

# How We Can Reduce Environmental Impacts through Recycling

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**Abstract** The widespread use of polyethylene terephthalate (PET) bottles presents significant environmental challenges. This study employs a cradle-to-grave Life Cycle Assessment (LCA), following ISO 14044:2006 guidelines, to evaluate the environmental impacts of three PET bottle recycling scenarios: 24%, 50%, and 86% recycling rates. Using a standardized 40-gram PET bottle as the functional unit, the study assesses key environmental impact categories, including water consumption, fossil resource scarcity, and global warming potential (GWP). The results indicate that increasing recycling rates significantly reduces environmental impacts, with the GWP decreasing from 0.12 kg CO<sub>2eq</sub> in the 24% recycling scenario to 0.0497 kg CO<sub>2eq</sub> in the 86% scenario. Water consumption is also reduced from 0.0139 m<sup>3</sup> to 0.0056 m<sup>3</sup>, while fossil resource scarcity decreases from 0.236 kg oil<sub>eq</sub> to 0.0952 kg oil<sub>eq</sub>. However, the land use category showed only a marginal reduction from 0.00252 m<sup>2</sup> crop<sub>eq</sub> to 0.00218 m<sup>2</sup> crop<sub>eq</sub>, indicating diminishing returns at higher recycling rates. Despite the benefits of recycling, this study emphasizes that reducing consumption should be the top priority in addressing PET-related environmental burdens. Minimizing unnecessary consumption and promoting sustainable production practices are critical to achieving long-term sustainability goals. These findings highlight the need for a

holistic waste management strategy that prioritizes reduction, followed by reuse and recycling, to effectively mitigate environmental impacts and support the transition to a circular economy.

**Keywords** PET Bottle, Plastic Waste, Life Cycle Assessment, Recycling

## 1. Introduction

Plastics have been a pervasive material in modern society since the 1960s, but they are difficult to biodegrade [1]. The management strategies for the recycling of plastics have turned obsolete, thereby fostering an increasing accumulation of plastic waste, such as Polyethylene terephthalate (PET). PET is a widely used polymer in the packaging industry, particularly for beverage bottles, due to its durability, hygiene, and cost-effectiveness. In 2021, an estimated 583 billion plastic beverage bottles were expected to be produced, with 62% using PET as the primary packaging material [2]. However, PET's resistance to decomposition poses significant environmental challenges. Improper disposal can lead to the release of toxins into soil and water [3],

while its degradation emits harmful substances, including microplastics [4], posing risks to ecosystems and human health [5].

Jakarta, as Indonesia's capital, generates a substantial volume of PET waste annually. According to Trisyanti et al. [6], approximately 257 PET bottles are discarded each year, contributing to 78% of the city's total beverage plastic waste. In Jakarta, only 24% of plastic waste from urban solid waste is recycled, leaving 76% unprocessed. Of this, 62% ends up in landfills, and 14% is directly released into the environment [7]. This highlights the urgent need to improve waste management systems. Recycling PET bottles is a promising solution, given the availability of advanced recycling technologies and the potential to support a circular economy by reducing raw material consumption and the environmental impacts associated with PET pellet production [2]. However, the recycling process itself generates environmental impacts, which necessitate a more nuanced evaluation.

Generally, life cycle assessment (LCA) of PET is focused on comparing different recycling types, which often attribute PET recycling to having lower global warming, energy, and water impacts when compared to virgin PET production. Mechanical recycling, the predominant method, involves processes such as sorting, baling, washing, grinding, compounding, and remelting PET waste into pellets. Each stage has its environmental footprint, from energy consumption to pollutant emissions [8]. While increasing the proportion of recycled PET waste can mitigate some environmental impacts, it does not guarantee a net reduction in overall impacts. Thus, a deeper investigation into recycling strategies and their environmental trade-offs is essential.

Numerous studies have applied LCA to assess the production and end-of-life processing of PET bottles [9,10,11,12], food packaging [13,14], and other plastic products [15,16]. However, most research published in reputable journals focused on developed countries or generalized recycling impacts, such as in Japan [9], China [10], England [11], while a study was conducted in Brazil [12]. Previous PET life cycle studies specifically on Indonesia assumed most of the downstream processes were together life-cycled with the collection process in MRF and recycling in the recycling facility. Few studies have comprehensively evaluated the environmental impacts of PET recycling in Indonesia [17,18], and do not extend the analysis until the end-of-life of PET bottles [19,20]. Research by Puspita et al. [20] highlights that plastic recycling processes can contribute to eutrophication and significant CO<sub>2</sub> emissions, leading to global warming. These findings underscore the importance of developing targeted recycling management strategies that minimize environmental impacts across all stages of the product lifecycle.

To address this gap, the present study employs a cradle-to-grave LCA to evaluate the environmental impacts of PET bottle recycling under three scenarios. By identifying the trade-offs and benefits associated with

each scenario, this research aims to inform sustainable waste management strategies and support Indonesia's transition toward a circular economy.

