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Greenhouse gas mitigation from polyethylene terephthalate waste recovery in an urban waste system

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ABSTRACT
Background: The waste management sector significantly contributes to greenhouse gas emissions, particularly through landfilling and open burning practices in developing countries. Polyethylene terephthalate (PET) plastic waste constitutes a substantial fraction of municipal solid waste and may generate considerable emissions when improperly managed. Previous studies have mainly employed life cycle assessment approaches, while facility-level inventory-based assessments remain limited. This study aims to quantify the greenhouse gas mitigation potential of a PET material recovery system using a location-specific inventory approach. **Methods:** An Intergovernmental Panel on Climate Change (IPCC) Tier 2 greenhouse gas inventory method was applied within a gate-to-gate system boundary covering collection and material recovery activities. Primary operational data were obtained from a PET material recovery facility in Depok City, Indonesia, with an annual processing capacity of 233,038 kg. Emissions from electricity consumption, transportation, and residual impurities were calculated and compared with a Business-as-Usual scenario consisting of landfilling and open burning. **Findings:** The material recovery system generated 39.29 t CO_2e/year, equivalent to 0.17 kg CO_2e/kg PET, while the Business-as-Usual scenario produced 363.54 t CO_2e/year or 1.56 kg CO_2e/kg PET, resulting in an emission reduction potential of 324.25 t CO_2e/year. These results indicate that PET material recovery systems generate substantially lower emissions than conventional disposal practices, supporting the role of circular waste management strategies in greenhouse gas mitigation. **Conclusion:** PET material recovery systems provide significant greenhouse gas mitigation benefits and represent an effective strategy for reducing emissions in the urban waste sector. Operational efficiency and impurity management were identified as important factors influencing emission reduction performance. **Novelty/Originality of this article:** This study provides a facility-level empirical greenhouse gas inventory using an IPCC Tier 2 approach, providing context-specific evidence beyond conventional life cycle assessment studies.

KEYWORDS: greenhouse gas mitigation; polyethylene terephthalate; urban waste management.

1. Introduction

The waste management sector is widely recognized as a significant contributor to greenhouse gas (GHG) emissions, particularly in rapidly urbanizing regions where landfilling and open burning remain dominant waste treatment practices (Leal Filho et al., 2025; Zhu et al., 2025). These practices release carbon dioxide, methane, and nitrous oxide, which substantially contribute to global climate change. In developing countries, infrastructure, data availability, and system integration limitations often result in

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incomplete emissions quantification, thereby weakening mitigation strategies and policy development (Jiao et al., 2024; Alaghemandi et al., 2024).

In recent decades, the composition of municipal solid waste has shifted toward a higher proportion of plastic materials due to increasing consumption and urban growth (Houssini et al., 2025; Gu et al., 2025). Polyethylene terephthalate (PET) is one of the most widely used plastics in packaging applications because of its durability and lightweight properties (Al-Sabagh et al., 2016). However, PET is produced mainly from fossil-based feedstocks, and its environmental impacts are influenced by both production and end-of-life management pathways (Zheng & Suh, 2019). Global assessments indicate that less than 10% of plastic waste is effectively recycled, with the majority accumulating in landfills or the environment (Geyer et al., 2017).

Material recovery and recycling are considered key strategies for reducing emissions by diverting waste from disposal pathways and reducing the need for virgin material production (Bengtsson et al., 2018; Cappucci et al., 2020). Several studies have demonstrated that mechanical recycling systems can provide significant emission reduction benefits compared witho landfill-based systems (Jeswani et al., 2021; Faraca & Astrup, 2019; Mazhandu et al., 2023). However, many previous studies have used life cycle assessment (LCA) to compare the environmental impacts of different waste management and recycling pathways (Jeswani et al., 2021). While life cycle assessment provides a comprehensive perspective, it often does not fully represent site-specific operational conditions, particularly in developing countries (Faraca & Astrup, 2019).

In contrast, inventory-based approaches following the Intergovernmental Panel on Climate Change (IPCC) guidelines enable the use of localized activity data, including energy consumption, transportation distance, and material throughput (IPCC, 2006, 2019). The Tier 2 approach was selected because it allows the use of country-specific activity data together with relevant IPCC default parameters. Despite its methodological advantages, empirical studies, particularly those focusing on facility-level emissions in developing countries, have limited application of this approach to material recovery systems (Li et al., 2024; Ma et al., 2024).

In Indonesia, plastic waste accounts for a significant proportion of municipal solid waste (Ministry of Environment and Forestry of the Republic of Indonesia, 2024). Urban areas, such as Depok City, face increasing pressure on landfill capacity, highlighting the urgency of effective waste management strategies (Hartono et al., 2022). Material recovery systems, often supported by informal sector actors, play an important role in diverting recyclable materials from disposal pathways (Gutberlet, 2023; Vogt et al., 2021). However, previous studies have primarily focused on the social and governance aspects of waste management, with limited attention to the quantitative assessment of GHG mitigation based on operational data (Bening et al., 2022; Hasan & Ghosal, 2023).

