as landfilling, incineration, waste-to-energy conversion (refuse-derived fuel: RDF), illegal dumping, or open burning. This residual waste predominantly consists of single-use plastics, such as bags, films, and bubble wrap, which are lightweight and difficult to collect. They are typically classified as non-valuable plastic waste and are most often disposed of through landfilling and open burning/dumping, respectively [48]. Similar challenges are observed in Vietnam and other ASEAN countries, where plastic waste recycling rates remain low at 0.3–0.4 million tons per year [37,47].

Since 2018, the Pollution Control Department of Thailand has implemented the Action Plan on Plastic Waste Management, which provides a roadmap to reduce plastic waste, increase recycling, promote a circular economy, and ultimately achieve sustainable plastic use and disposal [49]. To support these goals, various campaigns have been introduced by local communities, municipalities, and private sector entities [50–56]. These initiatives have demonstrated a reduction in plastic use, improving plastic waste management, and conducting environmental assessments, particularly with respect to GHG emissions. For example, the private sector "PET to PPE" campaign collected 200,000 plastic bottles to produce 10,000 personal protective coats in 2021, resulting in an estimated reduction of 45 tons of CO_2 equivalent [56]. Despite these achievements, many initiatives, particularly at the municipal level, have been discontinued due to challenges in sustaining long-term implementation [57,58]. For instance, in 2023, Pak Phayun Subdistrict Municipality launched the "Hazardous Waste and Plastic Bottle Separation Project" to divert plastic bottles from MSW and sell them to local junk shops [57]. Similarly, community-based initiatives such as the "Safe Food Project: Free of Foam and Plastic Bags" by the subdistrict administrative organization Pabon and the "Plastic Waste Management for Community Health and Global Warming Reduction Project" by Marue Botok subdistrict municipality were initiated but often proved short-lived [58].

Based on the authors' interviews with municipalities and local leaders, it was observed that residents typically separate valuable plastic waste, while low-value plastics such as plastic bags are rarely collected and usually end up in landfills. Also, municipalities have implemented various plastic waste collection initiatives, such as plastic waste donation, door-to-door collection, exchange-for-points programs, plastic waste banks, and collection points, but most were short-lived with low collection rates. As a result, municipalities seek to better understand the actual conditions of plastic bag collection, specifically, whether recycling under real-life conditions can be considered sustainable, and what minimum separation targets communities must achieve. These gaps in knowledge led to the following research questions: (i) Which plastic bag recycling technique under real-life conditions is more sustainable across different types of collection initiatives, i.e., door-to-door collection, plastic waste bank, and plastic waste collection point? and (ii) What minimum collection rate is required for plastic bag recycling to achieve sustainability in terms of economic, social, and environmental considerations?

Accordingly, this study aims to evaluate and compare the sustainability of plastic bag waste (PBW) recycling in Thailand under real-life conditions across economic, social, and environmental dimensions, using the AHP, a widely applied method for ranking alternatives. PBW was selected as the focus due to its low value and prevalence in MSW streams. The study was conducted in three municipalities in Northern Thailand, each differing in population density and community characteristics, with a focus on PBW. Each municipality also had its own PBW management strategies. The study spanned approximately one year, during which data was collected. Five selected experts participated in the AHP analysis. In addition, this study seeks to identify the minimum PBW collection rates required to achieve sustainable waste management in these municipalities. The findings and recommendations are intended to inform and strengthen future municipal plastic waste management strategies.

2. Methods

This study developed a sustainability assessment framework that integrates economic, social, and environmental dimensions. The framework, illustrated in Figure 1, is based on the ISO 14040 life cycle assessment (LCA) standard and is aligned with previous studies [24,59,60]. It consists of four components: (i) goal and scope definition, (ii) inventory data, (iii) sustainability assessment, and (iv) interpretation. The goal and scope focused on PBW collection in three municipalities, with the system boundary defined at the waste management stage, including household collection, transportation, and final management under both initiative and non-initiative scenarios. Inventory data were collected using both qualitative and quantitative methods based on predefined sustainability indicators, and plastic bag mass flows were quantified for each municipality. A sustainability assessment was conducted using the AHP, in which experts scored sustainability performance. Finally, the results were interpreted, and recommendations were formulated. Feedback loops were incorporated at every step, allowing reconsideration and revision of information as needed.

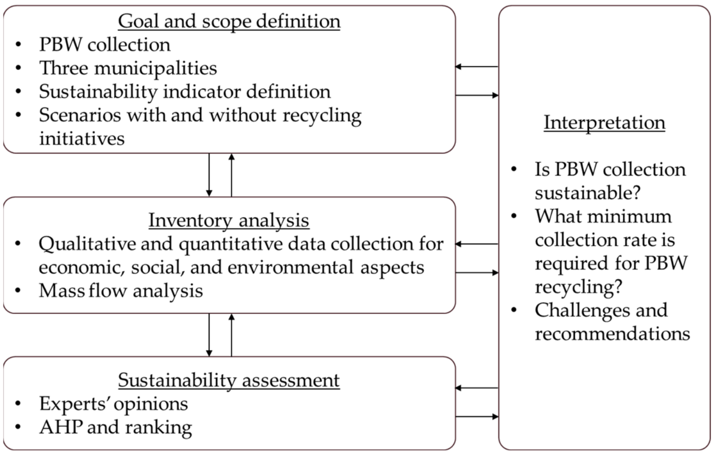

Figure 1. Sustainability assessment framework of this study.

2.1. Case Study Area

Three municipalities (Figure 2) were selected for this study to represent different community characteristics and PBW management initiatives. Also, their proximity to Naresuan University facilitated data collection. The first municipality (A) is in Phitsanulok Province, Thailand, and it represents a commercial area with a high population density of 1687.5 people per km^2. The second municipality (B), situated in Nakhon Sawan Province, reflects a tourist area. The main occupations of residents are agriculture and tourism-related activities, with a population density of 100 people per km^2. The third municipality (C) is in Phetchabun Province and is classified as a predominantly agricultural area. It has a population density of 109 people per km^2 and covers the largest area among the three, with more than 90% of its land dedicated to agriculture, including rice paddies, cornfields, sugarcane plantations, and vegetable farms. Detailed information on the three municipalities is summarized in Table 1. Even though municipality A has a much higher population density than municipalities B and C, comparing the three municipalities is meaningful because it allows the study to examine how variations in population density, land use, and community characteristics influence residents' PBW separation behaviors. Furthermore, each municipality implements PBW management initiatives tailored to its context, providing insights into the real-life sustainability of these approaches under different conditions.

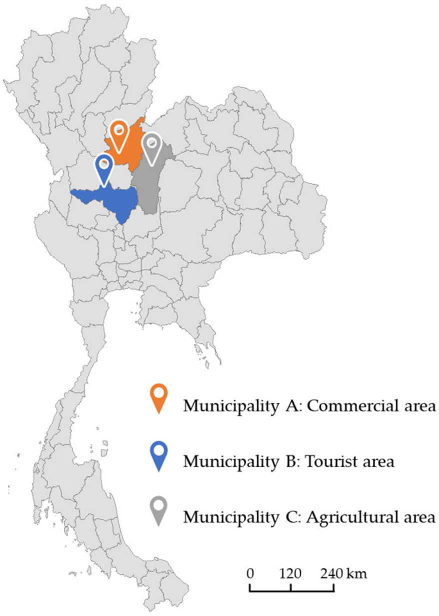

Figure 2. Selected municipality locations in Thailand.