## 2. Materials and Methods

### 2.1. PET Bottle Manufacturer

This study utilized data from a plastic manufacturing facility in Jakarta, Indonesia. The object of analysis was a 500 ml PET bottle weighing 40 grams. While no official data quantifies the share of 500 ml PET bottles in Jakarta's total PET waste, this bottle size is among the most commonly sold and used in the city. The manufacturing process involved the conversion of plastic pellets into finished PET bottles using blow molding machines. As the weight of the pellets required for production equals the weight of the finished bottle, this weight served as the basis for the analysis.

We limited the scope of PET Bottle to the main materials Purified Terephthalic Acid (PTA) which is synthesized from p-xylene, a petrochemical derived from crude oil refining or natural gas processing. The production process begins with the refining of crude oil, where naphtha is extracted as a key fraction. This naphtha undergoes catalytic reforming, producing a mixture of Benzene, Toluene, and Xylene (BTX), from which p-xylene is separated as the primary feedstock for PTA production.

In the next stage, p-xylene is oxidized using air, a cobalt-manganese-bromine catalyst, and acetic acid to form crude terephthalic acid (CTA). However, CTA contains impurities that must be removed before it can be used in PET production. The final purification step involves hydrogenation, which eliminates these impurities, producing high-purity PTA. This purified form of terephthalic acid is then used as a key raw material in the production of polyethylene terephthalate (PET) bottles, fibers, and films, making it an essential component of the plastic industry.

A randomized stratified sampling method was used to capture variations in raw material composition, manufacturing processes, and production efficiency across different batches. This method ensured that the collected PET bottles represented a diverse yet consistent dataset, reducing the risk of bias and enabling accurate environmental impact calculations. Bottles were selected at predefined production intervals (e.g., every 1000 units produced) to maintain repeatability in data collection while accounting for potential fluctuations in material inputs and process efficiency. To enhance precision and accuracy, the study incorporated triplicate measurements of key parameters such as weight, material composition, and energy use in production. These measurements were conducted using calibrated instruments and cross-verified against manufacturer records to ensure reliability. The data are reported as averages for consistency.

Information on the materials and energy required for the

production of PET pellets, including energy consumption during the manufacturing process, was also obtained from peer-reviewed literature and the Ecoinvent database, a comprehensive source of lifecycle inventory data. Additionally, data on the flow of plastic waste materials, including recycling rates and waste distribution at the study location, were derived from existing studies and relevant literature.

This methodological approach ensures that all material and energy flows are accurately represented, providing a reliable foundation for the Life Cycle Assessment (LCA) to evaluate the environmental impacts of PET bottle recycling under different scenarios. The study's scope, aligned with the cradle-to-grave framework, includes raw material extraction, production, and end-of-life stages to comprehensively assess environmental trade-offs. This study employed Simapro 9.4.0.3 software integrated with the Ecoinvent database, enabling comprehensive modelling and analysis of complex life cycle processes.

## 2.2. Goal and Scope Definition

The preparation of the Life Cycle Assessment (LCA) began with defining the goal, scope, and key parameters of the study. This included specifying the functional unit, system boundaries, and assumptions relevant to the PET bottle life cycle. The functional unit, which serves as a standardized measure for quantifying system inputs and outputs, was defined as a single 500 mL PET bottle weighing 40 grams.

The system boundary for this study adhered to a cradle-to-grave framework, encompassing all stages from raw material production to end-of-life treatment. The analysis included the production process of PET pellets, the manufacturing of PET bottles, and various waste management scenarios.

The primary objective of this study was to evaluate the environmental impacts associated with three recycling scenarios for PET bottles, with increasing recycling rates of 24%, 50%, and 86%. By analyzing these scenarios, the study aimed to identify the environmental trade-offs and benefits of higher recycling percentages, providing insights to inform sustainable waste management strategies.

The quality of recycled PET (rPET) plays a crucial role in determining its viability for reuse in high-value applications such as food and beverage packaging. Mechanical recycling processes may result in contamination, polymer degradation, or discoloration, which can limit the usability of rPET in closed-loop recycling systems. To address this, international standards, such as EFSA (European Food Safety Authority) and FDA (U.S. Food and Drug Administration) regulations, set strict criteria for food-grade rPET, requiring that at least 99% of the recycled PET originates from food-contact-approved bottles and that the purification process effectively removes contaminants.

For the three recycling scenarios evaluated in this study, the impact of substandard recycled PET—which fails to meet food-grade standards—was considered. In cases where rPET fails quality testing, it is often downcycled into lower-value applications such as textiles, strapping, and construction materials. While this reduces waste accumulation, it does not fully close the material loop, meaning that some proportion of virgin PET is still required for beverage bottle production. This contributes to continued fossil fuel demand and associated environmental impacts, particularly in the global warming potential (GWP) and fossil resource depletion categories.

## 2.3. Inventory Analysis

The inventory analysis phase involved collecting and compiling data on raw materials and energy consumption for each process across the different recycling scenarios. Both primary and secondary data were utilized to ensure comprehensive analysis.