Reliable GHG accounting is important for identifying effective mitigation measures in urban waste management. However, fragmented waste systems and limited facility-level operational data can make it difficult to quantify the contribution of individual recovery activities (Li et al., 2024). As a result, the climate benefits of localized recycling activities may not be fully reflected in municipal waste management assessments.

Material recovery facilities represent an important intermediate stage between waste generation and final disposal in urban waste systems. These facilities reduce the amount of recyclable materials entering landfills while simultaneously supporting circular economy practices through material reintegration into production systems. The environmental benefits of such facilities extend beyond direct emission reduction, including reduced pressure on landfill infrastructure, decreased environmental leakage of plastic waste, and conservation of natural resources through secondary material usage.

Another important aspect relates to the growing role of the informal sector within urban recycling systems. In many Indonesian cities, informal workers and community-based recycling initiatives strongly support waste collection, sorting, and material recovery activities. These actors significantly contribute to waste diversion and resource recovery, yet their role is often insufficiently represented within formal GHG accounting frameworks.

The absence of facility-level operational assessments may result in the underrepresentation of recycling-based mitigation contributions within municipal waste management planning. Therefore, integrating localized operational data into inventory-based emission assessments may improve the accuracy of waste sector mitigation estimates while simultaneously strengthening the visibility of material recovery systems within urban environmental policy discussions.

Therefore, this study aims to analyze the GHG mitigation potential of a PET material recovery system in an urban context using an inventory-based approach. This study adopts a gate-to-gate system boundary to capture facility-level operational emissions based on actual processing activities. This study applies a Tier 2 methodology to quantify operational emissions and compares them with a with a defined business-as-usual (BAU) scenario in which PET waste is assumed not to be recovered and be subjected to open burning.. This study contributes to advancing the application of inventory-based methods and supports the development of evidence-based policies for sustainable waste management and climate mitigation by providing empirical evidence based on localized operational data. Accordingly, this study addresses the following research question: What are the estimated GHG emission reductions associated with a facility-level PET material recovery system in Depok City compared with the defined BAU scenario?

2. Methods

2.1 Research design and approach

This study applies a quantitative GHG inventory approach to assess emissions from a PET material recovery system. The analysis follows the 2006 IPCC Guidelines and the 2019 Refinement. A Tier 2 approach is applied to the relevant waste-sector source categories using country-specific activity data together with applicable IPCC equations and emission factors. Facility-specific activity data for electricity consumption, transportation, and residual impurities are included within the defined gate-to-gate inventory. Unlike life cycle assessment (LCA) approaches, this method focuses on emissions associated with activities within the defined system boundary, making it suitable for facility-level analysis. The framework is used to quantify emissions from material recovery operations and compare them with a conventional waste management such as landfill with electricity production and incineration with electricity production scenario to evaluate mitigation potential (Evangelisti et al., 2015).

The Tier 2 methodology was selected because it enables the incorporation of operational characteristics that more accurately reflect the conditions of local waste management. To provide a more representative estimation of facility-level GHG emissions, parameters such as transportation activity, electricity consumption, equipment utilization, and material throughput were integrated into the emission calculations. This approach improves the reliability of the analysis by reducing dependence on generalized assumptions commonly applied in broader-scale assessments.

Additionally the inventory-based framework supports the identification of dominant emission sources within the operational system. This study provides a clearer understanding of operational processes contributing to overall environmental impacts by distinguishing emissions generated from transportation, energy consumption, and waste handling activities. This information is important for identifying opportunities to improve system efficiency and strengthen the role of material recovery systems as part of urban climate mitigation strategies.

2.2 Study area and system characteristics

This study was conducted at a PET material recovery facility in Depok City, Indonesia, which is a rapidly urbanizing area with increasing plastic waste generation. The facility operates as an intermediate processing unit that links collection systems with downstream recycling industries. Operational activities include material reception, weighing, sorting, and baling before transport. The facility processes approximately 233,038 kg of PET annually, providing a representative basis for estimating the emission. study area location is presented in Fig. 1.

The selected facility was chosen due to its active role within the local recycling network and the availability of operational data required for inventory analysis. As part of the urban waste recovery chain, the facility contributes to reducing the quantity of recyclable plastic materials destined for landfill disposal and unmanaged waste treatment practices. The operational characteristics of the facility reflect common conditions observed in developing urban waste systems, where material recovery activities are conducted with limited mechanization and rely heavily on manual sorting processes.

