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Research article

Enhancing circular plastic waste management: Reducing GHG emissions and increasing economic value in Rayong province, Thailand

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ABSTRACT

This study evaluates the greenhouse gas (GHG) emissions and economic value creation of plastic waste (PW) management in Rayong, Thailand, a city on the eastern Gulf Coast with a significant amount of generated and leaked PW. By analyzing current practices, and developing and evaluating improvement scenarios, the study explores strategies for reducing GHG and enhancing economic benefits across the PW management chain. Four primary routes with varying capacities handle approximately 5,445.55 tonnes of PW via source separation recycling (5.18 %), post-sorting recycling (9.30 %), energy recovery (54.86 %), and landfills or opened dump disposal (30.66 %). About 83.21 % of the 16 ± 6.9 % PW in municipal solid waste (MSW) is recyclable, primarily consisting of high-density polyethylene (HDPE), polypropylene (PP), low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), and polyethylene terephthalate (PET). The current management practice generates an economic benefit of approximately 1.68 million USD/yr or 310 USD/t of PW, compared to the proposed scenarios, which enhances recycling efficiency and reduces landfill and energy recovery waste, yielding 2.27–6.48 million USD/yr or 420.64–1200.33 USD/t of PW. The practice emits about 7,028.47 tCO_2e annually, while improved source and post-sorting efficiencies reduce GHG emissions by 2.86–3.17 times or −2.83 to −2.42 tCO_2e/t of PW or a total of over 13,078.60–15,268.44 tCO_2e. Burning PW increases approximately 1.6 times or 11,841.36 tCO_2e/yr. Enhancing recycling efficiency, particularly through source separation, is key to promoting more productive and valuable PW separation, increasing economic value and GHG mitigation by approximately 3.87 and 3.17 times, respectively. These findings provide valuable insights for local authorities and policymakers to develop strategic interventions and policies that align with the improved scenario by enhancing source separation and recycling. The results demonstrate that improving the efficiency

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of separation at the source is critical for transitioning from a linear PW management strategy to a circular economy, significantly reducing landfill waste and mitigating environmental threats.

1. Introduction

Plastic is one of the most single-use materials used in daily life, where it is produced, consumed, and discarded linearly into the environment, harming atmospheric, land, and marine ecosystems [1,2]. Based on a global population of 7.3 billion in 2015, it was estimated that the production of consumer-plastic products contributed to approximately 4.5 % of global GHG emissions and is projected to increase constantly to quadruple by 2050 [3,4]. Despite the large production volumes of the 8,300 million tonnes (Mt) of plastic produced between 1950 and 2015, only 21 % were handled correctly—9% were recycled and 12 % were incinerated, while over 79 % ended up in landfills or leaked into the environment [5]. Post-consumer plastic waste (PPW) is a major concern in its mismanagement, causing a primary source of marine litter [6]. Each year, approximately 0.8–2.7 Mt of plastic waste (PW) is disposed of in rivers and oceans [7]. This contamination is more challenging currently due to the increase in plastic product consumption for food packaging, grocery deliveries, personnel prevention, and healthcare devices, particularly during the pandemic [8,9]. The number of plastic packages used globally is expected to be 266 billion pieces in 2026 [10,11].

Various efforts worldwide are focused on tackling plastic waste via circular economy (CE) strategies and promoting source separation, reuse, recycling, and recovery for minimal material and energy loss [12]. About 175 nations adopted a global treaty on plastic pollution during the UN Environmental Assembly in Nairobi and intend to implement it by 2025. A critical determination of PW management is its circularity by maximizing the value of material utilization via recycling, where recycled materials are used to create new products instead of being subjected to burning processes or landfilling sites [13]. For instance, Japan launched a plastic resource circulation policy to recycle about 60 % of PW by 2030. The European Union (EU) issued the Circular Economy Package and the EU Action Plan for the Circular Economy to recycle approximately 55 % of packaging plastic by 2030 and reduce waste to landfills to less than 10 % [14]. However, only 32.5 % of the total PW was recycled, while the remainder was still incinerated or deposited in landfills [13]. This is an enormous loss in terms of economics; almost 95 % of plastic material loses its value after a short initial use cycle [15], and costs between 75 and 115 billion USD. In addition, the production of virgin plastic resin and PW incineration emitted approximately 850 metric tons of GHG pollution in 2019. This number is expected to increase significantly to 2.8 billion metric tons by 2050.

In Thailand, PW is a significant environmental challenge that is largely generated and ineffectively managed for more than a million tonnes annually [7]. Therefore, the nation targets promoting a low-carbon and zero-waste-to-landfill policy by encouraging sustainable consumption and material recovery. The Roadmap on PW Management (2018–2030) has been launched, aiming for 100 % recycling by 2027. However, only 19 % of the total generation, which was over 2 million tonnes of PW, was recycled in 2019, whereas approximately 65 % was disposed of in landfills, open dumps, and environmental leakage, the remainder was openly burned and incinerated [16]. This ineffective management caused an economic loss of 4 billion USD a year and mitigated opportunities for GHG emissions of 67 $MtCO_2e$ through recycling [17]. Despite several studies and policies aimed at promoting CE principles to reduce the impacts of PW, the extent of value loss and GHG emissions throughout the PW lifecycle remains constrained, particularly in developing countries where data on PW management are limited [18]. Comprehensive data, indicating the management cost, economic benefit, and emission potential of PW management throughout its lifecycle, is a critical determining factor for national policy direction and local implementation strategy. In this study, a quantitative and qualitative analysis of current PW management practices was addressed to identify gaps and management routes. The informative data and material flow were collected and analyzed to develop some scenarios that enhanced the recycling efficiency of PW management. These improving strategies are supposed to be a novelty for reducing PW management costs, enhancing economic benefit, and reducing GHG pollution emitted, which aligns with the circular economy approach and promotes the sustainability of PW management with minimal impact on the environment.