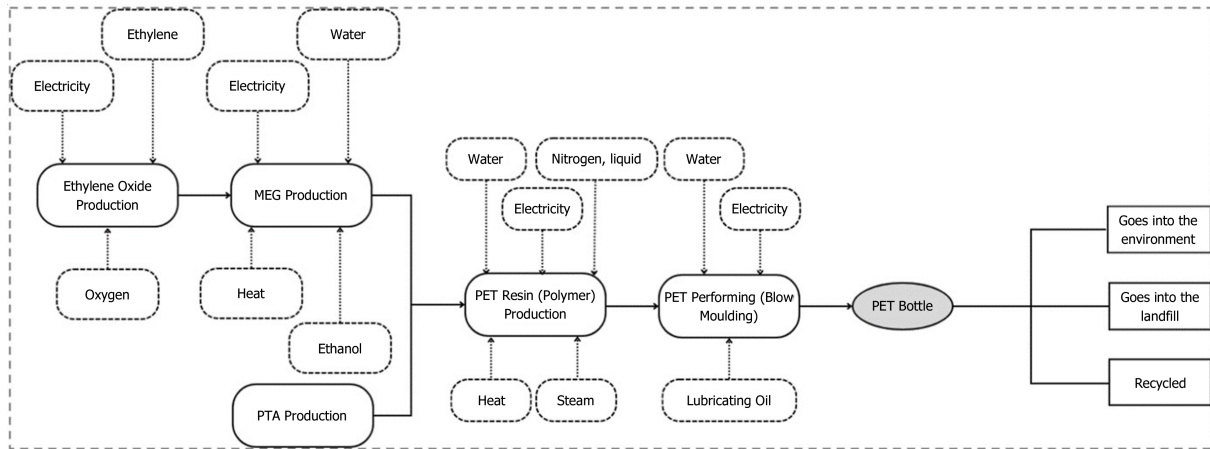
Primary data included the quantity of PET pellets required to produce a single PET bottle, the types of vehicles used for raw material procurement and distribution, and the mileage covered during production-related transportation activities. Secondary data encompassed information on the raw materials used for manufacturing PET pellets, chemicals involved in the production process, energy consumption, emissions, and waste generated. Material flow analysis data were also sourced from literature studies on similar processes.

The inventory data were systematically organized, with Figure 1 illustrating the flowchart of the PET bottle production process and Table 1 detailing the material inputs and outputs. The analysis leveraged Simapro 9.4.0.3 software, referencing data from Tamburini et al. [21], to quantify environmental impacts accurately across all stages of the PET bottle life cycle.

## 2.4. Impact Assessment

The impact assessment phase involved analyzing and categorizing the environmental effects of each PET bottle production process, as compiled during the inventory analysis, using Simapro 9.4.0.3 software. The ReCiPe 2016 Midpoint (H) methodology was applied, which evaluates environmental impacts across 18 categories. These categories represent midpoints in the cause-effect chain, enabling detailed assessment of specific impact contributors for each functional unit in the defined scenarios.

The environmental impacts were calculated by converting inventory inputs into corresponding impact units, ensuring consistency and comparability across scenarios. This approach allowed for a comprehensive evaluation of the environmental trade-offs associated with varying PET bottle recycling rates, providing valuable insights into the sustainability of each scenario.



**Figure 1.** System boundaries in the life cycle assessment (LCA) of the production of PET bottle in this study (MEG: Monoethylene Glycol, PTA: Purified Terephthalic Acid)

**Table 1.** Life cycle inventory (LCI) of data to produce a PET bottle (40 grams)

Input	Quantity	Unit	Unit Process @Simapro
<b>Synthesis of Ethylene Oxide</b>			
Electricity	0.00175	kWh	Electricity, medium voltage   APOS, RER
Ethylene	0.01580	kg	Ethylene, average   APOS, RER
Oxygen	0.00879	kg	Oxygen, liquid   APOS, RER
<b>Synthesis of MEG (Monoethylene Glycol)</b>			
Ethylene Oxide	0.01375	kg	-
Electricity	0.00745	kWh	Electricity, medium voltage   APOS, RER
Tap water	0.11804	kg	Tap water production, conventional with biological treatment   APOS, RER
<b>Synthesis of PTA (Purified Terephthalic Acid)</b>			
Purified Terephthalic Acid	0.01910	kg	Polyethylene terephthalate, granulate, amorphous   APOS, RER
<b>PET Resin Production</b>			
MEG	0.00668	kg	-
PTA	0.01662	kg	-
Electricity	0.01185	kWh	Electricity, medium voltage   APOS, RER
Heat	0.23894	MJ	Heat, district or industrial, natural gas   APOS, RER
<b>PET Bottle Production</b>			
PET Resin	0.01910	kg	-
Stretch Blow Moulding	0.01910	kg	Stretch blow moulding   APOS, RER

## 2.5. Interpretation

The interpretation stage followed the guidelines of ISO 14044:2006, focusing on evaluating the results of the Life Cycle Analysis (LCA) to address the study's initial objectives and limitations. This stage ensured that the findings aligned with the defined parameters and provided meaningful insights. Sensitivity analysis was conducted to assess the influence of input and output variations, as well

as the robustness of the chosen methodology, to address data uncertainties effectively.

The primary goal of this phase was to critically evaluate the LCA results, identify key environmental impacts, and draw evidence-based conclusions. These conclusions were intended to inform potential improvements in PET bottle production and recycling processes, contributing to more sustainable waste management strategies [20].