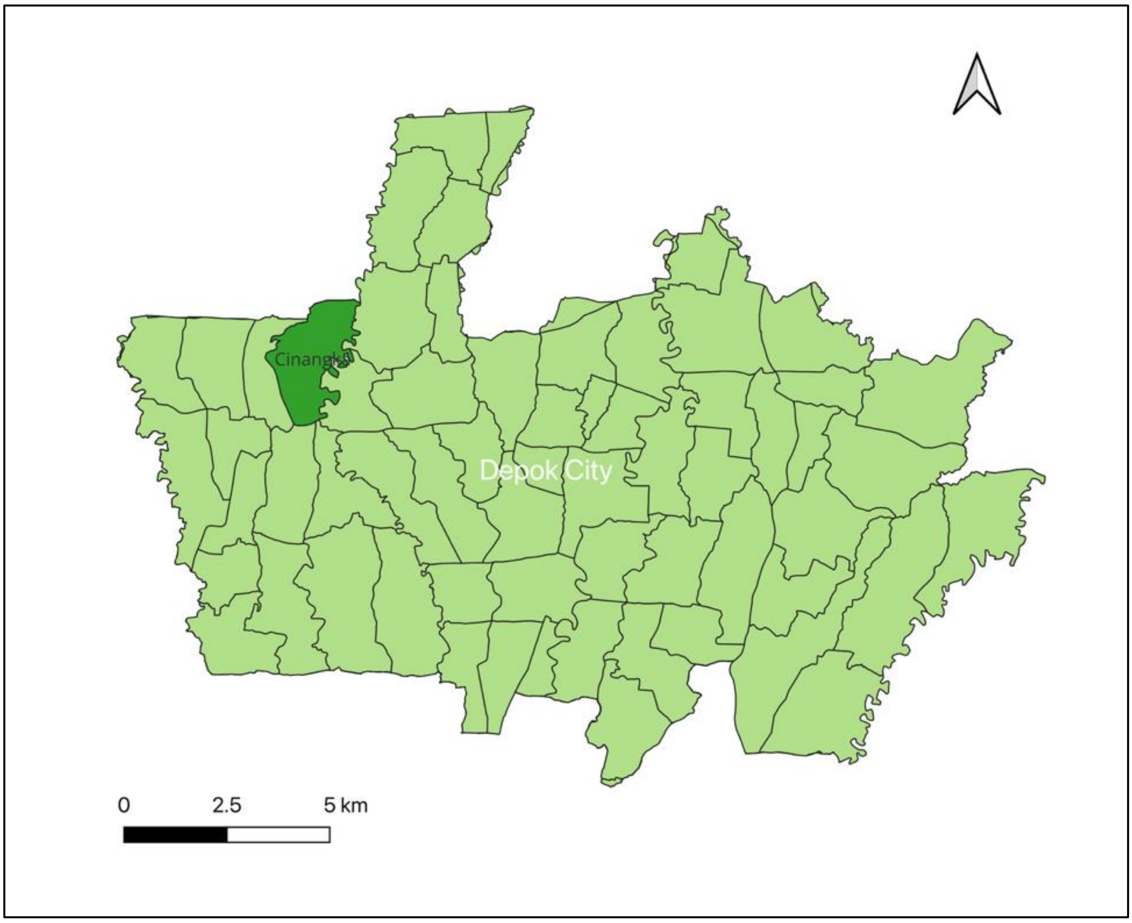

Fig. 1. Research location in Depok City, Indonesia

2.3 System boundaries and scenario definitions

The system boundary applied in this study is a gate-to-gate approach, covering all processes from the point where PET waste enters the facility to the point where the processed material exits as recyclable output. The system includes transportation, sorting, and recovery processes, excluding upstream production and downstream recycling. The system boundary and process flow are illustrated in Fig. 2. The gate-to-gate boundary was selected to isolate emissions associated with facility operational activities within the defined system boundary. This allows for a more accurate assessment of emissions that can be controlled or influenced at the system level, particularly in the context of urban waste management. A BAU scenario was defined as a reference condition in which PET waste is disposed of through unmanaged disposal and potential open burning. This scenario was selected based on reported waste management practices in Indonesia and is used as a baseline for evaluating the potential for emission reduction.