2. Research methodology

Rayong province was selected as a case study due to its location and its waste disposal and treatment facilities [19]. Seven main plastic polymers were focused on which were polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), and other types of plastics derived from various plastic products. Unlabeled plastics were identified as other plastics. The methodology was conducted in the following order: data collection and material flow analysis to understand the current city's plastic management flow, identifying routes and gaps and room for improvement. Then proposed scenarios aimed to improve recycling efficiency by increasing the ability of current management were developed. An evaluation was then carried out for the effectiveness of PW management and its impacts, focusing on GHG emissions and economic value loss in the context of CE principles. The final step involved analyzing and discussing potential recommendation strategies for improving and reducing the environmental impact of managing PW of the city. The details are as follows:

2.1. Study area and site description

Rayong is balancing its previous focus on the agriculture economy with new industry establishments which are subsequently negatively affected by large amounts of generated MSW. It was found that approximately 110 tonnes of MSW are generated daily from the registered population of 170,774 according to Rayong's records in 2021, which was then characterized to be 16 $\pm$ 6.9 % of PW.

Various practices and pathways exist to manage PW management at the local level in Thailand including Rayong. The PW management pathways across local areas are depicted in the supplementary material (Table A1) and fall within the scope of this analysis framework. These pathways These pathways involve several activities and units which were the community plastic-source separation/voluntary programs junk shops, recycling plants, waste transfer stations/public waste sorting, secure landfills/open dumping/control dumping, and waste-to-energy plants/RDF power plants.

2.2. Data collection and plastic waste characterization

Field surveys, questionnaires, secondary data reviews, and MSW quartering for composition analysis were methods employed to gather data on PW management systems in 2021. Understanding these systems involved 77 participants, divided into 14 participants from the formal sector (local authorities, waste management operators, companies, dealers, and recyclers) and 63 participants from the informal sector (waste pickers, collectors, and waste bank operators). Secondary information on Rayong's plastic waste management was reviewed from municipality reports, national reports, and previous studies in Thailand in collecting data on municipal solid waste generation, plastic consumption, population numbers, the value of recycled plastic resins, and the cost of treatment. The study focused on two main areas:

- Data on MSW and PW composition in Rayong was gathered using the quartering method according to the standard method ASTM D5231-92 (2003) [20] to examine characteristics in three zones at waste transfer sites. PW composition was classified in terms of seven types of plastic polymers (PET, HDPE, PVC, LDPE/LLDPE, PP, PS, and others) and common products (plastic bottles, plastic bags, plastic films, plastic cups and food containers, plastic disposable containers, and other plastic products). The composition of the waste was determined based on its wet weight at waste transfer stations located in three zones. Data were collected on weekdays and weekends during both dry and rainy seasons, over four days in January and June.
- PW collection for recycling and final treatments: Quantitative and qualitative data on PW collection for recycling were gathered monthly from multiple stakeholders, including 3 local authorities, 2 waste collection and treatment companies, 5 junk shops, 4 recyclers, 60 waste pickers and waste collection crews, and 3 operators involved in community plastic-source separation. Additionally, data records of MSW quantification from local authorities and waste characteristic results were used to estimate the amount of mixed PW destined for landfills and energy recovery.

2.3. Plastic waste flow and scenario development

2.3.1. Plastic waste flow analysis

Data from the PW generation and composition study was used to create a holistic picture of the PW management system using material flow analysis (MFA) [21]. In each route, the PW flow was performed by identifying the quantities of PW. Fig. 1 illustrates four routes of PW management in Rayong:

- *Route 1 (R1): Source Separation for Recycling*

PW is separated at the source, mainly household level after use through voluntary community-management programs (e.g., waste banks, plastic collection campaigns, plastic drop points). A waste bank is a system for collecting and sorting valuable plastic and other

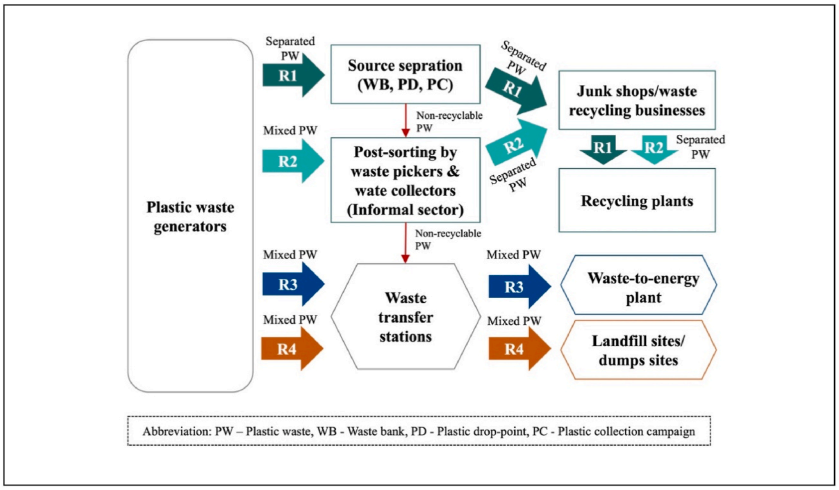

Fig. 1. Different routes of plastic waste management in Rayong: R1: Source separation for recycling, R2: Post-sorting for recycling, R3: Waste-to-energy, R4: Landfilling and dumps.

waste. People deposit waste, which is recorded in their account, and receive money or goods after the waste is sold to recyclers. Plastic drop points are designated areas for collecting PET bottles, plastic bags, and mono-layer plastic films. Voluntary campaigns, including plastic collection campaigns or exchange events, are organized by local authorities or community members to collect recyclable waste and encourage participation. The separated PW is then transported to junk shops or local recyclable trading businesses and transferred to recycling plants.

- *Route 2 (R2): Post-Sorting for Recycling*

Mixed PW is post-sorted handily at the roadside or transfer stations by waste pickers and waste collectors. The sorted PW is then transported to junk shops or local recyclable trading businesses and transferred to recycling plants.

- *Route 3 (R3): Waste-to-energy*

The PW residue from roadsides and waste transfer sites is collected by the municipality and transported to a waste treatment centre for combustion for electricity production.

- *Route 4 (R4): Landfilling and dumps*

Mixed PW contaminated in MSW collected from roadsides was collected and treated by landfilling, open dumps, or controlled dumps method.

