

Article

Transitioning Plastic Packaging Waste Management in Laos: Circular Solutions and Environmental Implications

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Abstract

Plastic packaging waste is an escalating environmental concern for Laos. The lack of an adequate waste management system and reliable data pose significant challenges for making informed decisions about future waste management and understanding the associated environmental impacts. This study addresses the data gap by estimating plastic packaging flows using United Nations international trade data (UN Comtrade) and a scenario-based emission model to further evaluate the environmental implications of alternative plastic packaging waste management pathways in Laos. Four case scenarios are modelled: S1 Business as Usual, S2 Ban on Open Burning and Open Dumping, S3 National Plastic Action Plan 2030, and S4 Mandatory Extended Producer Responsibility. The results show that S4 delivers the most favourable environmental performance by reducing emissions associated with a high recycling rate that replaces virgin plastic production, accounting for up to 63% lower emissions compared to S1. However, even under the most ambitious scenario S4, over 60% of waste is still landfilled, indicating that moving beyond end-of-pipe waste management is necessary. The findings highlight the need for an integrated policy package, in which mandatory extended producer responsibility acts as an enabling mechanism, alongside demand reduction, eco-design, targeted investment, and circular economy strategies, to reduce mismanaged plastic packaging waste and support long-term sustainability.

Keywords: plastic packaging waste; recycling; circular strategies; extended producer responsibility; Laos



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1. Introduction

Since the 1950s, global plastic production has grown exponentially, rising from approximately 2 million tonnes (Mt) to 438 Mt per year in 2017, with projections to surge to 1100 Mt by 2050 [1]. Plastic has become an essential material across diverse sectors, including packaging, infrastructure, automotive, electrical and electronics, agriculture and other industries, due to its lightweight, durable and versatile properties. Among various applications, plastic packaging holds the largest share, accounting for 44% of global plastic resin consumption in 2021. In the same year, China was the most prominent plastic producer, accounting for 32% of global production, followed by North America (18%), the EU 27 + 3 countries (15%), and the rest of Asia (17%) [2]. Accumulatively, approximately 9.2 billion tonnes of plastic have been produced since 1950, generating about 6.9 billion tonnes of plastic waste [1]. The volume of mismanaged plastic waste is increasing at an

alarming rate, rising from an estimated 60–99 Mt in 2015 and projected to reach 155–265 Mt annually by 2050 under the business-as-usual scenario [3]. Despite the rapid growth, about 39% was landfilled, 24% was incinerated through a formal system, about 22% was recycled, and the remaining 15% was mismanaged in 2020, potentially contributing to environmental leakage [4].

Plastic leakage into the aquatic environment has become a global environmental concern. It is estimated that between 4.8 and 12.7 Mt of plastic entered the ocean in 2010 [5], while about 19–23 Mt of plastics leaked annually into rivers, lakes, and oceans [6]. Meijer et al. 2021 [7] further refine these findings by identifying more than 1000 rivers responsible for 80% of global riverine plastic emissions, many of which are located in the Association of Southeast Asian Nations (ASEAN) countries. As a result, six out of ten ASEAN Member States (AMS), namely Indonesia, Malaysia, Myanmar, the Philippines, Thailand and Vietnam, have been consistently ranked among the top 10 sources of marine plastic pollution [5–7]. Furthermore, it is expected that the annual plastic leakage from ASEAN + 3 (10 AMS plus China, Japan and South Korea) region is expected to double from 3.5 Mt in 2022 to 7.1 Mt by 2050 if no significant interventions are made [8]. Despite the rapid growth, the waste management system (WMS) in most AMS remains in the early and transitional development stage, characterized by inadequate infrastructures, minimal waste-to-energy (WtE) capacity and a limited number of sanitary landfills and collection services, with a significant reliance on the informal sector for recycling [9].

Furthermore, the situation has worsened due to the global shift in the plastic waste trade following China's Green Fence policy and the subsequent import ban implemented in January 2018 [10,11]. ASEAN countries experienced a 233% increase from around 590 kt in 2016 to nearly 1.97 Mt in 2019, overwhelming local waste management capacities [12]. This unexpected surge in plastic waste imports over a short period placed immense pressure on ASEAN, and in response to these challenges, some AMS, namely Thailand, Malaysia, and Vietnam, implemented their own bans in response to China's restrictions [11]. To combat the plastic pollution and reaffirm their commitment to addressing plastic waste, ASEAN issued several guiding documents, such as the Bangkok Declaration on Combating Marine Debris in the ASEAN Region [13], the ASEAN Framework of Action on Marine Debris [14], the ASEAN Regional Action Plan for Combating Marine Debris in the ASEAN Member States (2021–2025) [15], and the ASEAN Declaration on Plastic Circularity [16]. The European Union's Plastic Strategy under its Circular Economy Action Plan [17,18] serves as a model for many regions globally, including ASEAN, focusing on the plastic life cycle interventions such as eco-design, recycled content mandates, and Extended Producer Responsibility (EPR) to transition and shift from a linear to a circular system. EPR plays an essential role in holding producers accountable for post-consumer waste and incentivising improvements in collection and recycling. While several ASEAN countries, such as Indonesia, the Philippines, Singapore, and Vietnam [19], are increasingly adopting similar approaches, Laos remains at an early stage of development [20], and a voluntary EPR framework was only recently outlined in its National Plastic Action Plan (NPAP) [21].

In recent years, waste management issues in Laos have increasingly become the national development priority and are attracting the attention of international donors and development partners. However, the availability of consistent and comprehensive data, particularly on plastic consumption and plastic waste flows, remains limited. This data gap poses a significant challenge to effectively formulate policy aligned with the waste hierarchy and circular economy principles.

Therefore, this study aims to estimate plastic packaging flows in Laos using United Nations International Trade Data (UN Comtrade) and to evaluate their environmental implications under four waste management scenarios. A scenario-based emission model

focusing on global warming potential is applied to compare alternative policy and treatment pathways. The results provide quantitative insights to support strategic policy planning and offer a replicable methodological framework for data-scarce contexts facing similar challenges in plastic packaging waste management.

2. Materials and Methods

The methodological approach for this study consisted of three main components. First, overall plastic flows in Laos were estimated using UN Comtrade to provide an overview of current consumption, which was then compared with national reports and secondary sources. Second, plastic packaging was selected as the focus for further analysis, in which packaging waste generation was estimated and categorized by polymer type to develop the model input. Lastly, a scenario-based emission model was applied to evaluate the environmental impacts of different waste management scenarios. A sensitivity analysis was conducted to address data limitations and uncertainty. Detailed procedures are described in the following subsections.

2.1. Municipal Waste and Plastic Waste Management in Laos

Municipal Solid Waste (MSW) and plastic waste management data in Laos are characterized by high variability and limited reliability. Reported figures differ widely between city-level surveys and national-level estimates, particularly regarding the per capita plastic waste generation rate and the estimated plastic share of MSW.