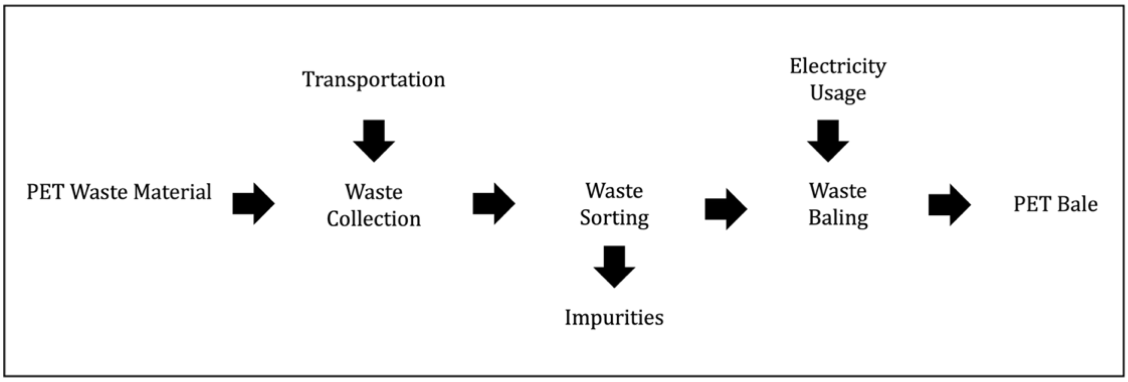

Fig. 2. System boundary of the PET material recovery system

2.4 Data collection and analysis of variables

This study used both primary and secondary data. Primary data, including annual PET throughput, electricity consumption, transportation distance, and residual impurity volume, were obtained from facility records and field observations covering the 2025 operational year. Secondary data include emission factors derived from the IPCC guidelines and relevant scientific literature. The main variables analyzed include activity data (material flow, energy consumption, and transport distance), emission factors, total emissions (kg CO_2e/year), and emission intensity (kg CO_2e/kg PET). Table 1 summarizes the activity data and emission factors used in this study.

Data quality control was conducted before emission calculations. Activity data were compiled from daily weighing and operational records, aggregated on a monthly basis, and reconciled against available shipment records and electricity consumption documents. The dataset was screened for missing entries, inconsistent units, and implausible values. Any discrepancies were checked against the original records and field observations before the annual inventory was included. The calculation sheets were cross-checked to ensure that the same units, system boundaries, and reporting periods were applied across all emission sources.

Table 1. Activity data and emission factors for the recovery of PET materials

Parameter	Value
PET volume (kg/year)	233,038
Electricity consumption (kWh/year)	7,284
Electricity emission factor (kg CO_2e/kWh)	1.08
Transport distance (km)	20
Transport emission factor (kg CO_2e/ton-km)	1.98
Impurity volume (kg/year)	14,229
BAU emission factor (kg CO_2e/kg)	1.56

(IPCC, 2006; 2019)

Emission factors were selected according to their compatibility with the defined activity data and gate-to-gate boundary. The electricity factor represents the national grid emission intensity applied to the measured annual electricity use. Transportation emissions were calculated using a ton-kilometer factor to reflect both the material mass and travel distance. To maintain comparability, the same methodological basis and global warming potential conventions were applied consistently to both scenarios.

2.5 Emission calculation

GHG emissions were calculated using an inventory-based approach by combining activity data with corresponding emission factors. The general equation used in this study is presented in Eq. (1). Where E represents emissions (kg CO_2e/year), AD represents activity data (e.g., kWh/year, kg/year, or ton-km/tear), and EF represents the emission factor.

$$E = AD \times EF \quad \text{(Eq. 1)}$$

2.5.1 Emissions from the electricity consumption

The emissions from electricity consumption were calculated based on the annual energy use and national grid emission factors. Emissions from electricity consumption were calculated as follows Equation 2. Where E_e represents emissions from electricity (kg CO_2e/year), EC represents electricity consumption (kWh/year), and EF_e represents the emission factor for electricity (kg CO_2e/kWh).

$$E_e = EC \times EF_e \quad \text{(Eq. 2)}$$

2.5.2 Emission from transportation

The transportation emissions were estimated using the ton-kilometer approach based on the material weight, transport distance, and emission factors, as shown in Eq. (3). where E_t represents emissions from transportation (kg CO_2e/year), W represents transported material (ton/year), D represents the average round-trip collection distance between waste sources and the facility (km), and EF_t represents the emission factor (kg CO_2e/ton-km).

$$E_t = W \times D \times EF_t \quad \text{(Eq. 3)}$$

2.5.3 Emissions from residual impurities

Residual waste emissions were calculated based on the amount of impurity sent to disposal and the associated emission factor, as shown in Eq. (4). Where E_r represents emissions from residual waste (kg CO_2e/year), W_r represents the amount of residual impurities (kg/year), and EF_r represents the emission factor for waste disposal (kg CO_2e/kg).

$$E_r = W_r \times EF_r \quad \text{(Eq. 4)}$$

2.5.4 Total emissions

The total emissions from the material recovery system were calculated as the sum of all emission sources in Equation 5. Where E_total represents the total emissions (kg CO_2e/year). This value reflects the overall GHG emissions generated within the system boundary.

$$E\_total = E_e + E_t + E_r \quad \text{(Eq. 5)}$$

2.5.5 Emissions intensity

The analysis also considers the emission intensity as an additional indicator for evaluating the environmental performance. Emission intensity was calculated by dividing the total emissions by the quantity of PET waste processed within each scenario. This approach enables a more standardized comparison between waste management systems by accounting for differences in waste quantities and operational scales.

$$EI = E\_total \,/\, W\_total \quad \text{(Eq. 6)}$$

Lower emission intensity values indicate more environmentally efficient waste management practices. The emission intensity was calculated to assess the environmental efficiency per unit of material processed in Equation 6. Where EI represents the emission intensity (kg CO_2e/kg PET) and W_total represents the total processed material (kg).