### 3. Results and Discussion

#### 3.1. LCA Result Discussion

A life cycle analysis (LCA) was conducted on the production and end-of-life treatment of PET plastic bottles, focusing on 500 mL single-use bottles. This sample size was selected as it represents the most commonly used PET bottle type in the market. The scenarios analyzed in this study were based on the waste distribution percentages reported by Putri et al. [7], assuming that the distribution of plastic waste—recycled, landfilled, and released into the environment—applies proportionally to PET bottles. Each scenario explored an increase in the recycling rate, with a corresponding decrease in the proportion of waste directed to landfills. The percentage of waste released into the environment was assumed constant across scenarios.

Given that PET bottle waste can take up to 450 years to decompose, the hypothesis posited that reducing landfill accumulation through increased recycling would lower the environmental impacts of the PET bottle life cycle. The results of the LCA confirmed that different recycling rates resulted in varying levels of environmental impact. An increase in recycling rates correlated with a measurable reduction in environmental impacts across multiple categories.

The analysis of the environmental impacts presented in Table 2 highlights the substantial benefits of increased recycling rates in mitigating the adverse effects associated with PET bottle production. Key improvements are observed across various environmental categories, such as water consumption, fossil resource scarcity, and global warming potential (GWP). For instance, GWP is significantly reduced from 0.12 kg CO<sub>2</sub> eq in R-24 to 0.0497 kg CO<sub>2</sub> eq in R-86, underscoring the potential of recycled PET (rPET) to lower carbon emissions and energy demand compared to virgin PET production. Similarly, reductions in human carcinogenic toxicity and ecotoxicity (marine and fresh-water) reflect the environmental advantages of diverting waste from landfills and reducing virgin material extraction [22]. However, persistent burdens, such as marine eutrophication and ionizing radiation, remain even with high recycling rates, highlighting the need for further innovations in recycling technologies and energy systems. Decarbonizing energy grids and adopting advanced chemical recycling methods could address these challenges while improving material recovery [23]. Additionally, systemic interventions such as Extended Producer Responsibility (EPR) schemes, consumer awareness programs, and sustainable bottle designs free from unnecessary additives are essential for

optimizing sustainability outcomes [24]. These findings emphasize the importance of integrating recycling improvements with broader waste management strategies to transition toward a circular economy and align with global sustainability goals, including the Sustainable Development Goals (SDGs).

The initial scenario of this study estimates the GWP for the production and end-of-life management of a single PET bottle at 0.12 kg CO<sub>2</sub> eq, slightly lower than the 0.134 kg CO<sub>2</sub> eq reported by Tamburini et al. [21]. This variation can be attributed to differences in system boundaries, energy sources, and site-specific conditions. Similarly, the land use impact of 2.52 m<sup>2</sup>crop eq per bottle in this study exceeds the 2.01 m<sup>2</sup> reported in Tamburini et al.'s analysis, highlighting potential discrepancies arising from regional agricultural practices and input data variability. These findings underline the importance of contextualizing results within the framework of local conditions and the methodologies employed.

Moreover, as recycling rates increase (e.g., R-86), substantial reductions are observed in key impact categories, such as water consumption and fossil resource scarcity. For instance, water consumption drops from 0.0139 m<sup>3</sup> in R-24 to 0.0056 m<sup>3</sup> in R-86, reflecting the lower resource intensity of recycled PET. Fossil resource scarcity similarly decreases, with R-86 showing a reduction of nearly 60% compared to R-24. These improvements align with findings from prior studies emphasizing the environmental benefits of using recycled PET over virgin PET [25]. However, discrepancies across studies, such as the land use impacts mentioned above, highlight the importance of harmonizing LCA methodologies to enable more consistent and comparable results.

The results in Table 2 demonstrate a clear trend: as the recycling percentage increases, the environmental impact decreases across most categories. The first scenario, with a 24% recycling rate, exhibited the highest environmental impacts. In the second scenario, where recycling increased to 50%, a noticeable reduction in impacts was observed. The third scenario, achieving an 86% recycling rate and eliminating landfill waste, showed the lowest environmental impact among all scenarios.

These findings indicate that increasing recycling rates at the end-of-life stage of PET bottles can substantially reduce the environmental impacts of their life cycle. However, not all impact categories showed significant reductions, suggesting that higher recycling rates alone may not fully mitigate environmental burdens. Figure 2 illustrates the percentage reduction in impacts for each category, providing a clearer view of the benefits and limitations of increased recycling.

