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Life Cycle Assessment of Municipal Solid Waste Management Systems in the ASEAN Region: Strategies toward Environmental Sustainability

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Abstract

Rapid urbanisation and consumption patterns shift in the Association of Southeast Asian Nations (ASEAN) has rapidly increased municipal solid waste (MSW) generation, resulting in environmental challenges such as greenhouse gas emissions, resource depletion and public health risks. This study evaluates the life cycle environmental impacts of MSW management systems in ASEAN, focusing on three areas of protection, including human health, ecosystem damage, and resource depletion, and translates these impacts into monetary units. Additionally, the study investigates mitigation potentials through the integration of circular economy policies. The environmental impacts associated with managing one tonne of MSW in ASEAN countries vary across countries, with impacts on human health varying from 6.60×10^{-4} to 19.68×10^{-4} DALYs (Disability Adjusted Life Years), on ecosystem quality ranging from 1.87×10^{-6} to 3.31×10^{-6} species-years, and resource depletion costs between -0.77 and 11.08 USD_{2013}. Total environmental damage costs from managing one tonne of MSW in ASEAN countries range from 199.49 to 434.88 USD_{2023}. The environmental costs of the MSW management sector in ASEAN countries range from 29 million to 24 billion USD_{2023} in 2024 and are projected to increase, ranging from 40 million to 28 billion USD_{2023} in 2030 and from 71 million to 38 billion USD_{2023} in 2050 if current systems remain unchanged. Indonesia faces the highest environmental costs in the region, due to its substantial MSW generation volume. Singapore is the only country that avoids environmental impacts from its MSW management systems, characterised by high recycling rates, significant energy recovery, and minimal landfilling. Circular economy has the potential to reduce the environmental costs by over 60%. Therefore, comprehensive reforms, including stringent landfill regulations and incentivised recycling practices, are essential to decrease reliance on open dumping and achieve sustainable waste management.

Keywords: Life cycle assessment; municipal solid waste management; ASEAN; circular economy; environmental sustainability

Introduction

Rapid urbanisation presents a critical challenge for governments and local municipalities in managing the increase in municipal solid waste (MSW) volumes in the Association of Southeast Asian Nations (ASEAN). As urban populations grow and consumption patterns shift, the volume of MSW generated has significantly increased, resulting in adverse environmental impacts such as pollution, greenhouse gas emissions, and resource depletion. Although ASEAN countries have made efforts to address MSW management, they continue to face barriers related to technology, infrastructure, financing, policy, and stakeholder participation [1]. Current MSW management practices in ASEAN countries, which are primarily reliant on landfilling and open dumping, have demonstrated inadequate capacity to sustainably address the associated environmental challenges [1], including greenhouse gas emissions, resource depletion, and public health risks. In response, the circular economy concept has gained prominence as a transformative approach to MSW management. This model emphasises resource recovery, recycling, and the reintegration of materials back into the production cycle, thus minimising waste and environmental impacts. By adopting circular economy principles, ASEAN countries have the opportunity to mitigate the environmental impacts of their MSW management systems, promote sustainable development, and enhance their resilience against future environmental challenges.

A critical review of life cycle assessment (LCA) studies on solid waste management in Asian countries, conducted by Yadav and Samadder [2], identified landfilling as the predominant disposal method, significantly contributing to greenhouse gas emissions and leachate pollution, whereas recycling and composting demonstrated notable environmental benefits. Menikpura et al. [3] evaluating integrated solid waste management strategies in Thailand using LCA found that a system combining recycling, composting, and landfill gas recovery could reduce greenhouse gas emissions by 40% compared to the baseline scenario. Material recycling provides the most substantial environmental benefits across various impact categories, highlighting the necessity for policies that promote recycling and diversion of organic waste from landfilling and expansion of the capacity of biological treatments and animal feed for improved environmental performance of MSW management systems. Gunamantha and Sarto [4] assessed several MSW management scenarios for a region in Indonesia and concluded that increased recycling and composting could substantially reduce environmental impacts compared to landfill-dominated systems. Although incineration offered environmental benefits through energy recovery, it resulted in higher impacts in certain impact categories compared to other MSW management systems. Consequently, Gunamantha and Sarto [4] recommended implementing policies to promote waste segregation and the development of recycling infrastructure.