Figure 1 provides an overview of waste composition in Vientiane and at the national level, compiled from multiple data sources. At the national level, organic waste accounts for the largest fraction of MSW, at 52%, followed by plastic at 16%, paper and cardboard at 7%, glass at 4%, metal at 4%, textiles at 2%, and other materials at 15%.

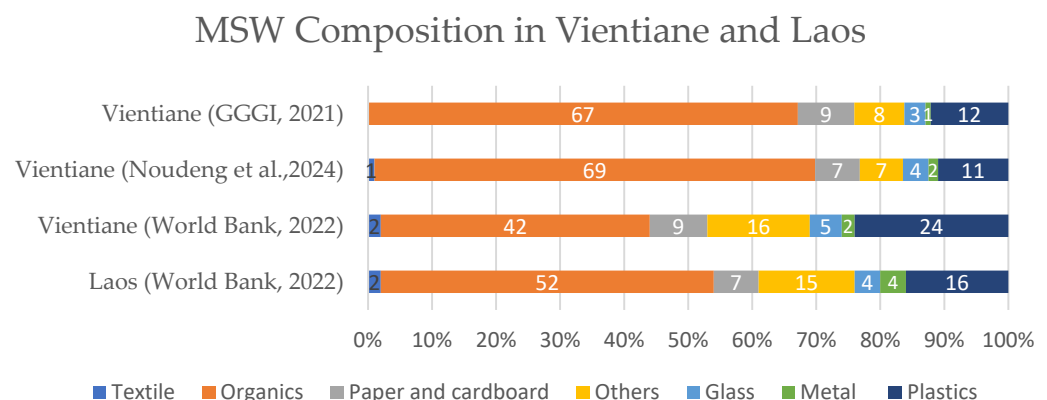


Figure 1. Waste composition in Vientiane and Laos [22–24].

In 2020, around 910,000 tonnes of MSW were generated in Laos, equivalent to 124 kg per capita per year, with projections indicating an increase to 1.4 million tonnes by 2035 [25]. In Laos, 95% of riverine plastic pollution comes from 10 single-use plastic (SUP) items, such as plastic bottles, caps, lids, shopping bags, other bags, food containers, straws, etc. [22].

According to a World Bank study of six cities in Laos, about 45% of plastic waste comes from food and drink packaging, 41% from household products, 8% from other packaging, 3% from personal care products, and 4% from fishing gear. The survey identifies PET, HDPE, and LDPE as the most prevalent forms of plastic polymers [22]. In 2019, around 40% of MSW was collected from households in Vientiane. Of this, 38.4% was sent to landfills, while 5% was diverted by waste pickers. Furthermore, 54% was subjected to improper disposal methods, including open dumping, open burning, and disposal into rivers, and 5.75% was recycled on site by recycling companies through the collection,

purchase, and sale of recyclable waste [23]. Furthermore, it was noted that approximately 37 informal dumpsites exist in Vientiane, and an additional 112 informal dumpsites are located across the five major cities in Laos [22,26].

The recycling sector in Laos is at an early stage of development stage, characterized by a significant presence of informal activities alongside a limited number of formal recycling enterprises. While formal recycling industries exist for several materials, including plastic, steel, glass, copper, and aluminium, the plastic recycling sector remains relatively small and geographically concentrated. It comprises approximately 6 collection and compacting centres, nine crushing facilities, and five recycling plants producing pellets and granules, primarily located in Vientiane and other urban cities, such as Pakse and Vangvieng [22].

Table 1 summarizes five representative sources of MSW and plastic waste generation at both the city and national levels in Laos. Across the literature, reported plastic waste generation in Laos ranges from 12 to 38 kg/cap/year, with Vientiane showing higher estimates, ranging from 36 to 63 kg/cap/year.

Figure 2 compares reported per capita plastic waste generation across ASEAN countries. The regional average is estimated at 31.8 kg/cap/year, with values ranging from 6 kg/cap/year in Myanmar to 87 kg/cap/year in Singapore, reflecting substantial differences in income levels, consumption patterns and data sources. In the Earth Action study [27], Laos is reported to generate approximately 12 kg/cap/year of plastic waste at the national level. This value differs from several national and city-level reports within Laos, which indicate higher per capita figures, particularly for urban areas such as Vientiane.

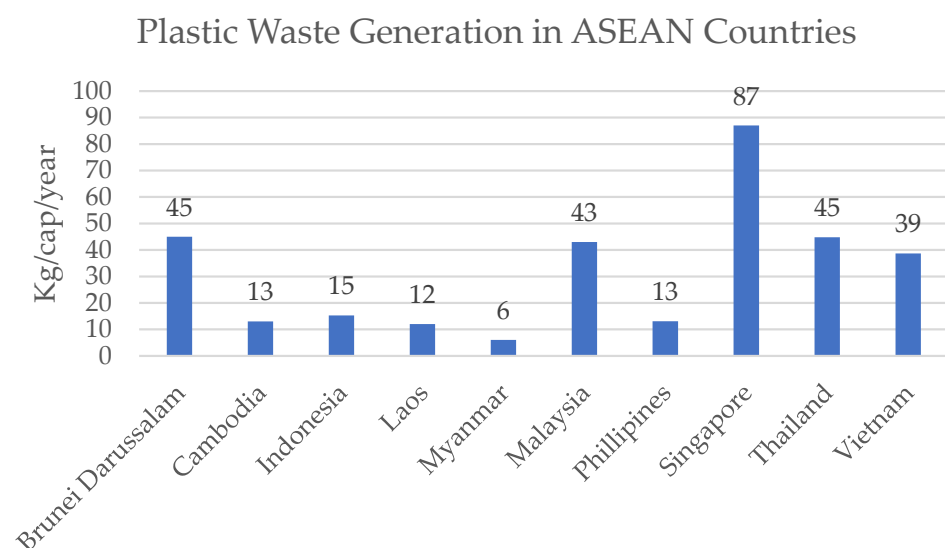


Figure 2. Overview of plastic waste generation in ASEAN countries [27–31].

This variability illustrates the challenges of relying on per capita plastic waste data in data-scarce contexts. It highlights the importance of using alternative approaches, such as trade-based material flow analysis. To reflect uncertainty in reported per capita plastic waste generation, this study adopts 20 kg/cap/year as the lower bound and 38 kg/cap/year as the upper-bound estimate for national-level modelling. These national-level values are used to cross-check the apparent plastic consumption estimates derived from the UN Comtrade data and to form the basis of a sensitivity analysis to assess the uncertainty and robustness of the plastic flow and environmental impact results.

Table 1. Overview of varied MSW and plastic waste generation rates at the city and national levels in Laos.