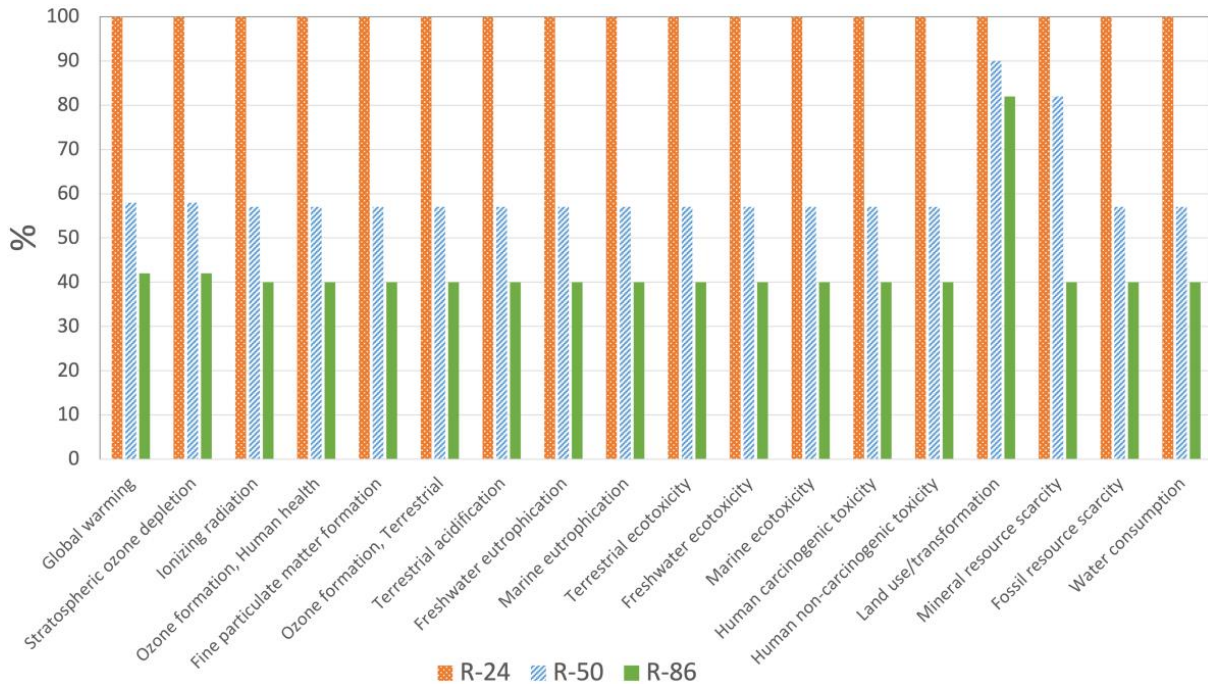
**Table 2.** LCA of the production of one bottle of PET (40 grams)

Impact Categories	Unit	R-24	R-50	R-86
Water Consumption	m <sup>3</sup>	0.0139	0.0079	0.0056
Fossil Resource Scarcity	kg oil <sub>eq</sub>	0.236	0.134	0.0952
Mineral Resource Scarcity	kg Cu <sub>eq</sub>	1.77 · 10 <sup>-6</sup>	1.01 · 10 <sup>-6</sup>	0.715 · 10 <sup>-7</sup>
Land Use	m <sup>2</sup> a crop <sub>eq</sub>	0.00252	0.00228	0.00218
Human non-carcinogenic toxicity	kg 1,4-DCB <sup>a</sup>	0.054	0.0308	0.0219
Human carcinogenic toxicity	kg 1,4-DCB	8.1	4.62	3.28
Marine Ecotoxicity	kg 1,4-DCB	1.43	0.818	0.58
Freshwater Ecotoxicity	kg 1,4-DCB	1.81	1.03	0.733
Terrestrial Ecotoxicity	kg 1,4-DCB	0.0367	0.0209	0.0148
Marine Eutrophication	kg N <sub>eq</sub>	0.0222	0.0127	0.009
Freshwater Eutrophication	kg P <sub>eq</sub>	2.59	1.48	1.05
Terrestrial Acidification	kg SO <sub>2eq</sub>	0.0774	0.0442	0.0314
Ozone Formation, Terrestrial Ecosystem	kg NO <sub>xeq</sub>	0.14	0.0801	0.0569
Fine Particulate Matter Formation	kg PM <sub>2.5eq</sub>	0.832	0.475	0.337
Ozone Formation, Human Health	kg NO <sub>xeq</sub>	0.12	0.0688	0.0489
Ionizing Radiation	kBq Co-60 <sub>eq</sub> <sup>b</sup>	0.00546	0.00311	0.00221
Stratospheric Ozone Depletion	kg CFC-11 <sub>eq</sub> <sup>c</sup>	0.00404	0.00233	0.00167
Global Warming	kg CO <sub>2eq</sub>	0.12	0.0692	0.0497

**Note:** <sup>a</sup> 1,4-DB : 1,4 dichlorobenzene

<sup>b</sup> Co-60 : Cobalt 60

<sup>c</sup> CFC-11 : Trichlorofluoromethane



**Figure 2.** Life-cycle impacts of production process of a PET bottle

Figure 2 illustrates the changes in environmental impacts across various categories for each recycling scenario, expressed as percentages. Scenario one (R-24), representing a recycling rate of 24%, exhibits the highest environmental impact and is set as the baseline with 100% impact across all categories. As recycling increases to 50% (R-50) in the second scenario, most categories experience a substantial reduction in environmental impacts, averaging a 40% decrease from the initial scenario. An exception is the land use category, which sees only a 10% reduction.