2.6 Business-as-usual emissions

The business-as-usual (BAU) scenario represents a counterfactual condition in which PET waste is not captured by the material recovery system and consequently remains within unmanaged waste pathways. Under these conditions, PET may accumulate in the surrounding environment or be subjected to open burning. Environmental leakage was treated as an unmanaged waste outcome rather than a direct source of GHG emissions. Therefore, the GHG estimate under the BAU scenario was based on the potential open burning of unrecovered PET.

The BAU scenario was modeled using the same annual PET quantity processed by the recovery facility, which is equivalent to 233,038 kg/year. The scenario does not represent the direct observation that every kilogram of unrecovered PET would necessarily be openly burned. Rather, it provides a standardized counterfactual baseline for estimating the potential emissions associated with a conventional unmanaged pathway in the absence of material recovery.

GHG emissions from open burning included fossil CO_2 released through the oxidation of the carbon contained in PET, as well as CH_4 and N_2O generated through incomplete combustion. The CO_2 contribution was calculated using a fossil carbon content of 0.63 t C/t PET and an oxidation factor of 0.58, resulting in 1.340 kg CO_2e/kg PET. CH_4 and N_2O contributions were calculated using emission factors of 6.5 and 0.15 kg/t waste and GWP values of 28 and 265, resulting in 0.182 and 0.040 kg CO_2e/kg PET, respectively. The total combined emission factor was therefore 1.56 kg CO_2e/kg PET.

2.7 Emission reduction analysis

Emission reduction analysis was conducted to quantify the environmental benefits associated with PET material recovery activities. The mitigation potential was determined by subtracting the total GHG emissions generated within the material recovery system from the emissions estimated under the BAU scenario. The analysis compares the emissions from the material recovery system and the BAU scenario. To evaluate the effectiveness of material recovery in reducing GHG emissions, emission reduction is calculated as the difference between both scenarios. The results are presented in terms of total and intensity emissions, allowing for a clear comparison across different waste management scenarios.

2.8 Assumptions and limitations of the study

Several methodological assumptions were adopted to simplify the emission estimation process and maintain consistency within the inventory framework. The study assumes that operational activities within the recovery facility, including transportation frequency, electricity consumption, and material handling practices, remained relatively constant during the observation period. In reality, operational fluctuations may occur due to variations in waste supply, equipment performance, and workforce capacity.

The study also assumes that the emission factors derived from IPCC guidelines and secondary references are representative of local operational conditions. However, regional energy sources, waste composition, technological efficiency, and transportation infrastructure may influence emission factors. As a result, the calculated emissions should be interpreted as estimated values rather than direct measurements of actual GHG releases.

Another limitation is related to the gate-to-gate system boundary applied in this study. The analysis focuses on facility-level operational emissions and excludes upstream processes, such as raw material extraction, and downstream processes, including secondary manufacturing and final product use. The findings primarily reflect the direct mitigation potential associated with waste recovery operations rather than the full lifecycle environmental impact of recycled PET materials.

3. Results and Discussion

3.1 Emission results of the material recovery system

The results indicate that the total GHG emissions generated by the PET material recovery system amounted to approximately 39.3 t CO_2e/year. These emissions are derived from three main sources: electricity consumption, transportation activities, and residual waste handling. Among these sources, residual waste contributes the largest share, followed by transportation and electricity use. The breakdown of emissions is presented in Figure 3. Electricity consumption accounted for approximately 7.87 t CO_2e/year, representing the energy demand required for sorting and processing activities within the facility. Transportation activities contributed approximately 9.23 t CO_2e/year, primarily due to the movement of materials from collection points to the facility. Meanwhile, emissions from residual impurities reached approximately 22.20 t CO_2e/year. The high contribution of residual waste indicates that the amount of material rejected during sorting is an important source of emission.