Level	Year	Population	Total MSW Generation (t/Year)	MSW Waste Generation Rate (kg/cap/Year)	Plastic Waste Composition (%)	Plastic Waste Generation Rate (kg/cap/Year)	Estimated Annual Plastic Waste (t/Year)	Sources	Remark
National	2020	7,346,533	910,000	124	16	20	145,600	World Bank, 2021 [25]	Overall waste report
National	2018	7,128,045	1,691,129	237	16	38	270,581	GGGI, 2018 [32]	Based on 0.65 kg/cap/day
National	2024	7,664,993	-	-	-	12	91,980	Earth Action, 2024 [27]	Based on the Plasteax modelling approach, plastic waste generation is 12 kg/cap/year
Vientiane	2020	683,000	354,050	518	12	63	42,840	GGGI & VCOMs, 2021 [24]	Based on 970 tons/day; 31% collection rate
Vientiane	2018	665,000	219,000	329	12	36	24,090	GGGI, 2018 [32]	Overall waste report

2.2. Plastic and Plastic Packaging Material Flows

Overview of the Approach

Plastic flows were quantified using a trade-based approach based on the UN Comtrade data. Apparent consumption was first estimated at the product group level to establish an overview of national plastic flows and subsequently disaggregated by polymer type. Based on this overview, plastic packaging was selected for detailed analysis. The individual calculation steps are presented in the following sections.

Step 1: Data source

Import and export data were obtained from UN Comtrade, an official, comprehensive international trade statistics database maintained by the United Nations Statistics Division and covering more than 200 countries and over 99% of the world's trade. UN Comtrade has been widely applied in academic research, policy analysis, and material flow studies [33].

Plastic-related trade flows were identified using the Harmonized Commodity Description Coding System (HS Code) developed by the World Customs Organization [34]. The dataset includes trade between the Lao People's Democratic Republic (reporter country) and the World (including all trading partners) for the period 2017–2023.

The analysis covers 6-digit HS codes under Chapter 39 (Plastics) and HS code 630533 (bags and sacks for packaging). Notably, this study excludes synthetic textiles and plastic-containing products (textiles, yarns, fabric, rubbers) classified under Chapter 40, 43, 54, 55, 56, 57, 59, 60, 61, 62, 63, 67, 85, 90, 94, 95, and 96.

This trade-based approach is broadly used in estimating the global plastic trades [35], regional plastic waste flow analysis [11], and e-waste flow estimation [36,37].

Step 2: Estimation of apparent consumption

To estimate the amount of plastics placed on the market (POM), an apparent consumption approach was applied [35,38,39]. The apparent consumption was calculated as the sum of domestic production and imports, minus exports, as shown in the following formula:

$$\text{Apparent Consumption} = \text{Domestic Production} + \text{Import} - \text{Export}$$

where

- Domestic production refers to polymer production either from a primary virgin source or a secondary source (recycled plastic from the previous year);
- Import includes all plastic entering the country in any form (primary polymers, plastic products, or plastics embedded in products);
- Export includes all plastic leaving the country, in any form.

A recent national study [26] reported 77 enterprises engaged in plastic manufacturing and recycling, with 17 companies contributing a combined annual capacity of 51,000 tonnes and an estimated polymer production of 35,853 tonnes. In the absence of information on polymer types and export shares, this figure is used as a contextual reference, and the global average polymer distributions are applied.

Step 3: Classification of plastic flows by product group

To facilitate the interpretation and modelling of plastic flows, all selected HS codes were grouped into five categories, following the HS code descriptions and classifications used in the global plastic trade study [35], namely (1) plastics in primary forms; (2) intermediate forms of plastic; (3) final manufactured plastic goods; (4) plastic waste; and (5) plastic packaging. This classification represents the first analytical level of this study and enables aggregation of plastic flows by product function prior to polymer-specific analysis.

Step 4: Classification of plastic flows by polymer type

In the second analytical level, HS codes were further assigned to polymer families, including low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyethylene (PE), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), “others”, and “not specified”.

For the HS codes that could not be directly linked to a specific polymer, the global average polymer distributions were applied [40], with the share of polypropylene (PP) at 19.3%, LDPE at 14.4%, PVC at 12.9%, HDPE at 12.5%, PET at 6.2%, polyurethane (PUR) at 5.5%, PS at 5.3%, and other polymers at 23.9%.

For waste stream polymer types, asterisks (e.g., PE*, PS*, PVC*) were used to distinguish waste materials from virgin polymers.

Step 5: Identification and quantification of plastic packaging flows

Plastic packaging was selected for detailed analysis due to its short service life (life span < 1 year), meaning that the consumption is likely to become waste within the same year of use [38]. This characteristic allows apparent consumption derived from trade data to be used as a proxy for annual packaging waste generation.

The plastic packaging flows were identified using 6-digit HS codes, namely 392310, 392321, 392329, 392330, 392340, 392350, 392390 and 630533 [35]. To better approximate the total packaging flows, about 44% share of plastic in primary form was additionally allocated to packaging based on global polymer end-use distributions reported in the literature [40].

After calculating the apparent consumption of plastic packaging for 2023, the quantities were further assigned by polymer type. Based on HS Code descriptions, only PE, “others”, and “not specified” could be directly identified. For packaging articles classified as “not specified”, the average polymer composition shares for plastic packaging, namely LDPE (29.5%), HDPE (16.7%), PP (26.6%), PET (18.9%), and other polymers (11.3%), were applied for polymer estimation [41]. These polymer allocation factors were used in the absence of Lao-specific composition data and were therefore treated as literature-based assumptions.

The result for 2023 was selected as the modelling year to represent the most recent and complete trade data available at the time of analysis. While multi-year trade data (2017–2023) were analysed to understand trends, a scenario-based emission model focuses on a single reference year to avoid mixing structural changes across time and to provide a clear policy-relevant snapshot of the current conditions.

This step ensures that plastic packaging flows are consistently represented both in terms of total quantity and polymer composition, which are subsequently used as inputs for scenario modelling. Detailed calculations, including HS code mappings, polymer allocation factors, intermediate results, and sensitivity analyses, are provided in the Supplementary Materials.

2.3. Scenario-Based Emission Model

2.3.1. Goal and Scope

The goal of this study is to quantify and compare the potential environmental implications of plastic packaging waste management in Laos in order to support strategic policy discussions by applying a scenario-based emission model to evaluate alternative plastic packaging waste management options using the Global Warming Potential (GWP) indicator, expressed in Kg CO₂ equivalent (kg CO₂-eq). This model combines mass-flow evaluation with process-specific emission factors. While life cycle-derived emission factors are used for model calculation, this study does not intend to represent a full life cycle assessment and does not assess multiple environmental categories [42]. Instead, the analysis focuses

on comparative greenhouse gas emissions under clearly defined system boundaries and scenario assumptions.

The functional unit is defined as 1 kg of plastic packaging waste generated in Laos and subsequently managed under a given waste management scenario. The functional unit represents mixed plastic packaging waste and is disaggregated into individual polymer fractions (e.g., LDPE, HDPE, PP, PET, PS, and other polymers) based on estimated composition shares. Each polymer fraction is then allocated to the treatment pathway according to the specific scenario-specific distributions. Emissions are first calculated on a per kg basis using this functional unit. To assess system-level and policy-relevant outcomes, the per kg results are subsequently scaled to the total estimated annual plastic packaging waste and then reported on a per capita basis. This approach allows the model to capture both differences in waste treatment pathways and changes in total plastic packaging waste across scenarios.