Further improvements are observed in the third scenario (R-86), where the recycling rate reaches 86%. This scenario reduces the environmental impacts of most categories by an additional 20% compared to the second scenario, achieving a 60% reduction overall from the first scenario. However, the land use category again shows the smallest decrease, with a 15% reduction from the first scenario and only a 5% reduction from the second scenario. These results indicate that while increased recycling rates significantly reduce environmental impacts, the reductions are not uniformly distributed across all impact categories.

Increasing the recycling rate of PET bottles derived from crude oil and petroleum-based feedstocks presents clear environmental benefits by reducing virgin plastic demand, lowering greenhouse gas (GHG) emissions, and conserving fossil fuel resources. Higher recycling rates enhance material reuse through mechanical and chemical recycling, while also enabling energy recovery through incineration in some cases. However, while this study has demonstrated a general trend of decreasing environmental impacts with higher recycling rates, the assumption that all categories will continue to show consistent reductions requires further scrutiny.

One key challenge is the uncertainty in environmental impact assessments (EIA) at higher recycling rates, particularly regarding diminishing returns in specific categories. For example, while scenarios with increased PET recycling exhibit notable reductions in water consumption, fossil resource scarcity, and GWP, the study found minimal improvements in land use efficiency and certain toxicity categories at the highest recycling rate (R-86). These diminishing returns indicate that simply increasing recycling rates does not always guarantee proportional environmental benefits, as certain trade-offs, such as the energy intensity of recycling operations, processing inefficiencies, and contamination-related downcycling, introduce complexities that must be accounted for.

Furthermore, uncertainties arise due to varying recycling process efficiencies and differences in waste collection systems across regions. While some studies suggest that higher recycling rates generally lead to lower emissions and waste accumulation, others highlight that the quality of recycled PET (rPET) and the fate of non-recyclable fractions significantly affect overall environmental outcomes. This aligns with findings that substandard rPET often cannot be used in closed-loop systems (e.g., beverage

bottles) and is instead downcycled into lower-value applications such as textiles or construction materials, which extends its lifespan but does not entirely replace virgin PET. Moreover, if recycling processes require additional energy input for sorting, washing, and reprocessing, the net benefit may be lower than expected, especially in regions where energy grids are heavily reliant on fossil fuels.

To refine these assessments, future research should incorporate experimental validation and scenario-based modeling to assess threshold points at which increased recycling rates lead to diminishing or even adverse environmental outcomes. This could include sensitivity analyses on energy intensity, material degradation, and contamination rates, as well as an exploration of policy mechanisms—such as Extended Producer Responsibility (EPR) and minimum recycled content mandates—to ensure that higher recycling rates translate into real environmental gains. By addressing these limitations, this study can provide a more nuanced and data-driven discussion on the complexities of PET recycling's environmental impact.

### 3.2. Comparing Jakarta's PET Bottle Recycling with Other Cities/Countries

Research shows that the environmental impacts associated with PET bottle recycling are significantly lower when collection rates are high. For instance, post-consumer recycling activities can lead to substantial reductions in energy use and emissions compared to producing virgin materials. However, this benefit is contingent upon effective logistics and collection systems that ensure high recovery rates.

Jakarta's PET bottle recycling rate remains relatively low compared to cities with well-developed waste management systems. In Europe, many countries have successfully implemented container-deposit schemes, significantly increasing PET bottle recycling rates. Norway, for example, has achieved over 90% recycling efficiency through a well-managed deposit-return system [26]. Similarly, Germany leads with a 97% recycling rate, supported by a deposit-refund system that incentivizes consumer participation [27].

Beyond Europe, Japan has also established an effective PET recycling system, reaching 85% in 2023, thanks to strict government-mandated sorting regulations, efficient collection systems, and strong public participation [28]. However, it is important to note that Japan's recycling statistics include incineration with energy recovery, a practice that remains controversial as it does not fully align with circular economy principles [29].

In contrast, the United States lags behind with a PET bottle recycling rate of only 33%, primarily due to state-level variations in collection policies and the absence of a nationwide recycling mandate [30,31]. This inconsistency results in higher landfilling rates and

increased plastic leakage into the environment, underscoring the need for federal-level standardization to improve recycling efficiency.

PET recycling in Indonesia remains underdeveloped, with a national recycling rate of 24%, far below the targets set under its National Plastic Action Plan [32]. Unlike developed nations that rely on formal collection systems, Indonesia's PET recycling is largely dependent on the informal sector, where waste pickers and small-scale aggregators collect and sell PET waste. The absence of formalized collection programs and deposit schemes has led to inefficient waste recovery and high plastic leakage into rivers and oceans.