Rotthong et al. [5] highlighted that the utilisation of by-products is crucial for reducing the overall environmental impacts of organic waste management systems in Thailand, and that improving energy recovery efficiency in waste-to-energy systems and compost production can further mitigate environmental impacts. Budihardjo et al. [6] suggested that low-income countries in Asia should prioritise waste reduction strategies, including recycling and waste management strategies aligned with their current capacities, to effectively limit landfill MSW and mitigate environmental impacts associated with MSW management. Previous studies have demonstrated that integrated MSW management approaches incorporating recycling, composting, and advanced treatment technologies generally offer greater environmental benefits than landfill-dependent systems. While LCA has been widely applied to evaluate the environmental impacts of MSW management strategies across most individual ASEAN member countries, a significant deficiency remains in region-specific studies.

ASEAN countries, such as the Philippines and Vietnam, have recently recorded notable economic growth rates, leading to increased urbanisation and consumption patterns. Moreover, the projections of MSW generation data from the World Bank Database indicate a substantial increase in future MSW generation rates within the region [7], as detailed in **Table 1**. These trends necessitate the implementation of environmentally sound MSW management strategies to mitigate the associated environmental impacts and support long-term sustainable development in the region. The implementation of such strategies is crucial, particularly considering the income level of the country and the projected rapid increases in future MSW generation rates. A comprehensive LCA study of existing MSW management systems within the ASEAN region is essential to evaluate the environmental impacts of current MSW management systems and to identify potential strategies for their effective mitigation. This study is the first regional LCA of MSW management systems in ASEAN that (1) evaluates the environmental impacts of MSW management systems across the region, (2) translates associated environmental impacts into monetary units, and (3) assesses mitigation potentials through the integration of circular economy practices. The study provides a regional overview of the environmental impacts associated with MSW management systems and the resulting damage costs across ASEAN. Evaluating environmental impacts of the waste sector at the regional level using a consistent LCA framework enhances comparability among countries and highlights the major hotspots in the region. This study presents the comprehensive circular economy scenarios that identify opportunities to improve the environmental sustainability of MSW management systems, fostering more sustainable and environmentally conscious development in the region.

Table 1 Current and projected MSW generation in ASEAN countries (adopted from [7])

Country	Income level	Population in 2024	MSW generated (tonnes/year)		
			2024*	2030	2050
Brunei Darussalam	HIC	462,721	249,231	262,788	307,979
Cambodia	LMC	17,638,801	1,420,963	1,702,523	2,641,058
Indonesia	LMC	283,487,931	78,780,335	87,958,248	118,551,290
Lao People's Democratic Republic	LMC	7,769,819	454,156	522,053	748,378
Malaysia	UMC	35,557,673	16,586,499	18,235,817	23,733,545
Myanmar	LMC	54,500,091	8,748,499	9,315,917	11,207,310
Philippines	LMC	115,843,670	17,268,025	20,039,044	29,275,773
Singapore	HIC	6,036,860	9,073,289	9,284,685	9,989,340
Thailand	UMC	71,668,011	31,027,578	32,484,794	37,342,182
Timor-Leste	LMC	1,400,638	70,222	91,347	161,765
Vietnam	LMC	100,987,686	14,110,296	15,922,186	21,961,818

*Estimated through interpolation based on projections for the years 2030 and 2050.
MSW = municipal solid waste, ASEAN = Association of Southeast Asian Nations, HIC = high-income country, UMC = upper-middle-income country, LMC = lower-middle-income country

Materials and Methods

The environmental impacts of MSW management systems in ASEAN were assessed using the LCA framework, as outlined in the ISO 14040 and 14044 standards [8, 9].

1. Goal and scope of the study

This study aims to quantify the life cycle environmental impacts of MSW management systems in ASEAN for the years 2024, 2030, and 2050. It evaluates the environmental impacts of current MSW management systems across three areas of protection (AoP) including human health, ecosystems, and resources. The study also explores future improvement potentials to mitigate environmental impacts from the waste sector in ASEAN.

The system boundary of this study encompasses all life cycle stages of MSW management within the region, starting with the collection and transport of MSW from households, followed by waste sorting and subsequent management through commonly applied MSW management systems in ASEAN countries, such as composting, incineration, recycling, landfilling, and open dumping, as shown in **Fig. 1.** Informal recycling processes are excluded from this study because their material flows and emissions are challenging to quantify, largely unregulated, and highly variable across different regions [10]. Landfills were classified into three categories: sanitary landfill equipped with landfill gas collection systems and energy recovery, controlled landfill lacking energy recovery, and unspecified landfill which lacks comprehensive or known details regarding management practices. Therefore, the unspecified landfill was considered as the unsanitary landfill based on the Doka LCI calculation tool [11], as detailed in ESM, section S1-8 [12].