The scenario framework is designed in line with the waste management hierarchy, prioritising upstream reduction before recycling and disposal. The target upstream reduction is included in this study; more details are discussed in the scenario development.

The waste management options considered in this study include open burning (OB), open dumping (OD), landfilling, and recycling, as they represent the most common and policy-relevant waste disposal practices in Laos.

However, reuse systems were not modelled in this study, as the reuse pathway is highly product-specific (e.g., refillable beverage bottles) and requires detailed assumptions about product design return rates, consumer behaviour, etc. Given that this study covers multiple types of plastic packaging, modelling reuse consistently and realistically was not feasible.

Waste-to-energy (WtE) was not included in the modelled scenarios, as such technologies are currently not implemented in Laos and are not part of NPAP or existing national waste strategies. The potential role of WtE as a future treatment option under more advanced infrastructure and regulatory conditions is discussed in Section 4. Despite this, transportation-related emissions between households and disposal or recycling facilities are excluded from the system boundary due to a lack of reliable data.

2.3.2. Life Cycle Inventory

Emission factor (EF) for waste treatment processes and virgin production of different plastic polymers were obtained from internationally recognised databases, including the Ecoinvent database, version 3.11 [43], the Waste Reduction Model tool, version 18 [44], and a peer-reviewed publication [45]. Due to the absence of Lao-specific emission inventories, background datasets representing Global (GLO), Rest of World (RoW), Europe (RER), and the U.S were applied. Where polymer-specific datasets were unavailable, inventories for mixed plastics were used.

Virgin plastic production EFs represent cradle-to-grave processes and were used as background data to quantify emissions associated with the replacement of unrecovered plastic material. End-of-life (EoL) EFs cover gate-to-grave processes and include only emissions from waste management activities.

For landfilling, direct greenhouse gas emissions from plastic are negligible because plastics are largely non-biodegradable under typical landfill conditions. Therefore, the landfill EF applied in this model represents emissions associated with operational and infrastructure-related activities such as waste handling, compaction, and site operations, rather than material composition.

Therefore, the waste treatment emission for open burning, open dumping and landfilling were calculated as:

$$GWP_{EoL} = M_{plastic} \times EF_{treatment}$$

where

- $M_{plastic}$: mass of plastic packaging undergoing the respective waste treatment (e.g., open burning, open dumping, and landfilling) [kg].
- $EF_{treatment}$: gate-to-grave emission factor for respective waste treatment process [kg CO₂-eq].

Product replacement emissions are the emissions associated with producing virgin material to replace material that is not recovered through recycling. These emissions were applied once at the system level and are proportional to the fraction of plastic packaging disposed of through open burning, open dumping, and landfilling and were calculated as:

$$GWP_{rep} = M_{unrecovered} \times EF_{production}$$

where

- $M_{unrecovered}$: mass of plastic packaging not recovered through material recycling and therefore disposed of via open burning, open dumping, and landfilling [kg].
- $EF_{production}$: cradle-to-gate emission factor for virgin plastic production [kg CO₂-eq].

Recycling was modelled using the avoided burden approach, whereby recycled plastic is assumed to displace the virgin plastic production. The net greenhouse gas emissions from recycling were calculated as:

$$GWP_{recycling} = M_{recycled} \times (EF_{recycling} - EF_{production})$$

where

- $M_{recycled}$: mass of plastic packaging entering the recycling process [kg].
- $EF_{production}$: cradle-to-gate emission factor for virgin plastic production [kg CO₂-eq].
- $EF_{recycling}$: emission factor associated with the recycling process [kg CO₂-eq].

Material losses during recycling were explicitly considered. Based on the literature for household plastic packaging recycling (PP), a 15% potential material loss rate was assumed and assigned to landfill disposal [46].

Therefore, the total greenhouse gas emissions for each scenario were calculated as the sum of waste treatment emission, product replacement emission, and recycling avoided burden, as shown in the following formula:

$$GWP_{total} = GWP_{EoL} + GWP_{rep} + GWP_{recycling}$$

Table 2 provides an overview of the emission factors used to calculate the environmental implications across the scenarios elaborated in the subsequent section. All details of the calculation are provided in the Supplementary Material.

Table 2. Overview of emission factors (kg CO₂-eq per kg plastic) used in scenario modelling [43–45].

Polymer	EF _{Open Burning} [43]	EF _{Open Dumping} [43]	EF _{Landfilling} [45]	EF _{Recycling} [43,44]	EF _{Production} [43,44]
LDPE	2.44	0.11	0.08	0.8	1.8
HDPE	2.44	0.11	0.08	0.8	1.6
PE	2.44	0.11	0.08	0.8	1.6

Table 2. *Cont.*

Polymer	EF _{Open Burning} [43]	EF _{Open Dumping} [43]	EF _{Landfilling} [45]	EF _{Recycling} [43,44]	EF _{Production} [43,44]
PP	2.44	0.11	0.08	0.78	1.6
PS	2.44	0.11	0.08	1.05	1.5
PET	2.44	0.11	0.08	0.69	1.45
Other polymers	2.44	0.11	0.08	1.05	1.9

2.3.3. Scenario Development

Table 3 provides an overview of the four plastic packaging waste management model scenarios in Laos. To assess the environmental implications of different plastic waste management alternatives, four scenarios were developed to explore the GWP associated with variations in open burning, open dumping, landfilling, and recycling. These scenarios are designed to represent both current waste management practices and policy-relevant system transition to circular solutions for future improvement.

Table 3. Overview of four plastic packaging waste management model scenarios in Laos.

Scenarios	Open Burning (%)	Open Dumping (%)	Landfilling (%)	Recycling (%)
S1 Business as Usual	27	27	38	8
S2 Ban on OB & OD	5	5	75	15
S3 NPAP 2030	5	5	70	20
S4 Mandatory EPR	0	0	60	40

The details of each scenario are described as follows:

- **S1 Business as Usual** represents the current MSW management in Vientiane, Laos [23]. Waste treatment shares comprise open burning (27%), open dumping (27%), landfilling (38%), and recycling (8%), reflecting limited collection coverage, continued reliance on informal disposal behaviour, and limited formal recycling capacity. No upstream reduction in plastic packaging consumption is assumed.
- **S2 Ban on Open Burning (OB) and Open Dumping (OD)**, assuming that waste collection services are improved and inadequate treatment options, such as open dumping and burning, are prohibited. However, a 5% share is retained for each practice to reflect persistent informal disposal, particularly in areas with limited service coverage. Diverted waste from OB and OD is primarily reallocated to landfilling (75%), with a modest increase in recycling (15%). This allocation reflects improved collection without significant expansion of recycling capacity. No upstream reduction in plastic packaging consumption is assumed in this scenario.
- **S3 NPAP 2030** reflects on the principal objectives and policy instruments of the National Plastics Action Plan (NPAP) for Laos from 2024 to 2030 [21]. In addition to improved waste management, this scenario incorporates upstream plastic reduction, reflecting restrictions on selected single-use plastic products, and a voluntary Extended Producer Responsibility (EPR) initiative, with at least 50 businesses participating to support recyclable collection and take-back programs. Upstream reduction is applied specifically to plastic bags (HS code 392321), with a 31.6% reduction rate based on empirical evidence from the EU Plastic Bag Directive [47]. On the waste management side, improved collections reduce open burning and dumping to 5% each. However, under voluntary EPR, recycling capacity is assumed to expand only modestly. This reflects the modest improvement without mandatory producer obligations or large-scale

investment in recycling infrastructure. As a result, diverted waste is predominantly directed to landfilling 70%, with recycling increasing to 20%.