A comparative Life Cycle Assessment (LCA) of plastic waste treatment in India and Indonesia found that Indonesia's environmental impact per kilogram of plastic waste is higher than India's, primarily due to lower mechanical recycling rates and higher reliance on open burning [31]. The carbon footprint of PET waste management in Indonesia is significantly larger, exacerbating climate change concerns. Meanwhile, India's higher PET recycling rate (nearly 90%) results from a more active informal sector and mechanical recycling processes, reducing environmental burdens compared to Indonesia. The country's capital generates the highest volume of PET waste but lacks a centralized recycling strategy. An estimated 2000 tons of plastic waste leaks into the ocean annually, making it a major contributor to marine pollution [32]. The introduction of Extended Producer Responsibility (EPR) policies aims to improve collection and recycling rates, but enforcement remains a challenge. Compared to Jakarta, Makassar has a slightly higher formal waste collection efficiency, contributing to a 17% PET recycling rate [31]. However, infrastructure limitations and low public awareness hinder large-scale recycling adoption. While other cities in Indonesia have active waste bank programs, PET recycling data is scarce. Community-driven waste management initiatives have shown promising results, but their scalability remains uncertain.

### 3.3. Overall Interpretation of the LCA

Jakarta's recycling rate of PET bottles is approximately 24%, reflecting gaps in collection efficiency, consumer awareness, and infrastructure. By adopting best practices from high-recycling cities, Jakarta could improve its waste management system, significantly reducing environmental impacts. If Jakarta (with 257 tons of PET bottle waste) adopts similar measures and increases its recycling rate from 24% to 86%, the city could save approximately 451,095 kg of CO<sub>2</sub> emissions annually, equivalent to removing over 95,000 cars from the road for a day. Additionally, 53,317 m<sup>3</sup> of water could be conserved, reducing stress on local water resources, while fossil resource consumption would decrease by 904,610 kg oil equivalents annually, reducing dependency on virgin

plastics.

Interestingly, the second scenario (recycling rate at 50%) appears to be more effective in achieving substantial impact reductions relative to the first scenario, reducing nearly half of the baseline impacts in most categories. In contrast, the additional reduction achieved by the third scenario, while notable, is comparatively less significant. This suggests diminishing returns in environmental benefits as recycling rates approach higher levels. One notable observation is in the land use category, where improvements are minimal across all scenarios. This is likely due to the persistent percentage of plastic waste that escapes into the environment and the additional land required for recycling facilities, even as landfill usage declines to zero [33,34]. While increasing PET recycling rates significantly reduces fossil fuel consumption, carbon emissions, and resource depletion, its impact on land use remains marginal. This is primarily due to the nature of PET production and waste management systems. Unlike materials derived from agriculture, such as bioplastics or paper-based packaging, PET is produced from fossil fuels, which require minimal land area for extraction and processing. Increasing PET recycling rates directly reduces the need for virgin plastic production, leading to significant energy savings and emission reductions. Studies show that recycling PET consumes up to 79% less energy than producing virgin PET, directly lowering carbon emissions from both feedstock extraction and plastic manufacturing [35]. However, because this process takes place in industrial zones with optimized land use, the reduction in fossil fuel consumption does not translate into significant land savings. Moreover, some PET waste remains non-recyclable due to contamination or degradation, maintaining a level of landfill dependency. Additionally, expanding recycling operations requires more sorting and processing facilities, offsetting potential land savings. Even at high recycling levels, a portion of virgin PET is still needed to maintain material quality, preventing significant reductions in upstream land use. Such findings indicate that while recycling is crucial, it does not fully mitigate other environmental impacts associated with PET waste management.

These findings emphasize the need for balanced waste management strategies that optimize recycling while addressing other environmental impact contributors, such as land use and waste released into the environment. Recently, public awareness of the severe threat that plastic waste poses to aquatic and terrestrial ecosystems has brought about an urgent request for more efficient plastic waste management [36]. However, a significant part of plastic debris cannot be tackled by the current recycling strategies, perpetrating the wrong habit to include waste in the traditional collection system. Equivalent concerns have been also expressed by the recyclers as standardized technologies are able to treat clean plastic waste only. Hence, in almost all EU countries, separate collection has been introduced to ensure the sustainable recycling of

post-consumer plastic packaging [37]. However, not all plastics are actually recyclable [38], [39]. There are few doubts about the need to optimize and reinforce the current recycling processes; however, the economics, energy requirements and the complete recyclability of this approach are argued over. This is because all the recycling processes have a low efficiency, and also a high CO<sub>2</sub> footprint [40]. There are a huge number of different streams of plastic waste, including commingled or mixed materials, which make the recycling process overly complex [41,42].

Optimizing waste collection and sorting systems is one approach, as improved efficiency in collecting and processing PET bottles reduces the need for landfill space. AI-driven robotic sorting technologies enhance material recovery rates and limit the footprint of waste handling facilities, while localized collection networks prevent the expansion of centralized sorting centers. Additionally, deposit-return schemes (DRS), similar to those in Germany, encourage bottle returns directly to processing facilities, further reducing landfill dependency. Another key strategy involves improving land use efficiency in recycling infrastructure by adopting high-density recycling hubs that integrate sorting, washing, and pelletizing operations within a single facility. Vertical recycling plants, which utilize multi-story designs, can also limit the land required for processing, particularly in urban areas where space is scarce. Moreover, repurposing underutilized industrial sites for PET recycling facilities can prevent the need for land expansion while promoting sustainable urban development.