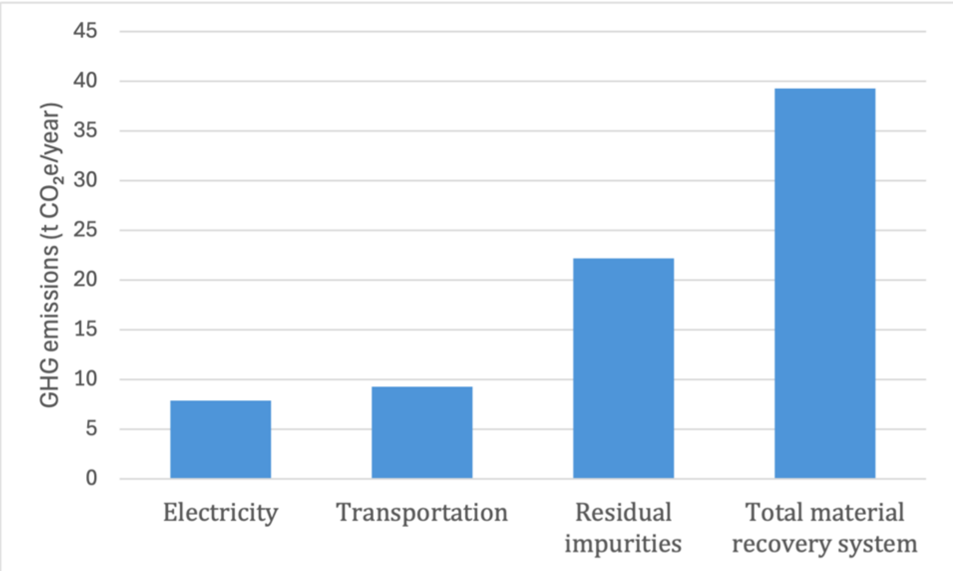

Fig. 3. GHG emission from the PET material recovery system (t CO_2e/year)

Although material recovery systems are more environmentally favorable than disposal-based systems, these findings demonstrate that operational inefficiencies still play a crucial role in determining total emissions. The high contribution of residual waste highlights the need for improved sorting efficiency and reduced contamination rates to enhance environmental performance. The findings suggest that process optimization should be prioritized in emission reduction strategies within the sorting stage. Improvements in segregation efficiency can directly influence the quantity and composition of residual waste, thereby reducing the overall emission burden. This reinforces the concept that environmental performance in recycling systems is determined not solely by technological presence, but also by the effectiveness of operational practices and material flow management within the system.

3.2 Emission intensity analysis

Emission intensity provides a measure of environmental performance by relating total emissions to the amount of material processed. The emission intensity of the material recovery system was calculated to be approximately 0.17 kg CO_2e/kg PET, while the BAU scenario reached approximately 1.56 kg CO_2e/kg PET. This significant difference indicates that material recovery systems are substantially more efficient in terms of emissions per unit of material. The lower emission intensity of the recovery system reflects the lower GHG emissions associated with PET recovery operations compared with the defined BAU pathway, which includes potential open-burning emissions. This difference highlights the potential emission benefits of diverting PET waste from the assumed BAU disposal pathway.

A more detailed interpretation shows that the emission intensity reflects not only the type of waste management system but also the efficiency of material recovery processes. A lower emission intensity indicates that a greater proportion of material is successfully recovered and retained within the system, thereby reducing the need for disposal and minimizing associated emissions. Conversely, higher emission intensity in the BAU scenario reflects inefficient resource utilization and higher environmental burdens per unit of material.

The results also suggest that emission intensity can serve as a useful indicator for evaluating and comparing different waste management strategies, particularly in the context of climate mitigation. In addition, emission intensity can be used as a benchmarking tool to evaluate system performance across different regions and operational conditions. Therefore, emission intensity is a practical and scalable indicator for supporting climate-oriented waste management strategies.

3.3 Comparison with the business-as-usual scenario

The BAU scenario, which represents unmanaged PET waste and potential open burning practices, generated substantially higher emissions than the material recovery system. Total emissions under the BAU scenario were estimated at approximately 363.54 t CO_2e/year. Compared with recovery system emissions of 39.3 t CO_2e/year, this corresponds to an estimated emission reduction of approximately 324.24 t CO_2e/year, or about 89%. The high emissions in the BAU scenario are primarily associated with fossil carbon oxidation and incomplete combustion during open burning, which generate CO_2, CH_4, and N_2O.

The comparison indicates that diverting PET from the defined BAU pathway can substantially reduce the overall GHG emission burden, although emissions remain associated with electricity consumption, transportation, and residual waste handling within the recovery system. This highlights the potential role of material recovery in reducing emissions within the defined study scenario.

Table 2. Comparison of GHG emissions and emissions intensity between the material recovery system and BAU scenario

Scenario	Total emission (t CO_2e/year)	Emission intensity (kg CO_2e/kg PET)
Material recovery system	39.3	0.17
Business-as-usual (BAU)	363.54	1.56

(IPCC, 2006; 2019)

3.4 Comparison with previous studies

The findings are directionally consistent with previous studies reporting lower GHG emissions from recycling compared with disposal-based pathways, although differences in system boundaries and assessment methods limit direct quantitative comparison. Jeswani et al. (2021) and Faraca & Astrup (2019) reported that mechanical recycling can significantly reduce GHG emissions by avoiding emissions from waste disposal and decreasing the demand for virgin material production.

However, this study differs from previous life cycle assessment-based studies by applying an inventory-based approach using facility-level operational data. This allows for a more accurate representation of actual emissions generated within the system, particularly in the context of developing countries where data availability and operational conditions differ significantly from global averages. In addition, the relatively high contribution of residual waste emissions observed in this study aligns with recent findings highlighting sorting system inefficiencies. This suggests that operational improvements remain a critical factor in maximizing the environmental benefits of recycling systems (Shukla et al., 2025; Fayshal et al., 2024).