- **S4 Mandatory Extended Producer Responsibility (EPR)** represents the implementation of mandatory EPR for plastic packaging. As in S3, 31.6% upstream reduction in plastic bags is applied, reflecting the prevention incentives embedded in EPR schemes. For the remaining waste, open burning and open dumping are eliminated, assuming nationwide formalisation of collection under mandatory EPR. Recycling increases to 40%, aligned with the average plastic packaging recycling rate observed in EU member states following EPR implementation [48]. The remaining 60% is directed to landfilling, reflecting the current technological constraints in Laos and the absence of alternative treatment options.

3. Results

3.1. Plastic and Plastic Packaging Material Flow

Table 4 presents export, import, domestic production, and apparent consumption of plastic in Laos between 2017 and 2023. Reported flows were relatively low during 2017–2019, coinciding with the HS code revision, which may have led to under-reporting or misclassification of certain plastics. From 2020 onwards, the data indicate a more consistent, gradual increase in imports, from 147 kt in 2020 to 168 kt in 2023. Exports remained relatively small compared to imports throughout the period, although they fluctuated considerably, peaking at 66 kt in 2020 before dropping to 14 kt in 2023. Note that domestic production is likely underrepresented, as the available figure reflects contributions from only 17 of 77 enterprises. Apparent consumption rose from 116 kt (16 kg/cap/year) in 2020 to 189 kt (25 kg/cap/year) in 2023.

Table 4. Overview of plastic flows in Laos from 2017 to 2023.

Year	Export (t/Year)	Import (t/Year)	Domestic Production (t/Year)	Apparent Consumption (t/Year)
2017	199	25,491	35,853	61,145
2018	4674	30,866	35,853	62,045
2019	89,703	113,006	35,853	59,156
2020	66,390	147,088	35,853	116,551
2021	33,127	135,171	35,853	137,898
2022	17,292	163,694	35,853	182,256
2023	14,275	168,402	35,853	189,980

Figure 3 shows the apparent consumption of plastics by group and polymer type in Laos in 2023. Plastic in primary forms accounted for the largest share of plastics placed on the market at 98 kt, reflecting the reliance on resins for domestic conversion and manufacturing, followed by the intermediate forms of plastic at 44 kt, plastic packaging at 31 kt (net packaging based on HS code description), and final manufactured plastics goods at 15 kt. About 18 kt of plastic waste remains in the country in the same year.

The analysis of trade data indicates that the majority of plastics were classified as other polymers, totalling 98 kt. Among the identified polymers, PVC accounted for the largest share at 19 kt, followed by PP at 15 kt, LDPE at 13 kt, and PE, PS, and HDPE at around 11 kt each. PET contributed the smallest identified share at 8.5 kt.

The plastic packaging figures presented in Figure 3 represent the net packaging identified directly from the relevant HS codes, accounting for 17% of the total apparent

consumption. To provide a more complete overview, an additional share of 44% of polymer in primary form was allocated to packaging, reflecting the global average end-use distribution [40]. Incorporating this allocation, the estimated total plastic packaging in 2023 amounted to 75 kt (10 kg/cap/year), which is approximately 40% of the total plastic consumption. At the polymer level, LDPE has the highest share at 19.7 kt, followed by PP at 15.8 kt, PET at 12.6 kt, PE at 8.1 kt, and other polymers at 7.5 kt. This consolidated amount of plastic packaging serves as the basis for the scenario modelling presented in the next section, where it is assumed to enter the system in the same year as consumption.

Table 5 compares results from trade-based and waste-based data. To enable a fair comparison with the trade-based apparent consumption model, the reported plastic waste generation figures were first narrowed down to plastic packaging, based on OECD (2022) [48], which reports that two-thirds of all plastic waste comes from applications with a lifespan of less than five years, of which packaging accounts for 40%, consumer products 12%, textiles 11%, and other applications the remainder. At the polymer level, a distribution of polymers is assumed, namely HDPE (57.4%), LDPE (17.4%), PP (7.3%), PS (4.8%), PET (5.9%), and other polymers (7.2%) [49].

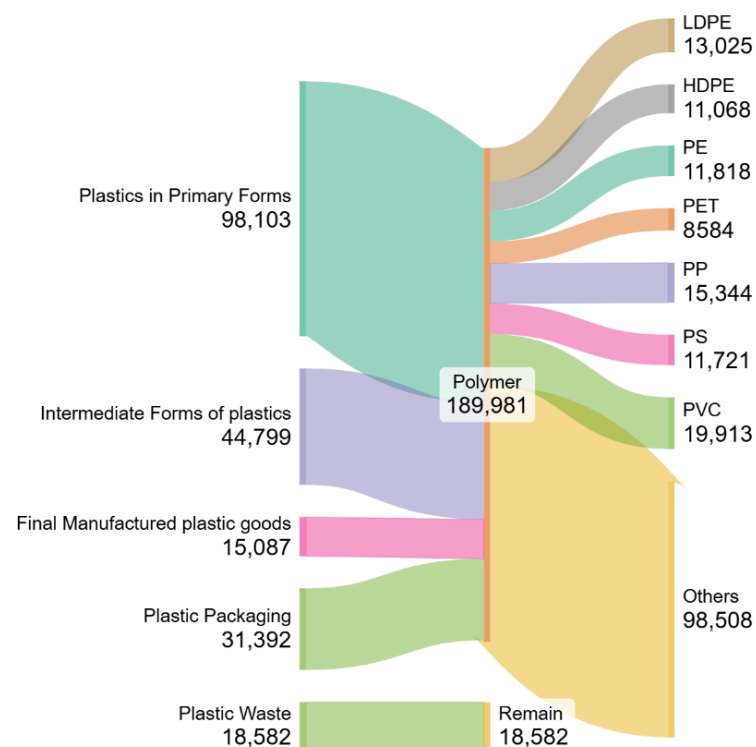


Figure 3. Apparent consumption of plastics by group and polymer type (t/year) in Laos, 2023.

The trade-based model and waste-based model 2 [32] showed very similar totals for plastic packaging, while waste-based 1 [25] reported an almost 50% lower amount. This lower estimate may reflect the relatively low collection rates in Laos (<50%). Secondly, while the trade-based and waste-based 2 models align closely in overall mass, their polymer-level distributions differ significantly. This likely results from waste-based 2 relying on the proportional data from a case study in Thailand [50], which may have had a greater share of others' plastic applications, rather than Laos-specific waste sorting. The discrepancy underlines the need for local MSW characterization to establish more accurate polymer fractions for packaging waste.