Furthermore, there is a wide debate in both the scientific community and among the politicians on how to efficiently combat the presence and the accumulation of plastic waste. On one side, it is argued to limit the use of certain type of single-use plastic materials, and in general, to replace plastic with biodegradable polymers, paper or glass items. It is thought that this approach will ultimately reduce plastic production and its disposal in the environment as waste. Yet, since plastic is difficult to degrade, and other materials will consume energy and release CO<sub>2</sub> during disposal, alternative materials will not necessarily have a positive impact on the environment. Plastic production has sharply increased over the last 70 years. In 1950, the world produced just two million tonnes. It now produces 400.3 million tonnes in 2022 [43].

The concept of 3R (Reduce, Reuse, Recycle) plays a crucial role in sustainable environmental management, with reduction being the top priority over reuse and recycling [44], [45]. Prioritizing reduction is essential as it focuses on preventing waste generation at its source, thereby minimizing the environmental impact associated with overconsumption and resource depletion. In the era of mass consumption, individuals and industries often engage in excessive consumption, leading to unnecessary material waste and increased environmental burdens [46]. By emphasizing reduction, it is possible to curb unnecessary

consumption, promote resource efficiency, and reduce material wastage [47]. Unlike reuse and recycling, which require additional energy and resources for processing and repurposing, reduction directly addresses the root cause of waste, leading to long-term sustainability. Implementing reduction strategies involves conscious efforts such as adopting minimalistic lifestyles, choosing durable and eco-friendly products, and optimizing production processes to minimize resource inputs. Ultimately, prioritizing reduction in the 3R hierarchy is critical for achieving a sustainable future by conserving natural resources, lowering carbon footprints, and fostering responsible consumption patterns.

It is also important to enhance the recycling technologies such as mechanical and/or chemical recycling. Traditional mechanical recycling involves collecting, sorting, cleaning, and reprocessing PET waste into new products. However, this method often results in lower-quality plastics due to polymer degradation during processing. Recent innovations aim to enhance the efficiency and output quality of mechanical recycling. For instance, advanced sorting technologies, such as high-speed laser spectroscopy, have been developed to improve the purity of recycled PET, making it suitable for food-grade applications. Chemical recycling presents an alternative by breaking down PET polymers into their monomers, which can be repolymerized into virgin-quality PET. This process addresses the limitations of mechanical recycling by enabling the treatment of contaminated or lower-quality plastics.

Indonesia has recognized the urgent need to improve its PET recycling infrastructure and has introduced several policy initiatives to enhance plastic waste management. As part of its commitment to reducing marine plastic pollution, the government launched the 2025 National Plastic Waste Reduction Roadmap, which aims to cut plastic waste leakage into the ocean by 70%. This roadmap outlines a multi-faceted strategy, including measures to reduce plastic consumption, redesign packaging for recyclability, and strengthen waste collection and recycling systems. One of the core strategies of the roadmap is to achieve a 30% reduction in plastic waste generation by encouraging reusable products and consumer awareness campaigns. Additionally, it targets a 70% improvement in waste management, focusing on upgrading collection infrastructure and expanding municipal and private-sector collaboration in recycling efforts.

Another significant policy development is the implementation of Extended Producer Responsibility (EPR) regulations, which aim to shift the responsibility of plastic waste management to producers. Under these regulations, companies are required to design and implement product take-back schemes, use more recycled materials in their packaging, and finance the collection and recycling of their plastic waste. The Consumer Goods Forum's Plastic Waste Coalition has been actively collaborating with businesses and policymakers to assess the feasibility of EPR adoption

in Indonesia and align it with global best practices. The Indonesian government has also introduced regulatory frameworks requiring businesses to submit waste reduction plans and meet specific recycling targets, ensuring that producers play a direct role in waste management solutions [48].

## 4. Conclusions

This study demonstrates that while increasing PET bottle recycling rates reduces environmental impacts, the benefits do not always scale proportionally, and process efficiency plays a crucial role. The findings indicate that higher recycling rates lead to significant reductions in global warming potential (GWP), fossil resource depletion, and water consumption. However, the study also highlights that certain environmental trade-offs emerge at higher recycling rates, such as increased energy consumption in processing and potential downcycling inefficiencies.

It is evident that increasing recycling rates significantly reduces the environmental impacts associated with PET bottle production and end-of-life management. The findings demonstrate a clear trend where higher recycling percentages lead to notable reductions in key impact categories such as water consumption and fossil resource scarcity. However, the results also highlight that these reductions are not uniformly distributed across all impact categories, with land use impacts showing relatively minor improvements despite higher recycling rates. This suggests that while recycling is an essential strategy for mitigating environmental burdens, it alone may not fully address the broader sustainability challenges posed by PET waste management. The diminishing returns observed at higher recycling rates emphasize the need for a balanced approach that combines recycling with other waste management strategies, such as waste prevention and reduction initiatives. Furthermore, by combining technological advancements in recycling with comprehensive policy frameworks, Indonesia has the potential to transform its PET waste management system and move towards a more sustainable, circular economy. However, achieving this requires continuous innovation, stronger regulatory enforcement, and greater collaboration between government, industry, and local waste collectors. Future research should focus on scaling up chemical recycling processes, assessing the economic feasibility of EPR schemes, and developing a standardized PET collection system that can be efficiently integrated into Indonesia's broader waste management strategy.

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