The utilisation of by-products generated during the MSW management process was included. In this study, the compost produced from composting of the organic fraction of MSW is regarded as a substitute for production of organic nitrogen, phosphorus, and potassium fertilisers. Energy recovery from the incineration of MSW is also evaluated as a substitute for generation of electricity with the country's energy mix. Similarly, landfill gas collected from sanitary landfills is considered an alternative source for the generation of electricity within the country's energy mix. Additionally, materials recovered from the recyclable fractions of MSW are considered substitutes for production of virgin materials.

The units of assessment employed in this study encompass "one tonne of MSW in wet weight, managed through existing MSW management systems in ASEAN countries in 2024," as well as the "total quantity of MSW managed in ASEAN countries for the years 2024, 2030, and 2050." The assessment of one tonne of MSW is intended to identify the major contributors within MSW systems in the region, while the evaluation of the total quantity of MSW aims to estimate the overall environmental damage costs attributable to the MSW management sector during the specified years. Beyond the evaluation of environmental impacts, the study further investigates potential mitigation strategies by developing scenario-based approaches specific to different MSW management systems.

2. Scenario description

The scenarios considered in this study are presented in **Table 2**. Business-as-usual (BAU) scenarios were developed by considering the composition of MSW and the share of treatment systems in each ASEAN country, along with the current and projected amount of MSW for the years 2024, 2030, and 2050. Improvement scenarios were defined according to the proposed global waste management goals [13] which aim to provide universal access to secure, sufficient, and affordable MSW collection services, while also aiming to reduce food waste at the consumer level. These goals focus on achieving sustainable and environmentally sound MSW management by eliminating uncontrolled dumping, and diverting MSW to improve reuse, recycling, and recovery rates.

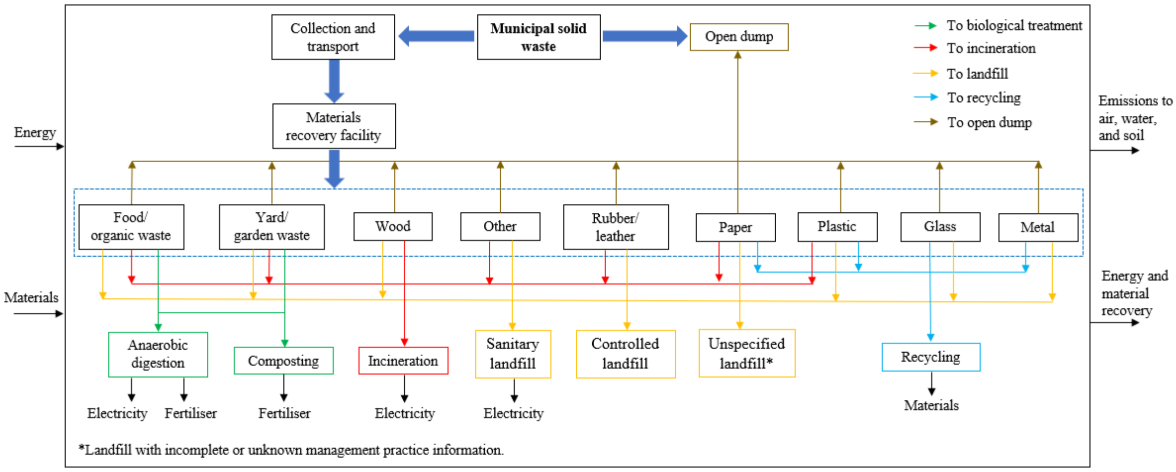

Fig. 1 System boundary of the study

Table 2 Description of scenarios

Scenario	Description
BAU 2024	Scenario reflecting current amount of MSW in 2024.
BAU 2030	Scenario reflecting projected amount of MSW in 2030.
BAU 2050	Scenario reflecting projected amount of MSW in 2050.
S1.1	Waste collection was increased from BAU level to 100%.
S1.2	Waste collection was increased from BAU level to 80%.
S2.1	Food waste was decreased from BAU level to 50%.
S2.2	Food waste was decreased from BAU level to 40%.
S3.1	Recycling was increased from BAU level to 50%.
S3.2	Recycling was increased from BAU level to 40%.
S4.1	Uncontrolled dumping was decreased from BAU level to 0%.
S4.2	Uncontrolled dumping was decreased from BAU level to 30%.
SCES	Waste collection was increased from BAU level to 80%, food waste was decreased from BAU level to 40%, recycling was increased to 40% from BAU level, and uncontrolled dumping was reduced to 30% from BAU level.