Table 5. The comparison of trade-based and waste-based plastic packaging generation.

Description	Trade-Based Model	Waste-Based 1 [25]	Waste-Based 2 [32]
Total plastic consumption (t/year)	189,980	145,600	282,923
Plastic consumption per capita (kg/cap/year)	25	20	38
Total plastic packaging input (t/year)	75,157	38,827	74,367
Plastic packaging input per capita (kg/cap/year)	9.8	5	10
Polymer level			
HDPE	11,190	22,287	42,686
LDPE	19,767	6756	12,940
PE	8150	-	-
PET	12,664	2291	4388
PP	15,814	2834	5429
PS	-	1864	3570
Other polymers	7572	2769	5206

3.2. Plastic Waste Trade in Laos

Figure 4 demonstrates the volume of plastic waste import, export, and net balance (import – export) in Laos from 2017 to 2023. The results reveal that trade in plastic waste in Laos has fluctuated sharply in recent years. The highest plastic waste import occurred in 2019, totalling 98.5 kt, followed by 63.7 kt in 2020. This is anticipated as a result of the strict implementation of China’s Green Fence Policy in 2018, leading to a transition in waste imports to Laos and other neighbouring countries [11,12]. Due to limited waste management capacity and infrastructure, the government of Laos imposed a ban on plastic waste imports, leading to a rapid decline to approximately 21.9 kt in 2023. While annual flows decreased, the cumulative volume of plastic waste from 2017 to 2023 totals approximately 202 kt. The fate of this material remains unclear, as official records do not indicate whether it was reprocessed or disposed of domestically. This uncertainty poses a potential risk, as such an amount could represent a significant additional burden on the national waste management system.

**Figure 4.** Quantity of plastic waste import, export, and net balance in Laos from 2017 to 2023.

In 2023, the net balance of plastic waste imports was 18.5 kt, with the net balance by polymer type dominated by other polymers at 15 kt, followed by PS at 1.7 kt, PE at 1.4 kt, and PVC at 0.4 kt. However, since imported waste is not systematically tracked through the MSW system, only domestic consumption of plastic packaging is considered in the scenario modelling. This ensures that the model reflects the waste arising from local consumption and managed within the national MSW.

3.3. Environmental Implications

Figure 5 shows the results of the environmental implications analysis of the four scenarios, showing a clear progression in emissions reductions due to the waste treatment options and policy implications from S1 Business as Usual through S4 Mandatory EPR. The S1 represents the current practices of plastic packaging waste management that heavily rely on open burning, open dumping, and landfilling, with the highest potential material losses compared to all scenarios, emitting the highest total emissions at 164,790 tonnes CO₂-eq from the different treatments for 75 kt of plastic packaging, translating to 21.5 kg CO₂-eq per capita.

When the regulations and enforcement transition to banning open burning and open dumping, as indicated in the S2 Ban on OB & OD, there is a substantial reduction in emissions of about 31% relative to S1, equivalent to 14.9 kg CO₂-eq per capita. However, this shift leads to increased reliance on landfills, and most of the potential plastic material is still lost in the system. This demonstrates that removing harmful practices alone is still inefficient without providing alternative recovery pathways.

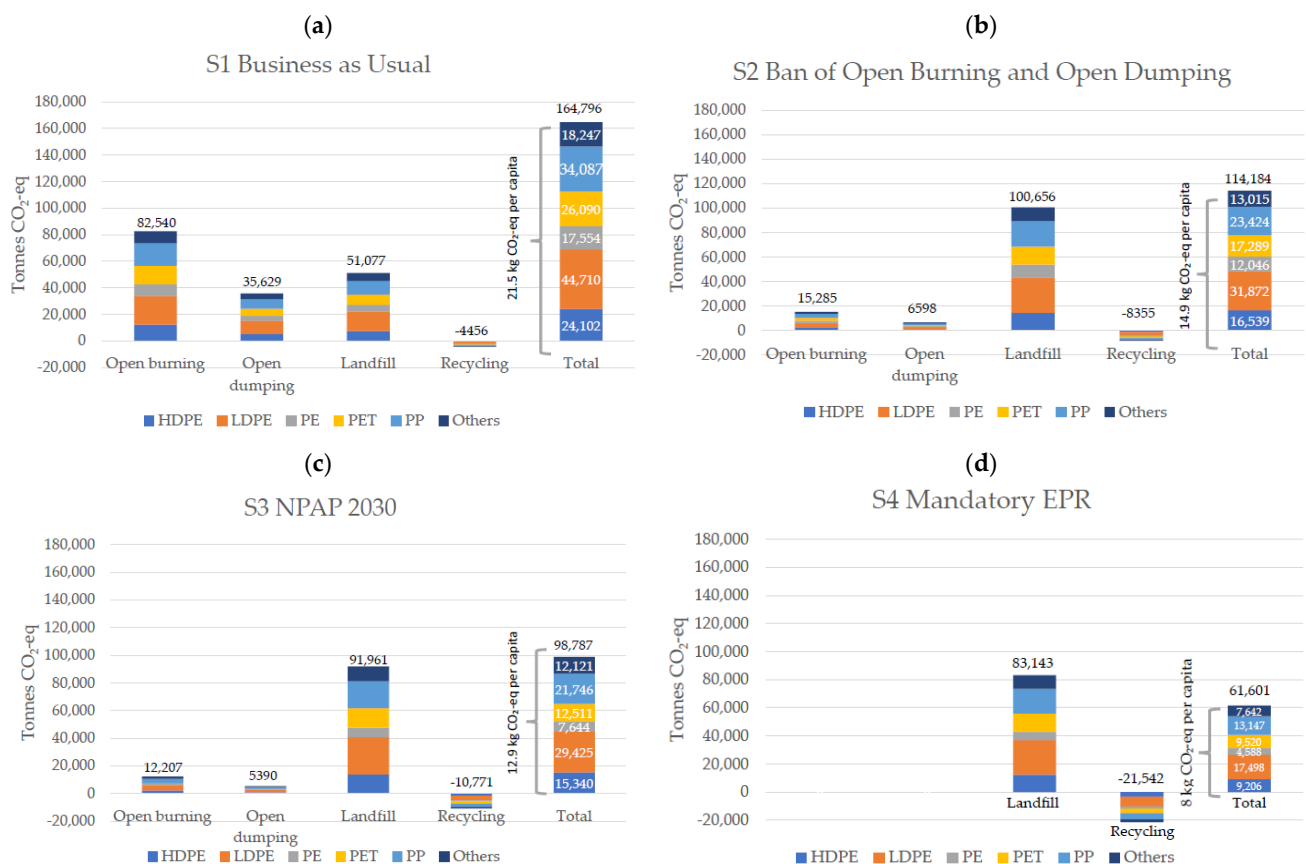


Figure 5. (a) S1 Business as Usual; (b) S2 Ban on Open Burning and Open Dumping; (c) S3 NPAP 2030; and (d) S4 Mandatory EPR.