Table 1. Municipality description.

Municipality	A	B	C
Location	Phitsanulok	Nakhon Sawan	Phetchabun
Municipality type	Subdistrict municipality	Subdistrict municipality	Subdistrict administrative organization
Characteristic	Commercial area	Tourist area	Agricultural area
Area (km^2)	8	70	110
Population density (people/km^2)	1687.5	100	109

2.2. Sustainability Indicator Definition

In the context of plastic waste management in Thailand, a comprehensive dataset of this study was developed to address the three dimensions of sustainability, i.e., economic, social, and environmental. Table 2 presents the overall indicators applied in the analysis. These indicators were derived from a literature review [36,37,44,45] and refined through discussions with municipalities, resulting in a final set of 22 indicators. The selected indicators were employed to assess the sustainability of both scenarios: with and without recycling initiatives. They were selected to capture not only the direct outcomes of plastic waste practices but also their broader implications for communities and the environment. The economic dimension comprised 13 indicators, which were categorized into three key issues: MSW collection, final-stage management, and economic benefits derived from waste trading. These indicators were deemed critical because waste collection and disposal represent the highest recurring costs for municipalities, while income from recyclable waste contributes directly to the financial feasibility of sustainable waste systems [36,37,45]. The social dimension included five indicators, focusing on community cooperation in plastic waste collection, employment from waste management activities, health and safety considerations, and the presence of supportive policies. These indicators reflect the recognition that waste management is a socially embedded process, requiring active community participation and institutional support [37]. Moreover, health and safety are essential considerations, as improper waste handling can impose long-term public health risks. The environmental dimension was represented by two core issues: MSW reduction and GHG mitigation. These were prioritized because Thai municipalities are increasingly concerned with reducing GHG emissions in alignment with national climate commitments and the global transition toward a low-carbon society [61]. In particular, reducing landfill dependency and promoting recycling not only conserves resources but also significantly reduces methane emissions, which have a high global warming potential.

Table 2. Indicators used for sustainability assessment.

Group	Issue	Indicator	Unit	Status
Economic	MSW collection	1. Fixed cost of garbage truck	Baht	Unfavorable
		2. Fuel cost	Baht/year	Unfavorable
		3. MSW collection	ton/month	Unfavorable
		4. PBW collection	ton/month	Unfavorable
		5. Valuable recycling waste collection	ton/month	Unfavorable
		6. Maintenance cost for garbage truck	Baht/year	Unfavorable
		7. Labor cost	Baht/month	Unfavorable
	Final management	8. Landfill fee	Baht/month	Unfavorable
		9. Transportation cost to plastic pellet and recycling companies	Baht/year	Unfavorable
		10. Recycling costs including tax	Million Baht/year	Unfavorable
	Revenue/benefit	11. Selling recycled waste	ton/month	Favorable
		12. Revenue from selling recycling products (179 Baht/piece)	Million Baht/year	Favorable
		13. Household collection fee	Baht/household/year	Favorable
Social	Community cooperation for PBW collection	14. PBW collection rate	%	Favorable
	Job creation for MSW collection	15. Employment opportunities for residents in the area	No. of people	Favorable
	Health and safety	16. Accidents during MSW collection	No. of accident	Unfavorable
		17. Health of MSW collection workers	-	Favorable
	Supportive policy	18. Local government policies to reduce waste to landfill	No. of project	Favorable
Environmental	MSW reduction	19. Waste reduction to landfill	ton/year	Favorable
	Global warming	20. GHG emissions from PBW transportation to plastic pellet and recycling companies	$kgCO_2eq$/year	Unfavorable
		21. GHG emissions from MSW collection transportation	$kgCO_2eq$/year	Unfavorable
		22. GHG emissions from landfill	$kgCO_2eq$/year	Unfavorable

Notably, all indicators were quantified, except for the health status of MSW collection workers under the social dimension, which was assessed qualitatively. The health status was determined through self-reported interviews, where workers rated their own health.

If a worker reported poor health, they were asked to indicate whether the condition was related to their MSW collection activities or due to other factors. This approach relied on workers' self-assessment rather than clinical or laboratory-based health monitoring. Each indicator was defined as a potential concern and classified according to its contribution to sustainability outcomes. A "favorable" status indicated a positive influence on the economic, social, or environmental dimensions, whereas an "unfavorable" status reflected adverse impacts. For instance, landfill emissions were categorized as an unfavorable indicator, as higher levels of GHG emissions impose greater environmental burdens compared to lower emission levels. This classification approach enabled a more systematic interpretation of indicator performance, ensuring that both the beneficial and detrimental aspects of MSW management were adequately captured.

2.3. Scenario Definition

Scenarios without and with recycling initiatives were evaluated in each municipality. Scenario 1 (designated as 1A, 1B, and 1C) served as the baseline, representing conditions without a PBW recycling initiative in municipalities A, B, and C, respectively. In this baseline scenario, none of the municipalities engaged in active collection of PBW, primarily because these materials are light and have limited economic value. MSW, including PBW, was collected directly from households by municipal authorities and subsequently transported to contracted landfills located near each municipality. During the collection process, however, some municipalities, specifically A and C, implemented informal separation of high-value recyclable materials such as PET bottles, glass bottles, and cardboard. These items were recovered by workers, who sold them to local junk shops as a supplementary source of income. This practice reflects the selective recovery of economically valuable recyclables, while plastic bags, due to their limited marketability, were excluded from the waste separation stream under baseline conditions.

Scenario 2 (designated as 2A, 2B, and 2C) reflected the actual operational conditions during the plastic bag recycling initiatives implemented between 2023 and 2024. In this scenario, PBW was actively collected through different community-based programs, tailored to the characteristics and contexts of each municipality. Municipality A adopted the initiative "From House to Plastic Bag Recycling", in which plastic bags were collected directly from households by municipal collection vehicles (door-to-door collection) on a biweekly schedule. Municipality B implemented a "Recyclable Waste Bank" program, encouraging residents to bring plastic bags to the municipal office, where they could exchange them for money or household products. Meanwhile, municipality C operated a "Plastic Bag Collection Hub", whereby residents deposited plastic bags at the homes of village headmen who acted as local collection agents. These diverse approaches reflected differences in community engagement, socio-economic conditions, and geographical scale among the three municipalities, as summarized in Table 1. In all municipalities, the mayors informed residents about these initiatives through public address systems, chief villager meetings, or village health volunteer meetings, with chief villagers and village health volunteers further communicating the information directly to residents. After collection, the plastic bags were transported to a plastic pellet manufacturer in Nakhon Pathom province, where they were sorted and processed into pellets. These pellets were subsequently supplied to a recycling company in the same area to produce bottle openers. The finished products were then returned to the respective municipalities for sale or use within local communities, thereby promoting a circular economy. The remaining MSW, excluding the plastic bags recovered under the initiatives, continued to be managed in the same manner as scenario 1 through direct collection and disposal at contracted landfills. Table 3 presents the summarized definitions of scenario 1 (without PBW recycling initiatives) and scenario 2 (with PBW recycling initiatives) across the three municipalities.