Direct comparison of emission values should be interpreted cautiously due to differences in system boundaries, functional units, and avoided material substitution. As shown in Table 3, previous studies generally report environmental benefits from plastic recycling, although direct quantitative comparison remains limited due to differences in methodological approaches and comparison scenarios.

Table 3. Comparison of the present study with previous plastic waste management studies

Study	Location	Main Comparison
Sharma et al. (2025)	Nepal	Applied a gate-to-gate LCA to compare mechanical recycling, chemical recycling, and landfill pathways. Mechanical recycling showed lower climate impacts than chemical recycling and landfill scenarios.
Mazhandu et al. (2023)	South Africa	Evaluated plastic waste management pathways and reported favorable environmental performance for mechanical recycling compared with other waste management options.
Gheewala (2023)	Thailand	Evaluated bottle-to-bottle and bottle-to-fiber PET recycling pathways and reported significant potential for GHG emission reduction.
This study	Depok, Indonesia	Applied a facility-level GHG inventory within a gate-to-gate system boundary to compare PET material recovery with the defined BAU scenario. The recovery system reduced emissions by approximately 324.24 t CO_2e/year, or 89%.

(Sharma et al., 2025; Mazhandu et al., 2023; Gheewala, 2023)

A key contribution of this study is its emphasis on operational-level emission quantification, which complements the existing literature on life cycle assessment. LCA provides a broader system perspective, whereas the present inventory focuses specifically on operational emissions within the defined facility boundary. The use of an inventory-based approach allows for a more precise representation of emissions under actual operating conditions, thereby improving the reliability of the assessment. This distinction is particularly important in developing country contexts, where site-specific factors, such as informal sector involvement, infrastructure limitations, and variability in waste composition, influence system performance. By incorporating real operational data, this study bridges the gap between theoretical environmental assessment models and practical implementation conditions.

3.5 Operational efficiency and system performance

The results indicate that operational performance plays an important role in determining the emission profile of the material recovery system. Although the recovery system substantially reduced GHG emissions compared with the BAU scenario, residual waste remained an important source of operational emissions. The relatively high contribution of residual waste indicates that the amount of material rejected during sorting influences the overall emission performance of the facility (Le Pera et al., 2023; Blasenbauer et al., 2024).

The emission profile further shows that electricity consumption, transportation, and residual waste handling represent the main operational sources within the defined system boundary. Among these sources, residual waste contributed the largest share of emissions, followed by transportation and electricity consumption. These results demonstrate that the environmental performance of the recovery system is influenced not only by the amount of

PET recovered but also by the operational emissions generated during material handling and processing.

The use of facility-level operational data also provides a more detailed representation of emission sources within the recovery system. Data on material throughput, electricity consumption, transportation, and residual waste allow the contribution of each operational component to be quantified and compared. This facility-level information can therefore support the assessment of operational performance and provide a more specific basis for GHG monitoring and reporting at the local level.

3.6 Implications for waste management and climate change mitigation

The modeled recovery system resulted in substantially lower emissions than the defined BAU scenario, in which PET waste was assumed not to be recovered and may remain unmanaged or be subjected to open burning (Salem et al., 2023; Cecon et al., 2023). The findings highlight the importance of integrating material recovery systems into urban waste management strategies. Infrastructure investments, improved sorting efficiency, and support for informal sector participation can further enhance system performance and maximize emission reduction potential (Perera et al., 2025).

Furthermore, an inventory-based approach provides a practical framework for monitoring emissions at the facility level. This is particularly relevant for developing monitoring, reporting, and verification (MRV) systems in climate mitigation initiatives, especially in rapidly urbanizing regions. The findings suggest that integrating emission assessment into routine waste management operations can support data-driven decision-making and policy development. By linking operational performance with measurable emission outcomes, stakeholders can better evaluate the effectiveness of waste management strategies and prioritize interventions that deliver the highest environmental benefits (Bandaranayaka et al., 2026).

The lower emission intensity observed in the material recovery scenario can also be interpreted from a broader circular economy perspective. By recovering PET waste and returning it to the material cycle, PET recovery can support circular material use. This finding supports previous studies indicating that mechanical recycling and material recovery contribute significantly to emission reduction by decreasing the demand for raw material extraction and primary plastic manufacturing. This approach is particularly relevant in urban waste systems because increasing waste generation is commonly accompanied by a growing demand for packaging materials, especially PET-based products.

The findings emphasize the importance of strengthening the material recovery infrastructure as part of urban climate mitigation strategies. In developing countries, waste management policies often focus primarily on waste collection and disposal, while the role of material recovery in reducing lifecycle emissions receives less attention. Expanding recovery capacity, improving source segregation practices, and supporting recycling market stability may contribute to not only waste reduction targets but also climate change mitigation objectives. Furthermore, the integration of informal waste recovery actors into formal waste management systems could improve collection efficiency and increase recycling rate in urban areas.