2.3.2. Scenario development

This study formulated five scenarios including current practice to evaluate existing PW management and its impact, as outlined in Table 1. The baseline scenario (S1) represents the current situation, encompassing all existing PW management routes (R1-R4) identified by the PW flow analysis in this study. Scenario 2 (S2) focuses on maximizing recycling at source, aiming to enhance source separation and reduce reliance on waste-to-energy and landfilling. Scenario 3 (S3) aims to improve the efficiency of recycling by maximizing the capacity and effectiveness of post-sorting facilities, thereby increasing the proportion of plastic waste recycled after collection. Scenario 4 (S4) prioritizes the use of waste-to-energy processes for plastic waste management, significantly increasing the proportion of waste managed through energy recovery rather than landfill. Scenario 5 (S5) focuses on enhancing source separation through the promotion of waste banks and recycling facilities, aiming to significantly increase the recycling rate and reduce reliance on waste-to-energy and landfills. All scenarios are introduced based on national goals to promote zero waste in landfilling and enhance recovery and recycling efforts [16,22].

2.4. Economic value and GHG emissions assessment

Different pathways in PW management have various impacts on economic and environmental aspects, as highlighted in previous studies [23,24]. The variables affected by these impacts include rate of waste collection, round-trip distance, energy consumption, type and number of vehicles, etc. Furthermore, the research assessed the impact of PW management in terms of material value loss and GHG emissions. To improve the current PW situation in Rayong, five scenarios (S1-S5) are being considered to evaluate their impact and propose improvements. The assessment is detailed below:

2.4.1. Economic value analysis

The cost of PW management includes transportation and treatment. The cost of PW disposal and recovery was calculated by fuel consumption during waste collection and using records of treatment fees from the local government in Rayong. Additionally, the cost of recycling was estimated by considering fuel consumption during plastic collection, transportation for source separation, post-sorting

Table 1
The percentage of plastic waste in each route across various scenarios.

Scenario		PW route ratios			
		R1	R2	R3	R4
S1	Current Practice	Existing rate	Existing rate	Existing rate	Existing rate
S2	Maximize Recycling	Maximizing rate	Existing rate	0 %	0 %
S3	Maximize Post-Sorting	Existing rate	Maximizing rate	0 %	0 %
S4	Maximize Waste-to-Energy	Existing rate	Existing rate	Maximizing rate	0 %
S5	Promote Waste Bank for Recycling	Increasing rate	Existing rate	Existing rate	0 %

Note: R1: Source Separation for Recycling; R2: Post-Sorting for Recycling; R3: Waste-to-Energy; R4: Landfill and Dumps; The existing rate refers to the current percentage of plastic waste (PW) processed through each route (R1-R4) based on the baseline scenario; Maximizing rate refers to the theoretical maximum capacity for processing PW through the specified route, aimed at optimizing the scenario's objective; Increasing rate refers to an enhanced percentage of PW processed through the specified route, representing an improvement over the existing rate and aiming to reduce PW sent to landfills.

steps to junk shops, and recycling manufacturing. It included recycling processing costs estimated using data obtained from local recycling plants, which included factors such as energy consumption and utilities. According to Riegg Cellini and Kee, 2015 [25], net economic value can be calculated by following Eq [1].:

$$\text{Net economic value (USD / yr)} = \text{total benefit} - \text{total cost} \quad [1]$$

where,

- Cost includes transportation costs, treatment and disposal fees, fuel consumption, and recycling processing costs. Data sources: survey data (bills/records/interviews), local government announcement fees, and reports.
- Benefit Components include revenue from selling PW material, the value of recycled resins, and benefits from electricity generation through energy recovery. Data sources: survey data (bills/records/interviews) and reports; the value of plastic recycling is based on the price of the most valuable recycled resins when recycling 1 tonne of PW by type (average efficiency 85–95 %) and the price of electricity generated from PW per tonne (USD/tPW) for non-recyclable PW, as shown in the Supplementary material (Tables A5–A6).

2.4.2. GHG emission evaluation

Evaluation of GHG emissions was conducted using the data from a life-cycle perspective, starting with waste generation (the point at which a material is discarded), recycling, energy recovery, landfill or open dumps. Variables in different PW management pathways were considered, including GHG generated by transport, processing, or treatment steps. Source reduction offset emissions from virgin material manufacturing. Recycling generates emissions from transporting and processing recycled materials but offsets emissions from raw material transport. End-of-life recycling emissions come from the collection and transport to recovery facilities. Combustion emits GHGs from transport to waste-to-energy facilities and combustion. Landfill and open dumps produce end-of-life emissions from transportation, as detailed in the supplementary material (Table A6).

The calculation method followed by the Thailand Greenhouse Gas Management Organization (TGO), a public organization, applied the emission factor (EF) in the Thai National LCI Database (TIIS-MTEC-NSTDA with TGO electricity 2016–2018; IPCC 2007) and WARM US EPA 2015 [26], as shown in the supplementary material (Tables A7–A8). The GHG emissions amount was expressed in tCO_2e/yr, and the calculation methods were based on the following equations.

$$\text{GHG } (tCO_2e / yr) = \text{Weight of plastic by types (tonnes) X Emission factor} \quad [2]$$

And,

$$\text{Net GHG } (tCO_2e / yr) = \sum GHGre + \sum GHGwte + \sum GHGlf \quad [3]$$

where, Net GHG = net GHG emissions or total GHG missions.

$\sum GHGre$ = the sum of GHG emissions related to transporting PW and recycling processes.

$\sum GHGwte$ = the sum of GHG emissions related to transporting PW and waste-to-energy processes/combustion with energy recovery.

$\sum GHGlf$ = the sum of GHG emissions related to transporting PW and landfilling/open dumps/control dumps processes.