Table 3. Definitions of scenario 1 and scenario 2.

Scenario	Definition
Scenario 1A	Municipality A without PBW recycling initiative, representing the baseline scenario. All MSW was collected and transported to the landfill. During transportation, some valuable recyclables were separated and sold to local junk shops.
Scenario 1B	Municipality B without PBW recycling initiative, representing the baseline scenario. All MSW was collected and transported to the landfill, with no separation of valuable recyclables.
Scenario 1C	Municipality C without PBW recycling initiative, representing the baseline scenario. All MSW was collected and transported to the landfill. During transportation, some valuable recyclables were separated and sold to local junk shops.
Scenario 2A	Municipality A with PBW recycling initiative, "From House to Plastic Bag Recycling". In this scenario, the actual amount of PBW was separated from the MSW stream at the household level, while the remaining MSW followed the same collection and landfill disposal process as in scenario 1A.
Scenario 2B	Municipality B with PBW recycling initiative, "Recyclable Waste Bank". The actual amount of PBW was separated at the household level, while the remaining MSW followed the same landfill disposal process as in scenario 1B.
Scenario 2C	Municipality C with PBW recycling initiative, "Plastic Bag Collection Hub". The actual amount of PBW was separated at the household level, while the remaining MSW followed the same landfill disposal process as in scenario 1C.
Scenario 3A, 3B, and 3C	Municipalities A, B, and C with PBW recycling initiatives, assuming a 25% collection rate of the total PBW.
Scenario 4A, 4B, and 4C	Municipalities A, B, and C with PBW recycling initiatives, assuming a 50% collection rate of the total PBW.
Scenario 5A, 5B, and 5C	Municipalities A, B, and C with PBW recycling initiatives, assuming a 75% collection rate of the total PBW.
Scenario 6A, 6B, and 6C	Municipalities A, B, and C with PBW recycling initiatives, assuming a 100% collection rate of the total PBW.

2.4. Data Collection and Analysis

Data collection was divided into three components: (i) without a recycling initiative, (ii) with a recycling initiative, and (iii) plastic bag characteristics. All municipalities were examined over the period 2022–2024, corresponding to the post-COVID-19 phase in Thailand, during which the pandemic had subsided, and community activities gradually returned to normal. This timeframe was considered appropriate, as it allowed for the assessment of waste management practices under relatively stable social and economic conditions, minimizing distortions caused by pandemic-related disruptions.

Data for the scenario without a recycling initiative were collected during the fiscal year 2023 (October 2022–September 2023). MSW, including PBW, was comprehensively assessed through interviews, secondary data analysis, and direct measurement. Key stakeholders involved in MSW management, such as municipal officers, collection workers, village headmen, and residents, were interviewed to obtain insights into operational practices and community participation. Secondary data, including municipal MSW reports, waste management costs, and demographic statistics, were also gathered and cross-validated with interview responses to ensure data consistency. In addition, the valuable recycling waste collection indicator was directly measured during MSW collection activities. After recyclable materials were separated by workers, they were weighed using a portable digital scale (Caggioni brand, maximum capacity 50 kg, minimum 0.01 kg).

Data for the recycling initiative was collected throughout the implementation period, spanning eight months from October 2023 to May 2024. Like the baseline scenario, data collection employed a mixed approach that included interviews, secondary data analysis, and direct measurement. The amount of PBW (indicator 4) was measured directly using a portable digital scale and recorded for total summation. Transportation costs (indicator 9) and recycling costs (indicator 10) were obtained from actual payments made by this study. In addition to municipal stakeholders, the industrial sector, specifically plastic pellet manufacturers and recycling companies, was also included through interviews and on-site measurements, i.e., PBW amount, recycling product. This broader scope ensured that the entire recycling chain, from collection to industrial processing, was accurately represented in the dataset. The data collection methods aligned with the defined sustainability indicators (Table 2) and are summarized in Figure 3. To ensure accuracy, some direct measurements and interviews were cross-checked with secondary data, and while minor uncertainties remain in self-reported information, these are unlikely to significantly affect the results.

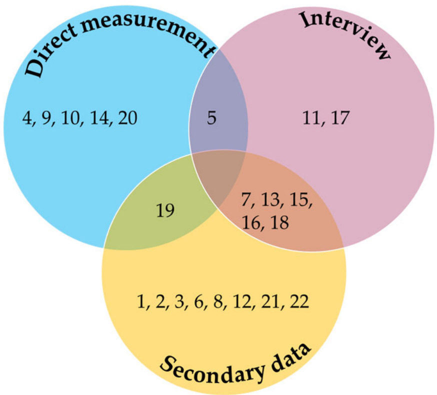

Figure 3. Summarize data collection methods based on sustainability indicators (Table 2).

Plastic bags collected under the initiative scenario were measured and characterized using the quartering method. In this procedure, three to four large bags of plastic waste were pooled together and evenly divided into four sections on a horizontal flat surface [62]. Opposite sections were then selected for analysis and sorted according to physical characteristics such as shape, thickness, and flammability. In Thailand, polyethylene (PE) and polypropylene (PP) constitute the predominant types of plastic bags and packaging materials, regardless of color or size. Their identification was confirmed using a burning test, as suggested by Treenate et al. (2018) [63]. During combustion, PE is indicated by the presence of dripping residue, whereas PP is characterized by a slower burning rate [63]. After identification, each category of plastic waste was weighed using the portable digital scale. The weight of each category was then compared with the total weight of the pooled sample to determine the proportional composition of plastic bag types.

For both the with and without initiative scenarios, the flow of plastic bags in all municipalities was analyzed using the STAN software version 2.7.101, which applies material flow analysis (MFA) principles to quantify and visualize waste streams from households to either landfills or recycling facilities [64]. This approach enabled a systematic assessment of plastic bag movement across different management stages, thereby providing a transparent and standardized basis for comparison between scenarios.

Following data collection, several indicators required further calculation. To address this, a set of assumptions was established, as outlined below:

- The revenue from selling recycling products indicator was estimated based on the quantity of plastic bags collected, which directly influenced the production volume of recycled products. In this study, the recycled product of focus was a bottle opener, priced at 179 Baht per piece, reflecting the market value of environmentally friendly products [65];
- The PBW collection rate indicator was evaluated by comparing the proportion of collected PBW with the average percentage of PBW typically found in landfills in Northern Thailand, as all three municipalities in this study are in this region. According to the report of the Center of Excellence on Hazardous Substances Management [66], PBW accounted for approximately 6.98% of the total MSW composition in this region. Therefore, in this study, 6.98% was assumed to represent the theoretical maximum (100% target) for PBW collection;
- For the GHG emission indicators (indicators 20, 21, and 22), emissions from three sources were assessed: transportation of PBW to plastic pellet and recycling companies, MSW transportation, and landfill disposal. The lifetime phase of the recycling product was excluded from the system boundary. Emissions were quantified in functional unit terms of kilograms of carbon dioxide equivalent per year (kgCO_2eq/year). The calculations followed the LCA framework as defined by ISO 14040 [59]. GHG emissions were estimated using Equation (1).

$$\text{GHG emissions} = \text{Activity data} \times \text{Emission factor} \tag{1}$$

where GHG emissions are expressed in kgCO_2eq/year, activity data represents the amount of MSW (kg/year) or fuel oil consumed (L/year), and the emission factor (EF) corresponds to GHG emissions per unit of activity (kgCO_2eq/kg or kgCO_2eq/L). The EF values were obtained from the Thailand Greenhouse Gas Management Organization (Public Organization) [67]. Consequently, emissions from PBW transportation to plastic pellet and recycling companies were compared across municipalities, alongside emissions from MSW transportation and landfilling.