BAU = Business-as-usual, SCES = circular economy scenario

The BAU scenarios (BAU 2024, BAU 2030, and BAU 2050) represent the current and projected amounts of MSW generation in ASEAN countries for the years 2024, 2030, and 2050. BAU scenarios assumed that the proportion of MSW managed by different MSW management systems and collection coverage in each country would continue unchanged, with no improvements. In scenarios S1.1 and S1.2, MSW collection coverage was elevated from BAU level to a proposed global MSW management target of 100% [13], whereas an alternative scenario considered an increase to 80%. Countries which achieved 80% collection coverage were evaluated according to their BAU collection coverage. The increased amount of the collected MSW was proportionately diverted into the various BAU MSW management systems.

In scenarios S2.1 and S2.2, the amount of food waste was reduced from BAU level to meet the proposed global waste management target of 50%, as recommended by the United Nations Environment Programme [13], with an alternative scenario considering a reduction of the waste management target to 40%. In the recycling scenario S3.1, recycling rates were increased from BAU levels to reach the proposed global MSW management goal of 50% [13]. As an alternative, scenario S3.2 improved recycling rates from BAU levels to 40%. Countries achieving recycling rates above 50% (S3.1) or 40% (S3.2) were assessed using their existing BAU recycling rates. In the controlled disposal scenarios (S4.1 and S4.2), the quantity of uncontrolled dumping was reduced from BAU level to align with the proposed global MSW management target of 0%, as proposed by the United Nations Environment Programme [13]. An alternative scenario considered a reduction of the waste management target to 30%, followed by proportional allocation to sanitary and controlled landfills. Countries achieving uncontrolled dumping rates lower than 30% were evaluated using their existing BAU levels for uncontrolled dumping.

3. Data collection and inventory analysis

The assessment was conducted using national data on annual MSW generation and composition, as well as shares of MSW management systems from the World Bank database [7], as provided in Electronic Supplementary Material (ESM), section S1-1 [12], and the reflective life cycle inventory (LCI) data for MSW management systems related to the income levels of countries. There is currently no standardised definition of MSW and its composition across ASEAN member states [14]. Notably, countries such as Myanmar, Philippines, and Vietnam incorporate industrial waste, construction and demolition debris, as well as toxic and hazardous waste within their respective definitions of MSW [1]. Due to these inconsistencies, national data on annual MSW generation and composition were sourced from the World Bank database [7]. Specifically, the annual MSW generation data for the year 2024 has been estimated through interpolation, using projections for the years 2030 and 2050.

The LCI for MSW management systems was compiled from our published research [15], Doka inventories of waste treatment [16], and peer-reviewed literature. The relevant technological data for MSW management systems across different income levels were sourced from Oo, Prapaspongsa [15]. Waste-specific and process-specific emissions from incineration, sanitary landfills, controlled landfills, unsanitary landfills, and open dumping of MSW were calculated using the Doka LCI calculation tool [11]. Waste-specific emissions are the emissions that originate directly during the degradation or treatment of MSW, based on the input MSW composition and the application of element-specific transfer coefficients. Process-specific emissions are the emissions that are directly associated with the operations, energy consumption, and material inputs of MSW management systems, independent of the MSW composition. LCIs for anaerobic digestion, composting, and recycling were compiled from our published research [15] and peer-reviewed literature. The inventory data for each MSW management system related to different income levels are provided in ESM, sections S1-3 to S1-10 [12].

The LCI for the collection and transport of MSW, including fuel consumption and emissions, was estimated based on the fuel technology, vehicle weight, and the type of vehicles operated in ASEAN countries, is provided in ESM, section S1-2 [12]. Due to limited data availability across ASEAN countries, this study selected 12-tonne trucks as the representative vehicle type for MSW collection and transport across the region, as the Thai government data catalogue indicated a predominance of small vehicles [17], and this same pattern was also observed in Laos [18] and the Philippines [19]. According to global diesel fuel sulphur levels reported by United Nations Environment Programme [20], Euro 6 (E6) standard was considered for high-income countries (HICs), while Euro 4 (E4) standard was considered for upper-middle-income countries (UMCs) and lower-middle-income countries (LMCs). The emission factors for MSW collection and transport vehicles were derived from the Tier 2 level from the EMEP/EEA Inventory Guidebook 2023 [21] and the life cycle inventories of waste treatment services [22]. For background data, the ecoinvent version 3.10 database was used [23].