3. Results and discussion

3.1. Current plastic waste management policy

The regulatory framework of waste management in Thailand is a continuous progression aligned with the global concern issues influencing the national policy which forces local municipalities to handle their waste and PW. Several tools and strategies have been set up centrally and implemented locally to increase recycling efficiency and reduce environmental threats. The Ministry of Natural Resources and Environment (MNRE) and the Ministry of Interior (MOI) are the principal agencies responsible for launching and driving plans and policies. Consequently, local governments are responsible legally for handling their waste for both collecting and disposal. The Thailand National Economic and Social Development Plan encourages zero waste in landfills and a circular economy for MSW and PW. In this policy, the 3Rs policy (Reduce, Reuse, Recycle) has long been a cornerstone of waste management efforts. The Roadmap on Plastic Waste Management (2018–2030), initiated by the MNRE, aims to promote the recycling of 100 % of plastic bottles, bags, films, caps, and food containers by 2027, and to eliminate all plastic waste from landfills. In support of this, the MOI has encouraged the implementation of waste banks for returning recyclable materials in all local government areas. The Notification on Solid Waste Management (2024) was also implemented by MOI to promote waste-to-energy systems for final waste disposal, providing a systematic approach to reduce residual waste and improper waste in landfills and dump sites. As a local government, Rayong is characterized as an industrial and population growth province that follows legal to national policy. Comprehensive waste management and disposal facilities initiated properly for recycling and waste-to-energy plant for final treatment. Despite these ambitious efforts, in Rayong, PW is still a problem. Many of them are discarded as residual waste, with only a small portion being recycled and some leaking into the ocean. This integration method of waste and PW management, in terms of routes, methods, and facilities exhibits significant differences in process efficiency, cost, benefits, and environmental impact [19].

3.2. Rayong plastic waste management

The main sources of PW in Rayong City are daily use plastic products which were consumed and discharged as waste, mainly mixed with other waste from several sectors including residential, commercial, industrial, and institutional sectors. Fig. 2 illustrates PW management systems, beginning with consumption, waste generation, and ending at end-of-life treatment or disposal. This system involves many units that function separately for separation both at source and post sorting, collection, recycling, and waste disposal facilities. Various types of PW were handled via multiple steps and units related to networks and stakeholders in both formal and informal sectors. In practice, people in a small unit of the community separated their PW at household or source separation. Various voluntary programs, e.g., waste banks, plastic drop-points, and plastic collection campaigns are operated by community leaders or authorities to promote activities for collecting recyclable and valuable plastics from households or retailers and reward them with consumer goods or money. A waste bank is a popular system for collecting and sorting valuable plastics from households or communities and depositing them in the bank. This bank activity exchanged PW with daily goods or recorded in their account a similar value to PW deposited. Another method is a drop point where plastics are dropped in the areas designated for collecting mainly PET bottles, plastic bags, and mono-layer plastic films, while voluntary campaigns, including plastic collection campaigns or exchange events, are organized by local authorities or community members to collect recyclable waste and encourage participation. Separated recyclable PW from this step had high quality and a high selling price for recycling due to its cleanliness.

On the other hand, most PW was non-separated as mixed PW, following the common steps in the city's waste management routes, from post-sorting for recycling to the final waste treatment processes. Some recyclable PW was discarded in MSW being post-sorted at the roadside or waste transfer station by waste pickers and waste collectors before being transferred to final treatment processes. The separated PW was then sold to junk shops, which are local businesses trading in recyclable material, and was then sorted by type, grade, and color before being sent to local recycling plants. The large amount of mixed PW that cannot be separated or remained in MSW was processed as a waste energy source to feed the RDF (refuse-derived fuel) production plant operated to treat MSW for electricity generation (9.8 MW). At the Rayong waste treatment centre, some of the mixed plastic was still disposed in of landfill/control dumps/open dumps. These various pathways for PW management in Rayong, as well as other cities, from generation to end-of-life treatment, promote different impacts and operating costs with benefits to serve sufficiently the current capacity of waste. The current waste management stages and potential improvement gaps remain understudied.

3.3. Waste and PW characterization

MSW generation in Rayong ranges from 0.5 to 1.0 kg/day/individual, bearing with plastics mainly plastic packaging for almost 90 % of 16 ± 6.9 % PW compared to other cities in Thailand, such as Nonthaburi, Phuket, and Phang Khon which accounts for