2.5. AHP Method for Comparative Sustainability Assessment

This study applied the AHP as outlined by Saaty (2004) to compare and rank the sustainability of PBW management scenarios [68]. The goal of the comparison was identifying the preferable option between scenarios with and without recycling initiatives for each municipality to achieve sustainability. The procedure followed six main steps: (i) constructing a pairwise comparison matrix, (ii) calculating the consistency index, (iii) determining the consistency ratio, (iv) identifying the best choice for each indicator based on collected data, (v) aggregating scores using indicator weights, and (vi) generating the final ranking.

All indicators were included in the pairwise comparison matrix, which was developed and evaluated through group discussions with five experts specializing in MSW management. The experts were selected based on their extensive experience and expertise across academia, consulting, manufacturing, and municipal sectors, with each having at least 10 years of professional experience in plastic waste management. The scoring followed Saaty's fundamental 1–9 scale, where a score of 1 denotes equal importance between indicators and a score of 9 indicates that one indicator is considered extremely more important than the other [68]. To ensure the validity of the comparisons, consistency was tested using the consistency index (CI) and consistency ratio (CR), as defined in Equations (2) and (3).

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

$$CR = \frac{CI}{RCI} \tag{3}$$

where λ_{max} is the maximum eigenvalue, n is the order of the matrix (22 in this analysis, corresponding to the total number of indicators), and RCI is the random consistency index, which is 1.64 for n = 22 [69]. A CR below 0.1 (10%) was considered acceptable; values exceeding this threshold required re-evaluation of the pairwise judgments to maintain reliability.

For step (iv), the best choice for each indicator was determined according to indicator status. If the status was unfavorable, the lowest value was selected as the best choice, and the ratio was calculated by dividing the best choice by the observed data. Conversely, for positive indicators, the highest value represented the best choice, and ratios were calculated by dividing each observed value by the best choice.

In step (v), aggregated scores were obtained by multiplying the pairwise comparison weights (step i) with the best choice ratios (step iv). Finally, the aggregated results were ranked and interpreted (step vi) to identify differences across scenarios and generate insights into the sustainability performance of plastic bag management alternatives. A higher score indicated that the scenario was closer to achieving sustainability.

2.6. Sensitivity Analysis

A sensitivity analysis was conducted by introducing four additional recycling scenarios (scenarios 3, 4, 5, and 6), representing 25%, 50%, 75%, and 100% recovery of the total PBW stream, as shown in Table 3. The reference value of 6.98% PBW composition in MSW, reported for Northern Thailand [66], was used as the baseline for defining these proportions. For example, 25% recovery corresponds to collecting 25% of the PBW fraction (scenario 3), or about 1.75% of the total MSW, while 100% recovery (scenario 6) represents the complete collection of PBW, equivalent to 6.98% of total MSW. These scenarios enabled comparison across different levels of plastic bag collection efficiency and provided insights into the potential sustainability outcomes of increased recycling rates. Furthermore, they represent plausible municipal targets for future plastic waste management, offering a strategic framework for setting progressive collection goals.

3. Results and Discussion

3.1. PBW and Flow Analysis

Without recycling initiatives, the cost data for municipalities A, B, and C are summarized in Table 4. Municipality A recorded the highest costs, primarily due to its commercial characteristics and high population density, which also resulted in the largest MSW generation among the three municipalities. The average monthly MSW collection volumes were 292.06, 34.50, and 90.83 tons for municipalities A, B, and C, respectively (Figure 4). PBW was not separated during this process and was included in the MSW stream transported directly to landfills. Among the three municipalities, municipality A generated the highest volume of MSW, followed by municipality C and municipality B. These differences were consistent with population density, as higher density areas typically produce greater waste volumes. However, the trend was not linear across all cases because of differences in land use, local economic activities, and community lifestyles. Municipality B, a tourism area, experiences seasonal fluctuations and service-sector activities that contribute to slightly lower waste generation than municipality C, which is predominantly agricultural. Based on these observations, population density alone does not strongly correlate with MSW generation. Due to the limited sample of three municipalities, formal statistical correlation could not be reliably assessed; however, the results suggest that other factors, such as land use and economic activity, play a significant role in influencing waste generation patterns.

Table 4. Cost data for municipalities A, B, and C under the baseline scenario (without PBW recycling initiatives).

Indicator	Unit	Municipality A	Municipality B	Municipality C
Fixed cost of garbage truck	Baht	8,775,000	2,381,500	4,800,000
Fuel cost	Baht/year	874,800	144,000	144,000
Maintenance cost for garbage truck	Baht/year	166,996	58,500	10,000
Labor cost	Baht/month	180,000	40,000	60,000
Landfill fee	Baht/month	141,648	13,800	54,498
Household collection fee	Baht/household/year	360	360	240