S3 NPAP 2030 outlines the future direction of plastic waste management in Laos through 2030. Within this, the system's primary policy intervention is to introduce a

voluntary EPR to encourage better collection and recycling. While this scenario modestly increases the recycling rate, total emissions are reduced by 40% relative to S1, corresponding to 12.9 kg CO₂-eq per capita. The reduction is only slightly greater than S2, reflecting strict enforcement of open burning and open dumping, as landfilling remains the dominant treatment pathway in both scenarios. This suggests that while voluntary EPR provides political momentum and helps transition to a future pathway, its actual impact remains limited without strict enforcement and systematic obligations.

S4 Mandatory EPR shows the most significant system transformation and emission reductions, with a 63% reduction relative to S1, corresponding to 8 kg CO₂-eq per capita. Mandatory obligations require producers to participate in waste collection and collection schemes, helping eliminate open burning and open dumping, and driving the recycling rate up to 40%. Furthermore, comparing S3 and S4 shows that regulatory enforcement is critical to achieving substantial improvements in the overall waste management system and recycling rates, thereby reducing emissions. However, even under the S4 scenario, 60% of plastic materials are still lost in landfills, reflecting existing treatment challenges and constraints across all scenarios and emphasising the need for complementary strategies such as waste prevention and reduction, reuse systems, and energy recovery.

Across all scenarios, LDPE consistently represents the dominant polymer, followed by PP and PET, reflecting their large mass shares in plastic packaging applications. Consequently, differences in environmental performance are driven primarily by changes in waste management pathways, while variations in polymers highlight priority targets for EPR design, plastic reduction measures, and recycling system improvements.

Sensitivity Analysis

Table 6 presents a sensitivity analysis comparing four scenarios from the trade-based model with those from the waste-based models. Given the variability and uncertainty in plastic waste data for Laos, a sensitivity analysis was conducted to test how the results change under different assumptions. To capture this uncertainty, two additional models were performed using the same scenario framework (S1–S4), but with the trade-based baseline replaced by national plastic waste values reported. Despite differences in mass and polymer profiles, all three models produced a consistent scenario pattern. Across all baseline assumptions, the relative performance of the scenarios remains unchanged, with S1 showing the highest emissions and S4 the lowest. This consistency indicates that while uncertainty in baseline data influences the absolute magnitude of emissions, the relative ranking of policy scenarios and the associated conclusions are robust.

Table 6. Sensitivity analysis of the trade-based and waste-based plastic generation model scenarios per capita emission (kg CO₂-eq).

Scenario	Trade-Based Model	Waste-Based 1 [25]	Waste-Based 2 [32]
S1 BAU	21.5	11.6	22.2
S2 Ban OB and OD	14.9	8	15.3
S3 NPAP 2030	12.9	7	13.4
S4 Mandatory EPR	8	4.2	8.1

4. Discussion

The environmental implications of system shifts and policy interventions are decisive in steering plastic waste management in Laos toward a sustainable, low-emission pathway. The four scenarios demonstrated how different choices of treatment from open burning, open dumping, landfilling and recycling reflect on the environmental complica-

tions from S1 Business as Usual to S2 Ban OB & OD, S3 NPAP 2030 with voluntary EPR, and S4 Mandatory EPR.

Open dumping and open burning are interlinked practices that significantly contribute to environmental and health risks, as evidenced by many studies and across many regions [51]. Among the four treatment options, open burning of plastic consistently results in the highest environmental impacts, a trend also observed in LCA studies for Indonesia, Vietnam, the Philippines [52], and Thailand [52]. Open burning contributes to air and soil pollution, as plastic packaging typically contains chemical additives, coatings, and adhesives that release harmful compounds when incinerated. Open burning of PET, LDPE, HDPE, PS, and PP releases hazardous gases, including carbon monoxide, dioxins, furans, and polycyclic aromatic hydrocarbons (PAHs) [53,54]. Exposure to emissions from inhalation of toxic substances has been linked to an increase in cardiovascular and respiratory diseases, neurological disorders and developmental issues. [55–57]. Open dumping in Laos has become increasingly evident, with at least 149 informal dumpsites identified throughout the country [22]. Similar trends are observed in an open dumping site in Samae San Subdistrict, Chon Buri Province, Thailand, where it is estimated that the site contains between 3.3 and 18 tonnes of organic additives and up to 26 tonnes of heavy metals [58]. These findings confirm that open burning and open dumping remain critical risks, and banning these practices reduces not only greenhouse gas emissions but also particulate pollution, mitigating direct exposure risks for the surrounding populations.

When considering landfilling as a predominant destination of plastic disposal, the existing condition of the controlled landfill in Vientiane (intended initially as a sanitary landfill) exhibits significant heavy metal contamination in soil, water, and vegetation, surpassing the thresholds established by ANESs, WHO, and Dutch Pollutant Standards, VROM (2000), hence posing an ecotoxicological concern [59]. Plastic in landfills can persist for a very long period, leading to soil degradation, groundwater contamination, and unintentional open burning that emits toxic pollutants and remains a source of microplastics [60,61]. Similar research from China found that the concentration of microplastics (0.03–5 mm) in landfill refuse was 81–133 item/g, with the evidence of polymer breakdown associated with plastic degradation present in leachate [62]. In Vientiane, microplastics have already been detected in urban canals, varying from a minimum of 0.38 items/m³ during the dry season to a maximum of 7.10 items/m³ in the rainy season. The predominant polymers identified in the water samples were PP, PE, PS, PET, nylon, and many other plastics [63]. In the waste hierarchy, landfilling is considered the least preferred method as it imposes several environmental and health implications and additionally potential material losses [64]. Research indicates that a landfill ban for recyclable and recoverable waste is necessary to achieve circularity for plastics, as it helps to increase recycling rates, where several countries in Europe, such as Austria, Germany, the Netherlands, Sweden, Switzerland have already enforced restrictions on landfilling [65].

EPR policies are widely recognized as a key instrument for improving plastic waste management, as they connect stakeholders across the value chain and influence system performance through economic incentives and regulatory obligations [66–68]. While voluntary EPR initiatives under the S3 NPAP 2030 scenario represent an essential first step toward improved plastic waste management, they remain insufficient to address the structural drivers of plastic waste due to partial participation, free-rider effects, weak enforcement, and insufficient financing [69]. However, even under a mandatory EPR scenario, a substantial share of plastic waste (up to 60%) is still assumed to be landfilled, highlighting that EPR should be understood as an enabling mechanism rather than a standalone solution and it requires integration with other measures.