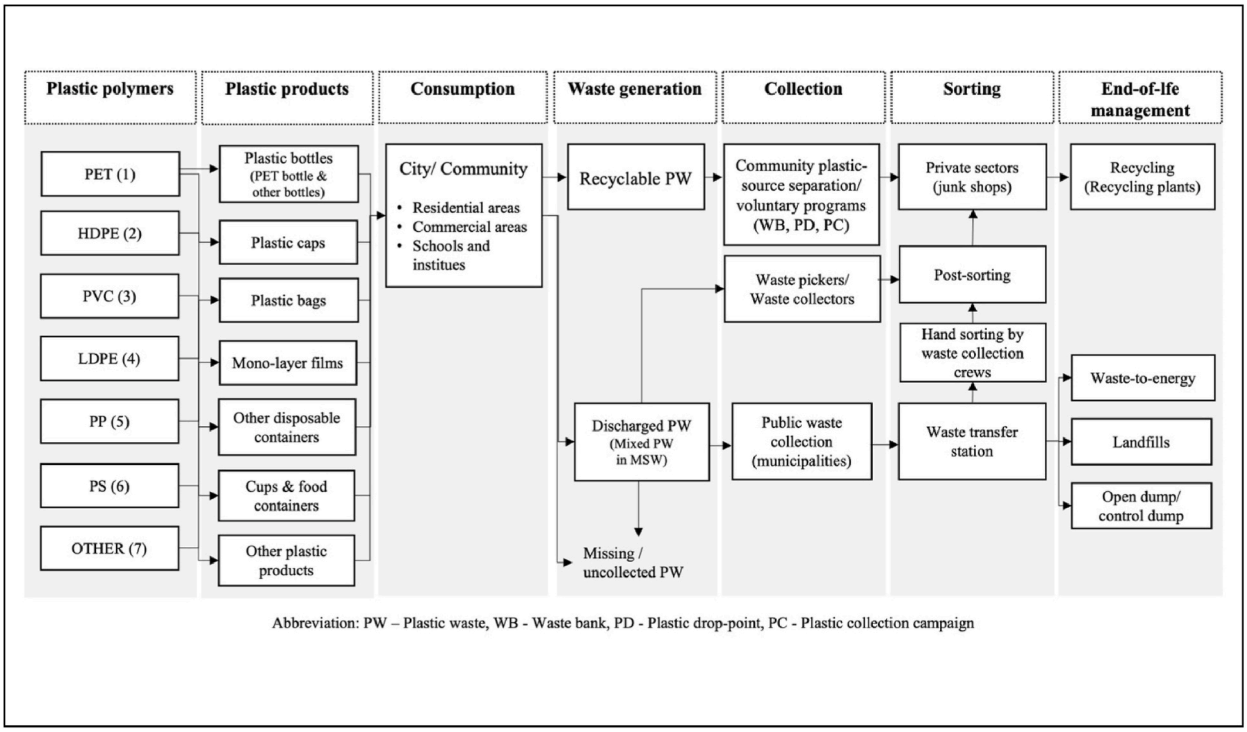

Fig. 2. PW generation, separation, collection, recycling, and treatment in Rayong.

approximately 14.4 %, 15.1 %, and 17.9 % PW, respectively [24,27,28]. In a broader context, PW is dominant in MSW in various regions. For example, PW mixed with all waste types comprises about 16.40 %, mainly from plastic containers and bags, in Muscat, Oman [29], 12.00 % in Muar, Malaysia [30], 11.70 % in Jakarta and 20.2 % in Bekasi, Indonesia [31], and approximately 15.2 % in Nur-Sultan, Kazakhstan [32]. These comparisons highlight the widespread challenge of managing PW effectively.

The composition analysis of the city's PW management units enabled the estimation of PW generation, separated PW for recycling, and mixed PW into seven types of plastic polymers, as detailed in the Supplementary Material (Fig. A3). PET, HDPE, LDPE/LLDPE, and PP were identified as the most common types of PW in Rayong, typically used for bottles, bags, films, and disposal containers. These plastic polymers are also essential for recycled resins in Thailand; however, the rate of collection for recycling was only 17.6 % [19].

This study revealed that recyclable PW from PET, mainly PET bottles constituted the highest proportion collected and recycled in Rayong. The community's plastic-source separation resulted in the separation of various plastics, especially HDPE and LDPE/LLDPE, derived from plastic bags and films. On the other hand, post-sorting focused on separating high-value and easy-to-handle products, such as plastic bottles (PET, PP). However, mixed PW discarded as MSW made from HDPE, PP, LDPE/LLDPE, and PET still made up a significant portion, accounting for approximately 83.2 %. These findings revealed inefficiencies in the current city's PW management and indicated suboptimal material utilization and value creation, underscoring a significant impact on both the environment and economic value. Addressing this gap of mismanagement through improved circulation could not only enhance environmental sustainability but also recapture economic value lost in the process.

3.4. PW flow and management route

The results of the PW flow in Rayong are shown in Fig. 3, which depicts that the total post-consumer PW generated yearly is about 5,445.5 tonnes. This PW was collected properly for almost 99.19 % or approximately 5,401.5 tonne/yr. The missing rate of PW collection was estimated based on the PW leaked data into the river and ocean, as monitored by Rayong's authority, for approximately 44 t/yr Similar findings but a higher number are stated in the Action Plan on Plastic Waste Management Phase II (2023–2027), where individuals generate approximately 35–40 kg of waste, with 3–5% of mismanaged waste potentially leaking into rivers and oceans annually [16].

It was found that over 80 % of PW or about 4,619.4 t/yr, ended up as mixed waste with other MSW with only 14.48 % of the total PW or 782.1 t/yr recycled. PW source separation in route 1 (R1) through waste banks, plastic drop-points, and plastic collection campaigns accounted for only 5.18 %, whereas the majority of recyclable mixed PW from the city route undergoes post-sorting handily in R2. The separations are conducted by the informal sectors, waste pickers and waste collectors with a recycling capacity of 9.30 %, or 502.2 t/yr. Similarly, in Bangkok, post-sorting is also mainly by hand and is vital to the recycling process which retrieves the recyclables from dumpsites, landfills, and waste collection trucks, and then sells them to waste buyers [33]. This informal sector's role is also seen in Bantar Gebang, Indonesia, where recyclable PW of more than 85 % was collected by the informal sector [31]. The main waste handling stream is proceeded via R3 for energy production constituting approximately 54.86 % (2,963.5 t/yr). However, there is the remaining portion of mixed PW, accounting for 30.4 % (1,655.9 t/yr), sent to landfills or dumped in open areas which promotes an enormous loss of material value and environmental threats.

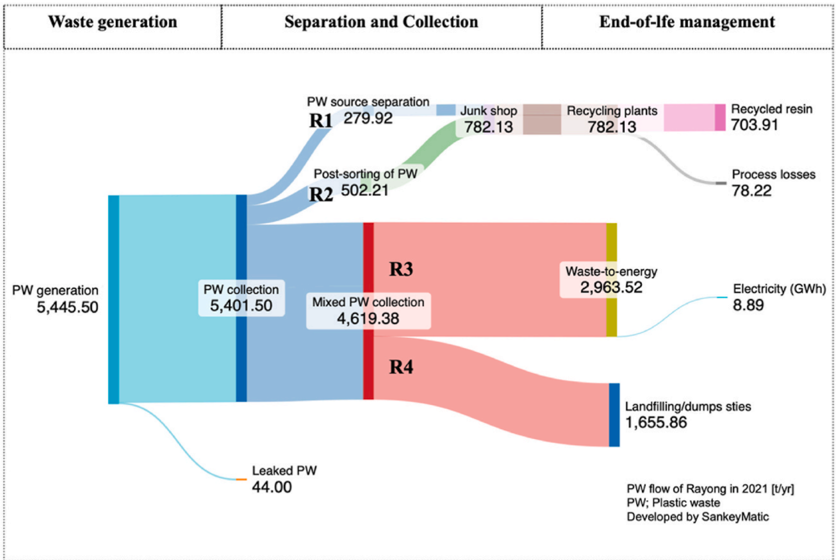

Fig. 3. PW flow and route of PW management in Rayong in 2021: R1: Source separation for recycling, R2: Post-sorting for recycling, R3: Waste-to-energy, R4: Landfilling and dumps.