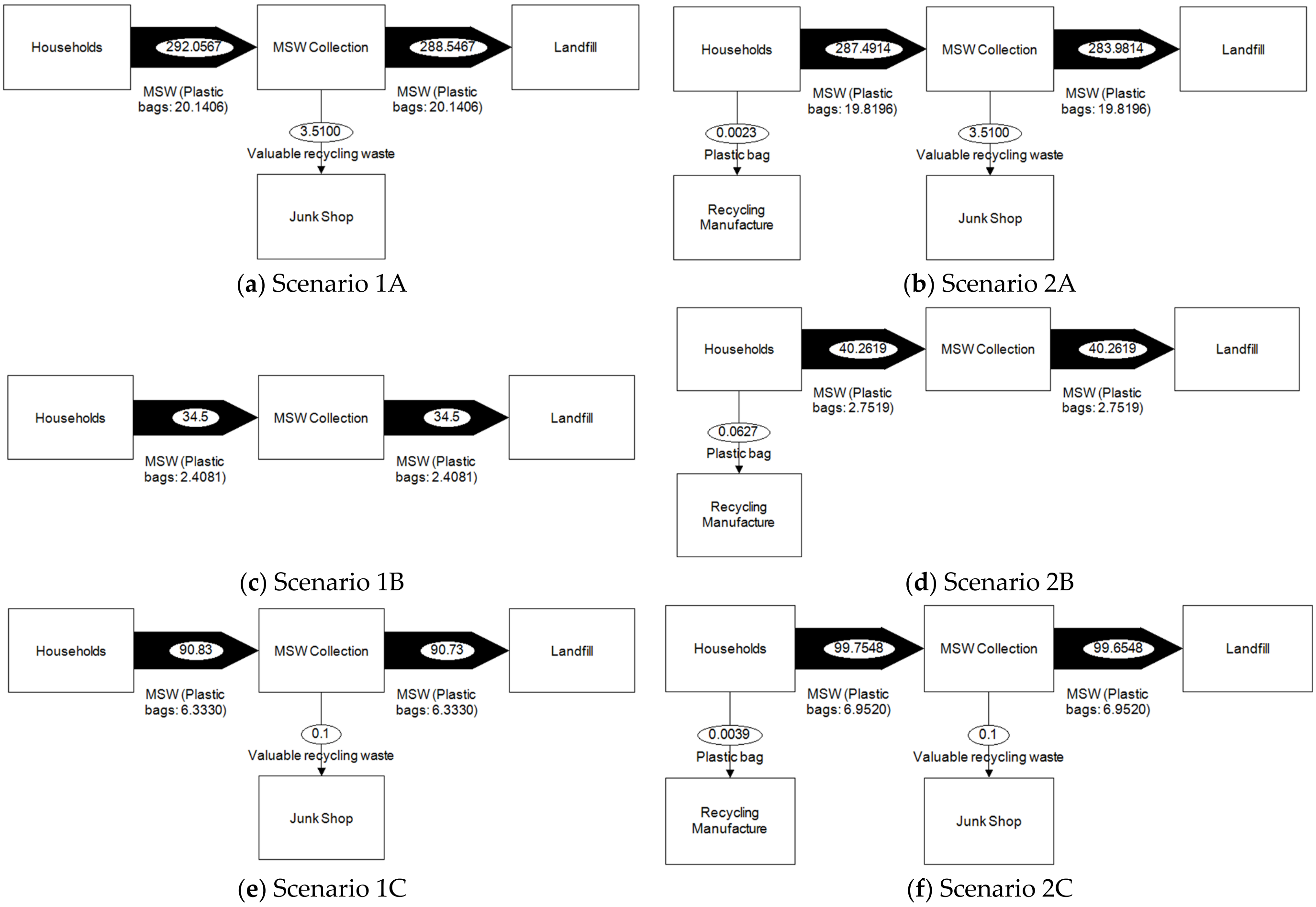

Figure 4. Mass flow of MSW and plastic bags (tons/month) under scenarios without and with recycling initiatives.

During the collection process, some valuable recyclables were collected in the municipalities. In municipality A, approximately 3.51 tons/month of recyclables were separated, while municipality C separated only 0.10 tons/month. No separation process was observed in municipality B. This highlights variation in informal recycling practices among municipalities, influenced by both community engagement and local operational systems.

With recycling initiatives in place, the average monthly MSW collection volumes were 287.49, 40.26, and 99.75 tons for municipalities A, B, and C, respectively. Compared with the baseline scenario, MSW generation in municipalities B and C increased, reflecting the national trend of rising MSW generation after the COVID-19 pandemic, which grew from 1.03 kg/capita/day in 2021 to 1.15 kg/capita/day in 2024 [70]. In contrast, the total MSW generation in municipality A decreased primarily due to the implementation of an organic waste collection program rather than as a result of PBW collection. For plastic bag recovery, households were required to collect plastic bags themselves under the respective initiatives. Municipality A collected only 2.30 kg/month of plastic bags through the "From House to Plastic Bag Recycling" initiative, representing the lowest recovery among the three municipalities despite its commercial setting. Municipality B achieved the highest recovery at 62.7 kg/month through its "Recyclable Waste Bank" program, while Municipality C collected 3.90 kg/month under the "Plastic Bag Collection Hub". These findings suggest that economic incentives provide stronger behavioral motivation for participation than voluntary or policy-driven measures. The "Recyclable Waste Bank" in Municipality B enabled residents to exchange plastic bags for cash or goods, creating direct and tangible benefits that encouraged higher participation. This aligns with previous studies showing that waste management participation is significantly influenced by personal norms and behavioral intentions [71], and that initiatives with economic incentives tend to be more effective than those relying solely on policy enforcement or social responsibility appeals [71–73]. Moreover, strong leadership and supportive policies, as observed in municipality B, could have played a key role in enhancing PBW collection efficiency. This included not only the leadership of the mayor but also the active involvement of chief villagers. Normalina et al. (2021) have also reported that leadership qualities of the mayor have a significant impact on the sustainability of plastic waste management by promoting residents' awareness and encouraging positive waste-separation behaviors [74].

The composition of collected plastic bags is illustrated in Figure 5. On average, the dominant waste fraction was opaque PE handle bags (72.87%), which are widely used in grocery stores, markets, and restaurants. Categorization by bag type shows that handle bags accounted for 86.69% of the total plastic waste, followed by non-handle bags (11.69%) and plastic films (1.62%). In terms of polymer composition, PE represented 86.18% of the total, while PP accounted for 13.82%. Similar findings have been reported in previous studies, where PE was also found to be the predominant plastic type compared to PP [75,76]. The collected plastic waste was subsequently transferred to a plastic pellet manufacturer. Following cleaning and separation, PE was processed into pellets due to its high share in the waste stream. These PE pellets were then utilized as raw material for bottle opener production, thereby contributing to the circular economy by repurposing plastic materials into new products.

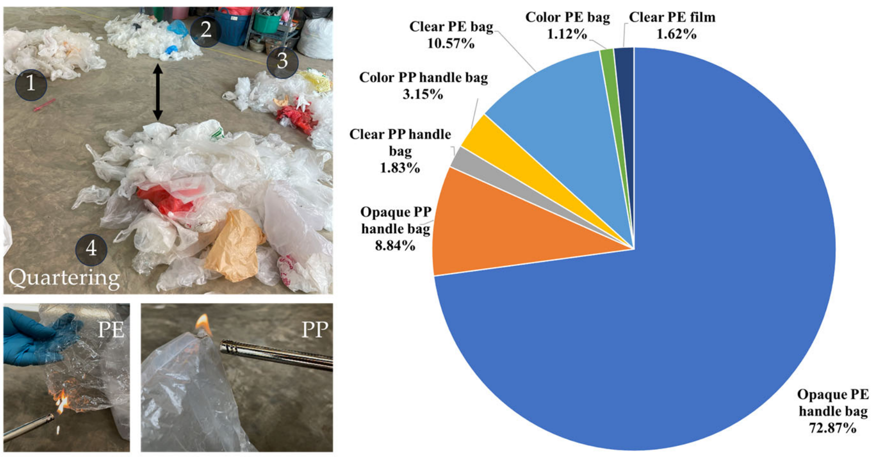

Figure 5. PBW quartering and composition.

To produce a single bottle opener, approximately 24 plastic bags, equivalent to 46.82 g, were required, comprising 40.35 g of PE and 6.47 g of PP, based on the actual PBW collected in this study. After classification, the plastic waste was processed into PE pellets at the plastic pellet manufacturer, as PE constitutes the major fraction of PBW. During separation and pelletizing, the PE mass was lost by approximately 3–4%. Consequently, 38.85 g of PE pellets were obtained and combined with an aluminum edge weighing 13 g, resulting in a total product weight of 51 g per piece. The relatively low weight of the opener is attributed to the internal free space within its structure. Production was carried out in batches of at least 100 units, with the total recycling cost estimated at 150 Baht per opener (equivalent to approximately 4–5 USD). The overall process flow for producing one PE-based bottle opener is illustrated in Figure 6.