Moreover, this model assumes efficient recycling for all polymer types and applies an optimistic 1:1 substitution between recycled and virgin plastics, which may overestimate the actual environmental gain [70]. In practice, recycling efficiencies vary significantly by polymer type, product design and contamination levels, and not all plastic packaging is technically or economically recyclable. This potential overestimation is particularly relevant given that the recycling stream in this study is dominated by LDPE, PP and PET, which are commonly recycled polymers but are often downcycled into lower-grade applications.

In addition, the analysis considers only formal recycling systems that use state-of-the-art technology. In many contexts, including Southeast Asia, informal recycling plays a significant role and often operates without adequate environmental and occupational safeguards, potentially leading to adverse environmental and human health impacts [71]. As a result, the recycling benefits estimated in this study should be interpreted as an upper bound under idealised conditions rather than as a representation of current real-world performance, particularly for the Lao context.

These limitations highlight the infrastructure bottleneck and the need for complementary upstream interventions focused on plastic reduction and prevention [72]. Such measures include product redesign, reuse and refill systems, and demand reduction strategies, which directly limit the amount of plastic packaging placed on the market and entering the waste stream.

Downstream solutions, such as waste-to-energy (WtE) [73] and Refuse-Derived Fuel (RDF) can play a role in managing non-recyclable plastic fractions. However, their environmental performance depends strongly on technological standards, emission controls and system integration [8,74]. Accordingly, WtE and RDF should be regarded as residual options, applied only after feasible prevention, reuse and recycling measures have been exhausted and implemented under strict environmental safeguards.

In a broader context, transitioning to a circular plastic economy requires policy interventions that address the full lifecycle of plastics rather than focusing solely on end-of-pipe measures. Pottinger et al., 2024 [4] show that a combined policy package that includes mandatory recycled-content targets, demand-reduction measures, targeted investment in waste and recycling systems, recycling targets, and packaging-related taxes can achieve substantially larger reductions in mismanaged plastic waste than measures focused primarily on recycling expansion. This evidence supports the waste hierarchy principles [64] and circular economy R-strategies which prioritize R0 Refuse, R1 Rethink, R2 Reduce, R3 Reuse, R4 Repair, R5 Refurbish, R6 Remanufacture, R7 Repurpose, ahead of R8 Recycle and R9 Recover, with the latter serving as a complementary measure rather than the sole solution [75].

In Laos, promising examples of circular innovation are emerging through voluntary and locally driven initiatives. Nature Ware, a local start-up, aims to reduce plastic food packaging by producing affordable and biobased tableware by using betel nut leaves [76]. Similarly, PatiHoub upcycle low-grade plastic waste into durable construction materials and furniture [77]. Savanir has also adopted a circular approach by transforming PET bottle into a tote bag, offering a sustainable souvenir while supporting the local community [76]. Meanwhile, the Plastic Free Laos label, developed by Econox, promotes eco-conscious practices across the hospitality sector by encouraging businesses to adopt plastic-free alternatives [78]. While these initiatives highlight the growing need for sustainable, circular approaches to plastic waste management, their impact remains limited without broader, systematic support. Therefore, the government and key stakeholders need to scale up these efforts through strong policy enforcement, notably curbing the demand for plastic and packaging consumption, imposing taxes on packaging consumption, implementing

mandatory EPR schemes, strategic investment in the waste management system and inclusive waste governance to fully adopt the circular principles into the national economy.

Limitations of this study

This study provides a conservative estimate of plastic consumption by excluding plastic products outside the UN Comtrade HS Chapter 39, such as synthetic textiles, rubber products, and other industrial applications. As a result, total plastic consumption may be underestimated, with a potential increase of up to 25% [35]. Future studies should consider including a broader range of plastic sectors, particularly synthetic textiles and rubber, when addressing a more comprehensive analysis beyond plastic packaging.

In addition, microplastic pollution is not addressed by our applied modelling framework, as it would require different indicators, system boundaries, and prevention-oriented strategies, and is therefore identified as an important area for future research.

Reuse systems and WtE were not modelled, as the analysis focuses on near-term policy-relevant waste management pathways currently practised or planned in Laos. In addition, the model reuse system is better suited to product-specific rather than overall plastic packaging within the scope of our study. Their potential role is therefore identified as a priority for future research.

Furthermore, it is essential to note that this study focuses solely on GWP as an impact category for modelling the environmental implications of different plastic waste management scenarios, given the lack of local inventory data for Laos and the use of available global emission factors. However, other impact categories, such as ozone depletion, human toxicity, ecotoxicity, and eutrophication, are highly relevant to the treatment methods under consideration. When feasible, local data collection, such as emission monitoring and local recycling inventories, should be considered to enhance the robustness of future assessments.

5. Conclusions

In the absence of comprehensive national statistics, this study demonstrates that UN Comtrade data can offer valuable insights into the flow of plastic packaging. It provides a practical approach to estimating consumption and waste-generation trends. In addition, the environmental implications are assessed through a scenario-based emission model on four scenarios: S1 Business as Usual, S2 Ban of OB & OD, S3 NPAP 2030, and S4 Mandatory EPR. These scenarios reveal how each waste management strategies result in significantly different emission outcomes. In these scenarios, four treatment options, open burning, open dumping, landfilling and recycling were analysed as they reflect the current waste management practices and capacity in Laos. Among the four treatment scenarios explored, S4 Mandatory EPR demonstrated the most positive environmental outcomes, producing the lowest greenhouse gas emissions at 8 kg CO₂-eq per capita, where S1 Business as Usual produces approximately 21.5 kg CO₂-eq per capita. This scenario highlights the benefits of formalizing EPR and improving the plastic collection and recycling rates. However, even under this most ambitious scenario, approximately 60% of plastic waste is still managed through landfilling, indicating that EPR alone is insufficient to fully transition to a circular plastic economy. In addition, these findings emphasized the urgent need for more comprehensive and upstream policy interventions. Measures such as mandatory recycled content, curbing demand for virgin plastic production, strategic investment in waste management systems, and introducing packaging consumption taxes could collectively help address mismanaged plastic waste in Laos. In addition, the downstream alternatives such as WtE and RDF could play a complementary role in managing residual, non-recyclable plastic fractions under appropriate environmental controls.

To advance toward a sustainable, circular plastic economy in Laos, a voluntary EPR initiative should be seen as an initial step rather than the final solution. Achieving suitable and lasting system changes requires transitioning to a mandatory EPR framework, combined with broader circular-economy strategies that cover the entire plastic value chain. In addition, this transformation requires a strong political commitment, effective regulatory enforcement, and inclusive stakeholder engagement to ensure both environmental effectiveness and social equity. Future policies should build on emerging local innovations, close existing data gaps, and incorporate systematic interventions that truly reflect the country's realities and capacities.

Nevertheless, this study is limited by the scope of the modelled treatment options and its exclusive focus on GWP as the sole impact category, assessed through a scenario-based emission model. Future work should incorporate more localised data, explore additional impact categories, such as toxicity and resource depletion, and evaluate a broader set of policy instruments. This would contribute to a more holistic understanding of the circular transition pathway, ultimately supporting more informed, targeted and effective policy and investment decision-making.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18052249/s1>.

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