The study also demonstrates that GHG mitigation from material recovery systems may generate co-benefits beyond emission reduction alone. Improved recovery systems can reduced landfill dependency, lower environmental pollution, and enhance resource efficiency in urban environments. The findings support the integration of waste sector mitigation strategies into broader urban sustainability planning. Municipal governments may incorporate material recovery targets into local climate action plans, waste reduction programs, and circular economy initiatives. The availability of measurable emission reduction data can further strengthen the justification for investment in recycling infrastructure and operational improvements within urban waste systems.

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3.7 System limitations and uncertainties

Despite the use of an inventory-based approach, several limitations should be considered when interpreting the results. First, the BAU scenario assumes that the same annual quantity of PET processed by the facility would otherwise be subjected to the defined open-burning pathway. This represents a counterfactual assumption rather than a direct observation of actual waste treatment for all PET waste in Depok. Therefore, the estimated 89% emission reduction is sensitive to the selected BAU assumption and should not be interpreted as a universal reduction rate.

Second, the analysis relies on emission factors derived from IPCC guidelines and secondary literature sources, which may not fully capture local operational variability and technological differences. Actual emissions from waste recovery activities may vary at the facility level depending on equipment efficiency, energy consumption patterns, waste composition, and operational management practices. Third, the study focuses primarily on GHG emissions associated with PET material recovery activities and does not include broader lifecycle impacts such as water consumption, air pollutant emissions, or economic performance indicators. Therefore, the environmental assessment presented in this study should be interpreted specifically within the context of GHG mitigation potential rather than as a comprehensive sustainability evaluation.

Fourth, the system boundary does not fully incorporate downstream recycling processes, secondary material manufacturing, or long-term market dynamics associated with recycled PET utilization. Exclduing these aspects may influence the overall estimation of avoided emissions and substitution benefits. In addition, transportation assumptions and waste flow variability may introduce uncertainty into the final emission calculations.

Uncertainty was assessed qualitatively rather than through probabilistic or sensitivity modeling because the study uses a single year of observed facility data and locally verified point estimates, while repeated measurements were not available for all inputs to define parameter distributions or variation ranges. Therefore, the reported values should be interpreted as point estimates for the observed reporting period, with the direction and principal sources of uncertainty explicitly identified.

Despite these limitations, this study provides valuable facility-level insights into the potential of PET material recovery systems to mitigate GHG in urban waste management contexts, particularly in developing countries where operational data remain limited. Future studies could improve the accuracy and robustness of emission estimates by incorporating region-specific emission factors, real-time operational data, and multi-year records. When sufficient datasets become available, future studies may further improve uncertainty characterization by incorporating additional operational data, repeated measurements, and probabilistic approaches.

3.8 Scalability and broad application

The findings of this study are specific to the operational characteristics of the investigated facility and the defined BAU scenario. Therefore, the estimated emission reduction should not be directly extrapolated to other facilities or urban waste systems, as emission performance may vary depending on waste characteristics, operational practices, transportation conditions, energy use, and the selected comparison scenario. However, the inventory-based methodology applied in this study may be transferable to other material recovery facilities. The framework can be adapted using site-specific activity data, relevant emission factors, and locally defined system boundaries to quantify operational GHG emissions under different conditions. Application of the framework in other locations would require context-specific assumptions and operational data. Differences in waste composition, infrastructure, collection systems, and facility characteristics should therefore be considered when interpreting or comparing results across locations. Accordingly, the methodology may support similar facility-level assessments, but the emission reduction estimated in this study should not be interpreted as directly scalable.

4. Conclusions

This study evaluated GHG emissions from a PET material recovery system in Depok City, Indonesia, using the IPCC Tier 2 approach and facility-specific operational data. The recovery system generated approximately 39.3 t CO_2e/year, compared with 363.54 t CO_2e/year under the defined BAU scenario. This corresponds to an estimated emission reduction of 324.24 t CO_2e/year, or approximately 89%, relative to the BAU scenario. Residual waste handling and transportation were identified as the main contributors to emissions within the recovery system, highlighting the importance of improving operational efficiency and reducing material losses.

The findings indicate that PET recovery can provide GHG mitigation benefits under the defined conditions. In addition to reducing emissions from waste disposal activities, material recovery supports circular resource use and strengthens environmental sustainability within rapidly urbanizing regions. The study provides a facility-level inventory framework that can support GHG monitoring and reporting in urban waste management. Integrating operational data on material throughput, electricity consumption, transportation, and residual waste into waste-sector inventories may improve the representation of local emission sources, particularly in developing countries where facility-level data remain limited.

The primary limitation of this study is the BAU assumption that the same quantity of PET processed by the facility would otherwise be subjected to open burning. Therefore, the estimated 89% emission reduction depends on this counterfactual assumption and should not be interpreted as a universal reduction rate. Future studies should incorporate sensitivity analysis, broader waste categories, and comparative assessments across multiple facilities and regions to improve the generalizability of the findings and support more comprehensive waste sector climate mitigation strategies.

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