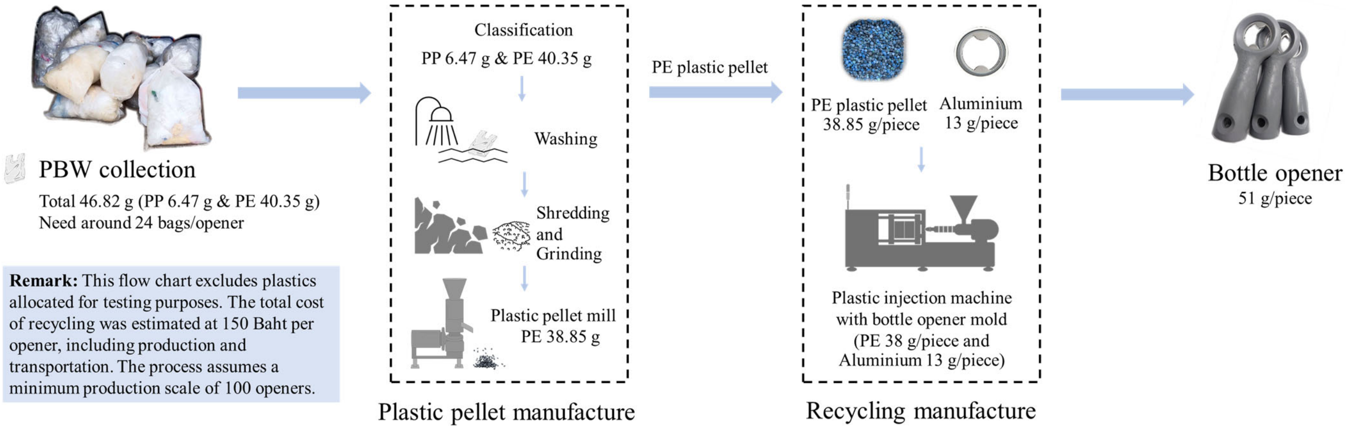

Figure 6. Flow chart of the production process for a single recycled bottle opener, including PBW collection, sorting, pelletizing, and final assembly.

3.2. GHG Emissions

GHG emissions in scenario 1 were derived solely from MSW transportation and landfill disposal, amounting to 12,389–87,450 kgCO_2eq/year and 328,426–2,780,263 kgCO_2eq/year, respectively. Landfills were the dominant emission source, contributing 96.36–98.34% of total emissions. The magnitude of MSW generated directly influenced the emissions, with municipality A exhibiting the highest values. In scenario 2, emissions were expanded to include MSW transportation, landfill disposal, and PBW transportation to plastic pellet and recycling companies. Landfills continued to account for the most emissions (96.76–98.48%), followed by MSW transportation (1.51–3.13%) and plastic bag transportation (less than 1%). The contribution from plastic bag transport was minimal due to the low quantities collected, particularly in municipalities A and C, where only one shipment per year was required. In contrast, municipality B required four shipments annually, making scenario 2B the highest emitter among the recycling scenarios. Overall, the comparison across municipalities revealed that total GHG emissions were generally higher in the recycling scenarios than in the non-recycling scenarios, except in municipality A. This exception occurred because MSW collection in scenario 2A was lower than in scenario 1A due to an organic waste initiative, leading to reduced landfill emissions. Conversely, in municipalities B and C, the increased MSW collection volumes and the distance to recycling manufacturers elevated emissions in scenario 2. Table 5 summarizes the GHG emission results across all scenarios.

Table 5. GHG emissions from scenario 1 (without recycling initiatives) and scenario 2 (with recycling initiatives).

Indicator	Scenario 1			Scenario 2		
	1A	1B	1C	2A	2B	2C
20. GHG emissions from plastic bag waste transportation to plastic pellet and recycling companies ($kgCO_2eq$/year)	-	-	-	126.57	436.66	127.03
21. GHG emissions from MSW collection transportation ($kgCO_2eq$/year)	87,449.70	12,388.71	14,574.95	87,449.70	12,388.71	14,574.95
22. GHG emissions from landfill ($kgCO_2eq$/year)	2,780,262.96	328,426.20	864,665.27	2,736,803.13	383,277.18	949,625.79
Total ($kgCO_2eq$/year)	2,867,712.66	340,814.91	879,240.22	2,824,379.41	396,102.55	964,327.78
GHG reduction (%)				−4.47	−3.19	−1.65

For assessing GHG reduction, a direct comparison between scenarios 1 and 2 was not feasible because of the differences in MSW collection rates. Instead, scenario 2 was further analyzed by comparing conditions with and without plastic bag separation. The results showed that GHG reductions were −4.47%, −3.19%, and −1.65% for municipalities A, B, and C, respectively. The negative values indicate an increase rather than a reduction in emissions. This outcome suggests that, under the actual conditions of plastic bag collection, the recycling initiatives did not achieve environmental benefits in terms of GHG reduction.

3.3. Comparative Sustainability Assessment by AHP

Based on expert evaluations (step i of the AHP procedure), all indicators were compared using pairwise comparisons. To assess the consistency of these judgments (steps ii and iii), the CI and CR were calculated for the economic, social, and environmental dimensions, as well as for overall sustainability. The results are summarized in Table 6, which includes λ_{max}, CI, n, RCI, and CR. For all three sustainability pillars and for overall sustainability, the pairwise comparison matrices exhibited acceptable consistency, as evidenced by CR values below the recommended threshold of 0.1.

Table 6. AHP consistency analysis.

Group	λ_{max}	CI	n	RCI *	CR	Status
Economic	14.51	0.13	13	1.56	0.080	Acceptable
Social	5.44	0.11	5	1.13	0.096	Acceptable
Environmental	4.12	0.04	4	0.89	0.045	Acceptable
Total	25.28	0.16	22	1.64	0.095	Acceptable

* obtained from [69].

The analysis of the economic assessment values revealed that scenario 1A achieved the highest economic score (0.518), followed by 2A (0.440), as illustrated in Figure 7. This result indicates that municipality A, without the recycling initiative, performed best in terms of cost-related indicators. The high score is attributable to its relatively stable and efficient MSW collection system, which resulted in lower fixed costs per ton of waste compared with other municipalities. In contrast, scenarios 1C and 2C had the lowest scores (0.386 and 0.309), reflecting the higher unit costs of waste collection in agricultural areas due to lower population density and smaller waste volumes. The recycling initiatives under scenario 2 further reduced economic performance because of additional transportation requirements and processing expenses for plastic bag recycling. In municipality A, less than one ton of PBW was collected, resulting in a one-time PBW transportation cost of 3500 Baht, which was significantly higher than the landfill cost of 485 Baht per ton of

MSW. Therefore, municipality A, without the recycling initiative, demonstrated the highest economic efficiency. These findings suggest that, under real-life conditions where plastic bag collection accounted for less than 0.5% of the total MSW, the recycling initiatives were not economically viable.