3.5. PW management: GHG emissions, and economic value evaluation

3.5.1. Current practice GHG emissions and economic value

In Table 2, GHG emissions and economic value are evaluated from four current management routes of Rayong City and are summarized. It was found that various factors in managing waste and PW influenced their operating cost and benefits. The difference in resource consumption and collection routes is promoted differently from different distances of transportation, energy or fuel consumption which promotes an economic expenditure and benefit and GHG emissions.

From four routes of current PW management (R1-R4), the total cost expenditure was around 690,850 USD per year. This operation is the major of the investment directed towards processing for recycling and treatment processes for energy recovery. The main benefits of PW management in Rayong were derived from recycling and energy recovery processes amounting to a total of 2.58 million USD each year, which were derived from recycling and energy recovery processes. Recycling emerged as the most beneficial generation aspect, contributing nearly 60 % of the overall benefits, particularly through source separation in R1 and post-sorting in R2. These recycled plastic generated the highest revenue from selling to recycle plants to produce recycled mixed plastic products [27].

As shown in Fig. 4, managing 1 tonne of recyclable PW at the source for recycling (R1) yielded approximately 3.85 times higher benefits than sending PW to produce electricity or waste-to-energy (R3). Specifically, the net economic value for R1 was 1,231.23 USD/tonne, while R3 had a net economic value of only 319.52 USD/tonne. While the source separation in route 1 (R1) reduced significantly the transportation expenses compared to post-sorting routes (R2). This expenditure was reflected significantly in the higher benefits of R1 for 2,073.09 USD/tonne, compared to 1,866.53 USD/tonne of R2. PET mainly PET bottles was the most recyclable plastic polymer that was collected in Rayong and generated the highest benefit from recycled products of 750–1,250 USD/t. PET and HDPE plastic waste generally yielded the highest revenue from recycling due to their valuable material and recycling ability [34].

It was observed that the segregation of plastic materials at source by type and ensuring cleanliness not only enhanced their value but also fetched higher prices at the recycling place market. These high-quality recycled plastics facilitate higher-quality recycled products and an effective recycling process. This observation is demonstrated clearly by the net economic value returned of R1, which exceeds that of all other routes. Furthermore, plastic, as one of the recyclables, generated the highest revenue from the sale of recycled products, further emphasizing the economic efficiency of source separation (R1) over other routes. In contrast, landfill and open dumps are the least effective routes, with no value-added returned and increasing the cost of waste elimination for the local government by approximately 40.5 USD per tonne of PW while excluding an indirect loss of opportunity from land and resource use for treatment which confirmed such economic loss and environmental disadvantages of these treatment methods.

Fig. 4 shows that GHG emissions from R1-R4 for PW management in Rayong accounted for 7,028.47 tCO_2e/yr or an average of 1.30 tCO_2e/t of PW. Route 1 (R1), involved a source separation, and Route 2 (R2) post-sorting handily for recycling depicted the most significant reduction capacity for GHG emissions, achieving about 2.87 tCO_2e/tPW and 2.40 tCO_2e/tPW, respectively. This reduction is achieved by saving fuel consumption and raw materials for new plastic manufacturing, with source separation reaching almost 3.0 times compared to post-sorting. However, the amount of PW managed in R1 was lower than in R2 due to limited covering capacity and mainly as a voluntary activity at the household segregation encouragement program.

For large city waste management, Rayong commonly invested in a large facility to handle and treat waste using incineration with energy recovery for electricity generation (R3). This route effectively reduces waste volume but generates significant GHG pollution of 8,884.44 tCO_2e/yr an average of 3.0 tCO_2e per tonne of burned PW. Landfilling and open dumps in R4 are also current treatment strategies, although generating quite low direct emissions of approximately 151.27 tCO_2e/yr but a high negative impact such as land use, plastic leakage, and loss of resource value. Therefore, the findings on the current status of PW management in Rayong underscore that source separation and post-sorting for recycling are effective methods to reduce GHG emissions and enhance the economic value of the recycling process. However, the volume of PW managed through these methods is still low compared to other final treatment

Table 2
GHG emissions and economic value of the four routes of PW management.

Impacts	Routes				
	R1	R2	R3	R4	Sum
Economic value					
Cost (USD/yr)	54,594	485,954	119,952	67,023	908,580
- Transportation cost	14,606	89,366	98,784	55,195	257,952
- Processing cost	396,588	396,588	21,168	11,828	650,628
Benefits (USD/yr)	580,290	937,391	1,066,866	–	2,584,547
- Recycling	580,290	937,391	–	–	1,517,681
- Waste-to-energy	–	–	1,066,866	–	1,066,866
Net economic value (USD/yr)	344,639	451,436.37	946,914	(67,023)	1,675,700
GHG emissions					
Raw material reduction (tCO_2e/yr)	(862.14)	(1,506.93)	–	–	(2,369.08)
Transportation (tCO_2e/yr)	40.03	243.60	270.73	151.27	705.63
Processing (tCO_2e/yr)	18.54	59.67	8,613.71	–	8,691.92
Net GHG emissions (tCO_2e/yr)	(803.58)	(1,203.66)	8,884.44	151.27	7,028.47

Note: 1 USD = 35 THB; Net landfilling emissions include only CO_2e emitted from transportation-related emissions from landfilling; Values within parentheses () represent negative values for the cost of waste management and GHG emissions reduction; R1: Source Separation for Recycling; R2: Post-Sorting for Recycling; R3: Waste-to-Energy; R4: Landfilling and Dumps.