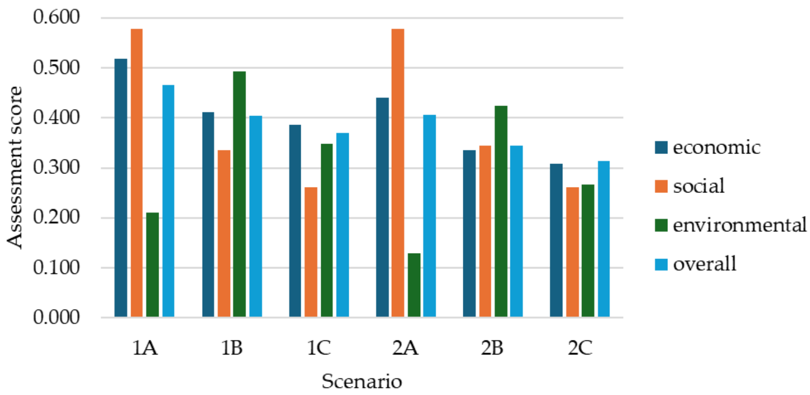

Figure 7. Sustainability assessment scores of scenarios 1 and 2 across the three municipalities.

For the social aspect, both scenarios 1A and 2A achieved the highest social scores (0.577). This outcome suggests that, although residents in municipality A were less directly engaged in plastic bag collection practices, the large volume of MSW required the involvement of around 20 workers in waste management, thereby creating employment opportunities. In addition, municipality A had complementary initiatives, such as organic waste collection, that strengthened social participation. By contrast, municipalities B and C recorded lower social scores (as low as 0.261 in scenarios 1C and 2C), reflecting weaker community engagement and limited public motivation to participate in recycling activities. An exception was observed in municipality B, where the "Recyclable Waste Bank" initiative encouraged participation through financial incentives, leading to relatively better performance compared with municipality C.

The environmental results showed that scenario 1B (0.494) ranked highest in the environmental dimension, followed by scenario 2B (0.423). This is because municipality B collected a higher volume of recyclable plastic bags, thus avoiding more waste in the landfill. On the other hand, municipality A scored the lowest in both scenarios (0.210 in 1A and 0.129 in 2A) because of its higher MSW generation rates, leading to more landfill disposal and higher GHG emissions. Although initiatives reduced organic waste, plastic bag collection volumes were insufficient to yield a significant environmental benefit.

The overall scores suggest that scenario 1A (0.466) was the most sustainable option (Figure 7), followed by 1B (0.405) and 2A (0.405). This is due to a balance of strong economic efficiency and high social participation in municipality A without recycling, as well as environmental benefits in municipality B. However, scenarios 2B and 2C had noticeably lower overall scores (0.344 and 0.314), because recycling initiatives introduced additional costs and GHG emissions from transportation while not collecting sufficient volumes of plastic bags to offset the environmental burden. These results suggest that the economic and social pillars exerted greater influence on overall sustainability than environmental indicators. Similar observations have been reported by Hopewell et al. (2009), who highlighted that the major challenges in plastic recycling are economic feasibility and social behavior related to collection and participation [77]. Although recycling initiatives are conceptually favorable, they did not enhance sustainability performance under real-life conditions, primarily due to limited plastic bag collection, long transportation distances, and higher costs.

3.4. Sensitivity Analysis Outcomes and Interpretation

The additional recycling scenarios (3, 4, 5, and 6) were developed to evaluate plastic bag recovery rates of 25%, 50%, 75%, and 100% of the total PBW stream. As shown in Table 7, scenario 6A emerged as the most sustainable option. Scenarios with higher recovery rates, particularly 6A, 5A, and 4A, consistently ranked highest across economic, social, and environmental pillars, reflecting the advantages of economies of scale, greater recovery efficiency, and substantial GHG reductions from avoided landfilling. Socially, municipality A benefited from increased employment opportunities for residents involved in collection and sorting, which served as a key contributor to its overall sustainability score. In contrast, scenarios 2C, 3C, and 1C ranked lowest, highlighting that recycling initiatives in agricultural areas without sufficient scale or efficiency are unlikely to deliver sustainability benefits. The overall sustainability scores of municipalities B and C were mainly driven by environmental factors, particularly GHG emission reductions and enhanced environmental awareness. Within each municipality, scenario 6 consistently represented the most favorable outcome, indicating that full recovery (100%) of plastic bags offers the strongest pathway toward sustainable waste management. This finding is consistent with previous studies, which emphasize that recycling, particularly at high collection rates, is more sustainable than landfilling or incineration [3,33,34,77–79]. For example, Samitthiwetcharong et al. (2024) demonstrated that plastic waste separation and recycling in Rayong Province, Thailand, increased economic benefits by approximately fourfold and reduced GHG emissions by threefold compared to business-as-usual conditions [34]. Therefore, achieving 100% recovery is key to sustainable plastic waste management. However, if sufficient volumes cannot be collected, the system is unlikely to be sustainable, as demonstrated in this study. In such cases, maintaining the current management practices could be more practical than implementing recycling initiatives that are ineffective or economically unviable.

Table 7. Sustainability assessment ranking across all scenarios.

Group	Scenario 1			Scenario 2			Scenario 3			Scenario 4			Scenario 5			Scenario 6		
	1A	**1B**	**1C**	**2A**	**2B**	**2C**	**3A**	**3B**	**3C**	**4A**	**4B**	**4C**	**5A**	**5B**	**5C**	**6A**	**6B**	**6C**
Economic	4	7	9	6	13	17	5	16	18	3	14	15	2	12	10	1	11	8
Social	9	16	18	8	15	17	5	13	14	3	11	12	2	7	10	1	4	6
Environmental	17	8	13	18	11	15	16	7	12	14	4	9	10	2	5	6	1	3
Total	6	11	14	10	16	18	5	15	17	3	12	13	2	9	8	1	7	4

Note: Shaded cells represent the highest and lowest rankings.

The results further indicated the threshold levels of plastic bag collection required to achieve sustainability compared with the baseline (scenario 1). For municipality A, a minimum collection rate of 25% was sufficient to outperform scenario 1A. In municipality B, however, at least 75% recovery was necessary to yield sustainability benefits, while municipality C required a minimum of 50%. These findings suggest that municipalities should target practical collection rates of 25–75% of total PBW to move toward sustainable waste management and support the transition to low-carbon communities. Importantly, municipal characteristics also play a decisive role. Commercial areas demonstrated greater sustainability potential than tourist or agricultural areas, primarily due to higher MSW volumes, which enhance the benefits of landfill diversion and improve the feasibility of plastic bag recovery.

International experiences provide further insights. In Germany, plastic packaging separation and collection rates reached 99.2% of the total packaging waste stream [1,80]. In India, collection and recycling in industrial areas achieved recovery rates of 47%, with a daily capacity of approximately 1000 tons [1,81]. In Denmark, household plastic recycling reached 63%, reducing GHG emissions by about 13,000 tons CO_2eq/year [34,82]. Many of these countries continue to set higher collection and recycling targets as part of long-term sustainability strategies. For example, the European Union aims to reuse and recycle 100% of plastics by 2030, while South Korea has targeted a 50% reduction in plastic waste and 70% recycling by 2039 [34]. In Thailand, the Roadmap on Plastic Waste Management (2018–2030) has set ambitious targets to phase out foam food containers, single-use plastic cups, lightweight plastic bags (<36 microns), and plastic straws, with the ultimate goal of integrating them into a circular economy [47,49]. However, the current progress remains far from these expected goals, emphasizing the urgent need for more effective plastic waste collection systems.

3.5. Key Challenges for PBW Collection

The results of this study, supported by interviews, secondary data, and direct measurements, indicated that the challenges of PBW collection under real-life conditions can be grouped into two main categories: internal municipal management and external municipal management.