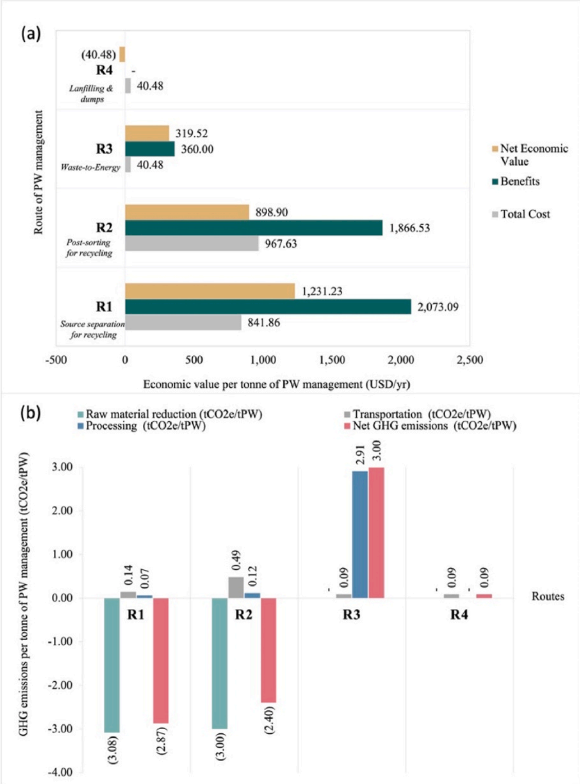

Fig. 4. Economic value (a) and GHG emissions (b) per tonne of PW management for different routes in Rayong.

routes. While waste-to-energy and landfill are still the main methods of PW management in Rayong with less consideration of environmental protection and restoring costs. This evidence confirmed a need for improved waste management strategies that prioritize recycling and minimize the use of incineration and landfill.

3.5.2. *Improved PW management proposed scenarios*

To enhance circular PW management, reduce GHG emissions and increase economic benefit, some analyzed scenarios based on the results of the current PW management route (scenario, S1) analysis were developed and divided into 4 scenarios (S2-S5). The different process efficiencies were simulated according to each scenario of improvement and are summarized in Table 3 for GHG emissions and economic benefits.

The economic value and GHG emissions of S1-S5 are depicted in Fig. 5. The results reveal that maximizing recycling by optimizing PW source separation to the highest capacity (90.7 %) promoted the greatest GHG reduction and increased economic value to 1,200.33 USD/tPW and −2.83 tCO_2e/tPW, respectively. Similarly, maximizing the post-sorting rate and facilities contributes to significant GHG

Table 3
Ratio of R1-R5 in different scenarios.

Routes	Unit	Scenarios				
		S1	S2	S3	S4	S5
R1	%	5.18 %	**90.70 %**	5.18 %	5.18 %	**35.84 %**
Source Separation for Recycling	tPW/yr	279.92	4,899.3	279.9	279.92	1,935.78
R2	%	9.30 %	9.30 %	**94.82 %**	9.30 %	9.30 %
Post-Sorting for Recycling	tPW/yr	502.21	502.21	5,121.57	502.21	502.21
R3	%	54.86 %	**0.00 %**	**0.00 %**	**85.52 %**	54.86 %
Waste-to-Energy	tPW/yr	2,963.52	0	0	4,619.37	2,963.52
R4	%	30.66 %	**0.00 %**	**0.00 %**	0.00 %	0.00 %
Landfilling and Dumps	tPW/yr	1,655.86	0	0	0	0

Note: S1: Current Practice - represents the baseline scenario, reflecting the current situation; S2: Maximize Recycling - represents the maximized source separation to enhance recycling and reduce waste-to-energy and landfilling; S3: Maximize Post-Sorting - represents the increased recycling efficiency by maximizing post-sorting facilities; S4: Maximize Waste-to-Energy - represents the waste-to-energy processes to reduce landfilling; S5: Promote Waste Bank for Recycling - represents the enhances source separation through waste banks to increase recycling and reduce waste-to-energy and landfilling.

emission reductions (−2.42 tCO_2e/tPW) and boosts economic benefits to 916.12 USD/tPW. A similar finding was also stated by other cities, such as Nonthaburi, about 1 tonne of separated recyclable PW generates revenue between 850 and 1,150 USD [27]. The promotion of waste banks according to the central government policy for recycling at the source, combined with energy recovery to reduce landfill waste can enhance an economic value of 700.15 USD/t of PW. Although GHG emissions were lower than the current levels, this method still releases 0.39 tCO_2e per tonne of PW from its combustion process. Conversely, promoting waste-to-energy by increasing capacity to 85.52 % as a main disposal method to generate electricity from plastic waste, can reduce landfill use significantly, but results in a huge emission of GHG for 2.19 tCO_2e/tPW or approximately doubling compared to recycling one. These results are similar to those found in South Korea in 2017, where incinerating 2.7 Mt of PW generated 3.6 Mt of CO_2e, which could be avoided by recycling, reducing emissions by 6.6 Mt of CO_2e [35]. Additionally, this method yields lower economic benefits of only 420.64 USD/tPW.

It is depicted clearly that all proposed scenarios improved a better environment quality by reducing GHG emissions and economic costs more effectively than the current PW management, with some limitations remaining for improvement for Rayong's situation. Promoting such campaigns to encourage people to separate at source for recycling is important to practical implementation. Enhancing source separation for recycling, such as through the implementation of community waste banks, could be an effective option to replace PW burning and landfilling. This approach could significantly improve the sustainability of PW management in terms of both GHG emissions reduction and economic benefits in line with the circular economy approach.

3.6. Enhancing circular PW management strategy

The different treatment strategies depict some different operating costs, economic benefits, and environmental pollution from GHG emissions. A huge opportunity to enhance economic value via recycling of plastic material that could enable it to be circular which reduces costs and GHG emissions. These findings are challenging for Rayong's PW management, particularly regarding waste minimization, material use optimization, and low-carbon emission practices. The current system relies heavily on a linear economy model by mainly burning PW for energy recovery or dumping to landfill sites which leads to an enormous loss of valuable materials and generates high pollution of GHG.

From the proposed scenarios, it was found that promoting source separation for recycling is the most effective strategy, resulting in an increase of economic benefits 3.87 times and halving GHG emissions or 3.17 times compared to normal situations. At maximum

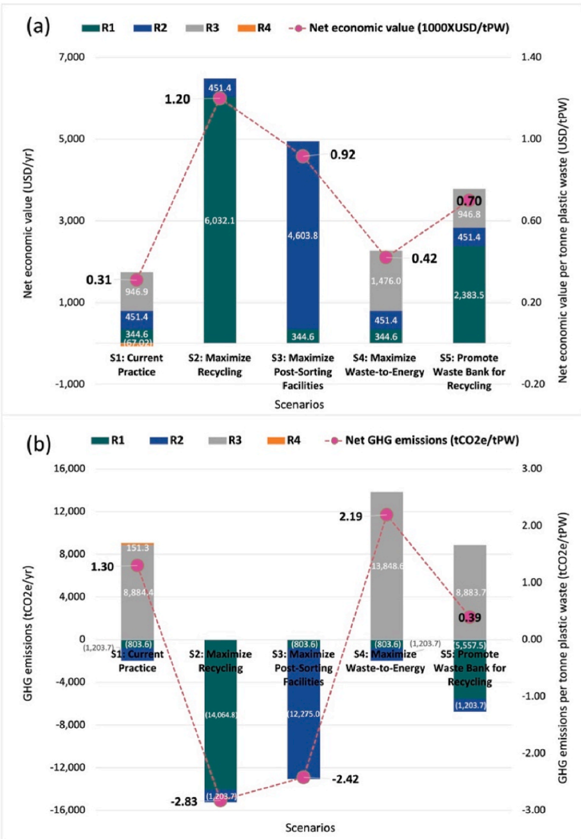

Fig. 5. Economic value (a) and GHG emissions (b) of four scenarios of PW management in Rayong.

recycling at a source of 90.70 %, it could generate about 6.48 million USD/yr and reduce GHG emissions by approximately 15,268.44 tCO_2e/yr. This underscores the critical need for waste segregation policies at the household level. This result has also been seen in Denmark where an efficient source segregation from households can achieve a 63 % recycling rate into high-value products [36]. While enhancing post-sorting efficiency facilities to the maximum of 94.82 % achieves about 4.95 million USD/yr and reduces emissions by 13,078.60 tCO_2e/yr. It also offers substantial economic and environmental benefits, though slightly less than source separation. The informal sector's role and post-sorting facilities for PW collection are vital for returning discarded valuable materials to the city's recycling process. However, this method can result in some loss of plastic quality from contaminations mainly from food and wet waste which affect consequently recycled quality plastic and the recycling process [37]. A similar finding was reported in Iran, a source separation increased economic value 2–3 times by reducing management costs compared to the post-sorting [23]. In addition, the waste-to-energy approach from burning PW is essential for landfill waste reduction and handling non-recyclable materials. This treatment method generates largely the highest amount of GHG and obtains lower economic benefits compared to recycling strategies. A similar study in Turkey confirmed that recycling is superior to incineration and landfill for processing PET and other PW promoting an economic worth of 168 million USD from Turkey's recycled plastics in 2030 [38].

It is worth noting that prioritizing recycling and improving waste sorting processes are crucial factors for the sustainability of PW management. This process enhances material circulation, reducing environmental impact, and maximizing economic benefits. An increase in collection rates and recycling separation will significantly mitigate PW mismanagement, material value loss, and GHG emissions. Most PW can potentially be recycled using existing technology; however, some types are difficult to handle and require alternative processing techniques. To achieve recycling goals and support circular development, involvement is needed at all stages of plastic management, from production and design to end-of-life management [16]. Additionally, despite these improvements, about 44 t/yr of PW leaks into the environment, indicating a critical need for enhanced management practices to prevent environmental contamination and further optimize material recovery. The study highlights the need of each scenario for enhancing source separation and recycling policies. Implementing effective waste segregation and maximizing the recycling processes will lead to substantial environmental and economic benefits. These findings are crucial for local authorities and policymakers in developing targeted strategies and policies aligned with national circular economy goals, particularly in achieving plastic recycling targets and zero waste to landfills. This research underscores the potential benefits and applications of adopting comprehensive and strategic approaches to PW management, not just in Rayong Province but also in other regions aiming to enhance sustainability in plastic waste management practices.

4. Conclusions

The results demonstrated a clear opportunity for the enhancement of economic benefits and reduction of GHG emissions from PW management. An enhancement of recycling efficiency, especially by source-separation could promote more productive and valuable separation of PW. Although about 99.19 % of the total generation of 5,445.5 t/y of PW was collected, over 80 % of it ended up as mixed waste resulting in a recycling rate of only 14.48 %. The remained PW was burned for energy production for approximately 54.86 % and disposed of in landfills or open dumps for 30.4 %. These two methods wasted almost 85.26 % of plastic materials value after a short cycle of use and emitted about 7,028.5 tCO_2e every year. This current management practice generates a low economic benefit valued at only approximately 1.68 million USD/yr or 310 USD/tPW compared to 2.27–6.48 million USD/yr for the proposed scenario that enhances recycling efficiency and reduces landfill waste, and energy waste. Maximizing source separation and PW collection for recycling through community initiatives, such as waste banks, could reduce GHG emissions by nearly 15,000 tCO_2e/yr or −2.83 tCO_2e/tPW and potentially increase 3.17 times an economic benefit from the current situation. These findings provide valuable insight for local authorities and policymakers to develop strategic interventions and policies that can produce an improved scenario by enhancing source separation and recycling. A significant reduction of GHG emissions and an increase in economic value could enable the achievement and sustainable waste and PW management in Rayong province which could as a consequence serve the national goals for circular economy promotion and zero waste to landfill policy. Moreover, this insight gained from the research can also serve as a model for other regions seeking scenarios to enhance their PW management towards sustainability. Future research should explore innovative technologies for PW processing from production to end-of-life treatment to optimize economic and environmental impacts. Comprehensive strategies are also needed to address PW leakage and promote sustainable development.

Data availability statement

Data included in article/supplementary material/referenced in article.

CRediT authorship contribution statement

Sutisa Samitthiwetcharong: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Orathai Chavalparit:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation. **Kultip Suwanteep:** Writing – review & editing, Conceptualization. **Takehiko Murayama:** Writing – review & editing, Supervision. **Pratin Kullavanijaya:** Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Sutisa Samitthiwetcharong reports financial support was provided by National Research Council of Thailand. Orathai Chavalparit reports financial support was provided by Thailand Science Research and Innovation Fund Chulalongkorn University. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e37611.

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