3.5.1. Internal Municipal Management

- People behavior

Although residents in all three municipalities expressed awareness of PBW pollution, their actions often contradicted this awareness. In Thailand, plastic products are widely consumed in daily life, and plastic bags, the main target of this study, are inexpensive, ubiquitous, lightweight, and perceived as low-value waste. Consequently, many residents demonstrated little motivation to collect or separate them for recycling. This result is consistent with Wichai-Utcha and Chavalparit (2019), who highlighted weak public engagement as a critical limitation [7]. Similarly, SEI (2021) reported that awareness of plastic waste issues does not necessarily translate into behavioral change. Several factors contribute to this gap, including (i) perceived practicality and convenience in daily consumption, (ii) lack of opportunities to adopt alternatives, (iii) entrenched habits, and (iv) the tendency to shift responsibility to others [83].

- Leadership

Weak leadership also emerged as a key challenge for PBW collection. Leaders include not only municipal authorities but also village headmen. Even when municipalities had strong municipal leadership, weak engagement by village headmen often resulted in low PBW collection. Observations from village headmen meetings in this study revealed that a few participants (approximately 2–3 out of 20 per meeting) expressed reluctance to participate, perceiving the impacts of plastic waste as distant from their daily lives and seeing little personal benefit in changing their behavior. Therefore, strong leadership at both municipal and village levels is crucial for effectively communicating the importance of PBW collection and fostering behavioral change among residents.

- Initiatives and policy

Municipal initiatives were found to encourage public participation, particularly those offering incentives. However, none of the initiatives achieved significant PBW collection volumes, primarily because municipalities lacked formal, targeted policies for PBW and other plastic waste. National-level policies and regulations would therefore be useful in enabling municipalities to establish corresponding local policies and strengthen collection practices.

- Geographic and economic constraints

One of the most significant barriers was the low proportion of PBW in total MSW, which reduced the economic attractiveness of collecting and transporting these materials. Even when PBW was collected, the financial return from selling recyclables was insufficient to cover logistical costs, especially in municipalities located far from recycling facilities. Irregular collection practices further reduced efficiency and discouraged participation. These findings are in line with Hopewell et al. (2009), who noted that lightweight and mixed plastics are difficult to separate and recycle effectively, and Chapman et al. (2024), who emphasized transportation challenges [77,78].

3.5.2. External Municipal Management

- Inter-municipal collaboration

Weak collaboration between municipalities created unintended consequences. For example, in some areas, residents were unwilling to separate and collect PBW; consequently, they disposed of their waste in neighboring municipalities, which undermined participation and reduced the overall effectiveness of the system. Stronger collaboration, with neighboring municipalities adopting consistent policies and actions, could help influence and improve public behavior toward PBW collection.

- Governance consistency

Although Thailand has a national roadmap for plastic waste management, its implementation at the municipal level has been inconsistent. MSW consists of many fractions, and government priorities often shift from year to year, for instance, focusing on organic waste management one year and on plastic waste the next. This lack of continuity undermines long-term planning and discourages consistent public participation.

In summary, these challenges highlight the structural, behavioral, and policy barriers that hinder effective PBW collection, reinforcing the need for systematic sustainability evaluation and targeted interventions to strengthen MSW management.

3.6. Recommendations

To overcome the challenges of PBW collection under real-life conditions, several actions are recommended. First, public engagement should be strengthened through continuous awareness campaigns, combined with incentive-based initiatives that encourage households to separate even low-value plastics such as PBW. Second, leadership capacity at both municipal and village levels must be enhanced, as strong and consistent leadership is critical for mobilizing communities and sustaining initiatives. Third, municipalities should adopt clear local policies aligned with the national roadmap, ensuring that PBW management receives consistent attention rather than shifting priorities year to year. Fourth, financial and logistical barriers can be addressed by promoting local recycling hubs or partnerships with nearby recycling facilities to reduce transport costs. Finally, inter-municipality collaboration should be strengthened so that consistent policies and actions are applied across regions, preventing waste leakage and reinforcing behavioral change among residents. In addition, municipalities should establish clear and practical collection targets, with evidence from this study suggesting that at least 25–75% of PBW must be collected to achieve sustainability benefits. Setting such targets would not only provide measurable goals for local authorities but also help align municipal practices with national and international waste management strategies.

In addition, this study was geographically confined to three municipalities in Northern Thailand. Future research could expand the analysis to include additional municipalities in other regions of Thailand or in other countries, to adapt the findings under diverse socio-economic and geographic contexts. Moreover, subsequent studies could also investigate other types of plastic waste.

4. Conclusions

This study evaluated the sustainability of PBW management in Thailand under real-life conditions, focusing on three municipalities with and without recycling initiatives. Using the AHP method combined with sensitivity analysis, results revealed that current recycling practices were largely ineffective, with collection rates below 0.5% of MSW, limiting their environmental and economic benefits. In some cases, initiatives even increased GHG emissions due to additional transportation. Commercial area, municipality A, demonstrated the greatest potential for sustainable management due to higher MSW and plastic waste volumes. Sensitivity scenarios indicated that higher recovery rates (50–100%) substantially improved sustainability, with 100% recovery in the commercial municipality (scenario 6A) achieving the best outcomes. Importantly, thresholds differed by municipal characteristics: commercial areas required at least 25% recovery, while tourist and agricultural municipalities needed 75% and 50%, respectively, to outperform baseline conditions. Therefore, the findings highlight that while recycling is theoretically the superior strategy compared to landfilling, its success depends on sufficient collection volumes, economies of scale, consistent policy focus, and effective public participation. Weak institutional consistency, limited attractiveness of initiatives, and high transportation costs remain critical barriers in real-life conditions. Furthermore, this study revealed administrative weaknesses and a lack of awareness among both village chiefs and citizens, which limited the effectiveness and scalability of the initiatives across different communities. This lack of engagement was reflected in the very low PBW collection rate compared with other recyclables, such as tin cans, cardboard, and glass bottles, which typically reach much higher recovery percentages, as shown in municipalities A and C. To move toward sustainable plastic waste management and low-carbon communities, municipalities must combine practical collection targets, economic incentives, inter-municipal collaboration, and strong local leadership. Without addressing these structural and institutional challenges, recycling initiatives are unlikely to achieve significant sustainability benefits. Based on the results of this study, other regions of Thailand and/or other countries could evaluate their PBW collection strategies and other waste management initiatives, helping to select suitable approaches and set minimum collection targets to achieve sustainability. In addition, future research could extend this study to assess additional types of plastic waste, and by applying AHP in larger and denser urban settlements.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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Conflicts of Interest: We declare that we have no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

3Rs	reduce, reuse, and recycle
AHP	analytic hierarchy process
CI	consistency index
CR	consistency ratio
EF	emission factor
GHG	greenhouse gas
LCA	life cycle assessment
MCDM	multi-criteria decision-making
MFA	material flow analysis
MSW	municipal solid waste
PBW	plastic bag waste
PE	polyethylene
PET	polyethylene terephthalate
PP	polypropylene
PROMETHEE	preference ranking organization method for enrichment evaluations
RDF	refuse-derived fuel
TOPSIS	technique for order of preference by similarity to ideal solution
VIKOR	viekrite-rijumsko kompromisno rangiranje

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