4. Life cycle impact assessment

The life cycle environmental impacts of MSW management systems in ASEAN countries were assessed using the SimaPro v9.6.01 [24]. The ReCiPe 2016 v1.1 (Hierarchist) method was applied to quantify the environmental impacts of the MSW management sector at the endpoint level, covering three areas of protection: damage to human health measured in Disability Adjusted Life Years (DALYs), damage to ecosystem diversity quantified in species.yr, and damage to resource availability expressed in USD_{2013} [25].

5. Monetary valuation

The environmental impacts at the endpoint level on human health and ecosystem damage were converted into monetary values to improve their interpretability and support informed decision-making. The budget constraint method was applied to monetise the life cycle environmental impacts based on the concept that the average annual income per capita reflects the maximum amount an individual is willing to pay for an additional year of life [26]. According to Weidema [26], Quality Adjusted Life Years (QALYs) serve as a metric for evaluating impacts on human health and are considered the reverse of Disability Adjusted Life Years (DALYs). The monetary value associated with a DALY was estimated at 74,000 EUR_{2003} with an uncertainty range of 62,000 to 84,000 EUR_{2003} [26]. For ecosystem damage, the value of a Biodiversity Adjusted Hectare Year (BAHY) was calculated relative to the monetary value of a QALY. This estimate was based on a conversion rate of 52 BAHY per QALY, resulting in a monetary value of 1,400 EUR_{2003} with an uncertainty range of 350 to 3,500 EUR_{2003} [26]. The resource scarcity is quantified as USD_{2013} in the ReCiPe 2016 method. The monetary values of human health, ecosystem damage and resource scarcity were calculated with Eq. (1) to estimate the future value of the Monetary Conversion Factors (MCFs) in 2023 for the study as it is the latest year available from the World Bank database [27]. The average inflation rate in European region from 2003 to 2023 is 2.43%, while the average inflation rate in the United States for the period from 2013 to 2023 is 2.52% [27]. MCFs of human health and ecosystem damage in EUR_{2023} are converted into USD_{2023} by using the EUR to USD exchange rate (1 EUR_{2023} ~ USD_{2023} 1.08) (International Monetary Fund, 2025).

$$\boldsymbol{MCF_{(t)} = MCF_{2003} \times (1 + r)^{t-2003}} \quad \text{(Eq.1)}$$

Where, r = average inflation rate from 2003 to 2023
t = considered year of monetary valuation (2023)

The MCFs for human health and ecosystem impacts were found to be 129,314 USD_{2023}/DALY and 59,395,017 USD_{2023}/species.yr, respectively. The uncertainty associated with the monetary valuation approach was also examined by assessing the uncertainty ranges of DALY and BAHY. Details of MCFs are provided in ESM, section S2 [12].

6. Sensitivity analysis

A sensitivity analysis was performed to evaluate the robustness of the results of the assessment. In accordance with ISO 14040 and ISO 14044 standards, sensitivity analysis is conducted within the framework of LCA to address the uncertainty and inherent variability in the study [8, 9]. Sensitivity analysis was conducted on variations in MSW collection and transport distances, as well as on the future global renewable electricity mix. The minimum and maximum MSW collection and transport distances in East Asia and Pacific region from World Bank report [28] and the projected future global renewable energy mix for the year 2030 and 2050 [29] were applied to evaluate the influences of the changes in inputs on the results of assessment.

Results and Discussion

1. Environmental impacts from the municipal solid waste management sector in ASEAN countries

The life cycle environmental impacts of managing one tonne of MSW in ASEAN countries for the year 2024 were assessed and compared using country-specific MSW management data to identify the major contributors within MSW systems in the region. **Fig. 2** presents the environmental impacts and environmental costs of MSW management in ASEAN countries. The negative values denote the avoided burdens (environmental benefits), whereas positive values represent increasing impacts (environmental damages). The magnitude of the values presents a relative indicator of impact for each category. The net environmental impacts and damage costs per tonne of MSW management in ASEAN countries in 2024 are also provided in **Table 3**.

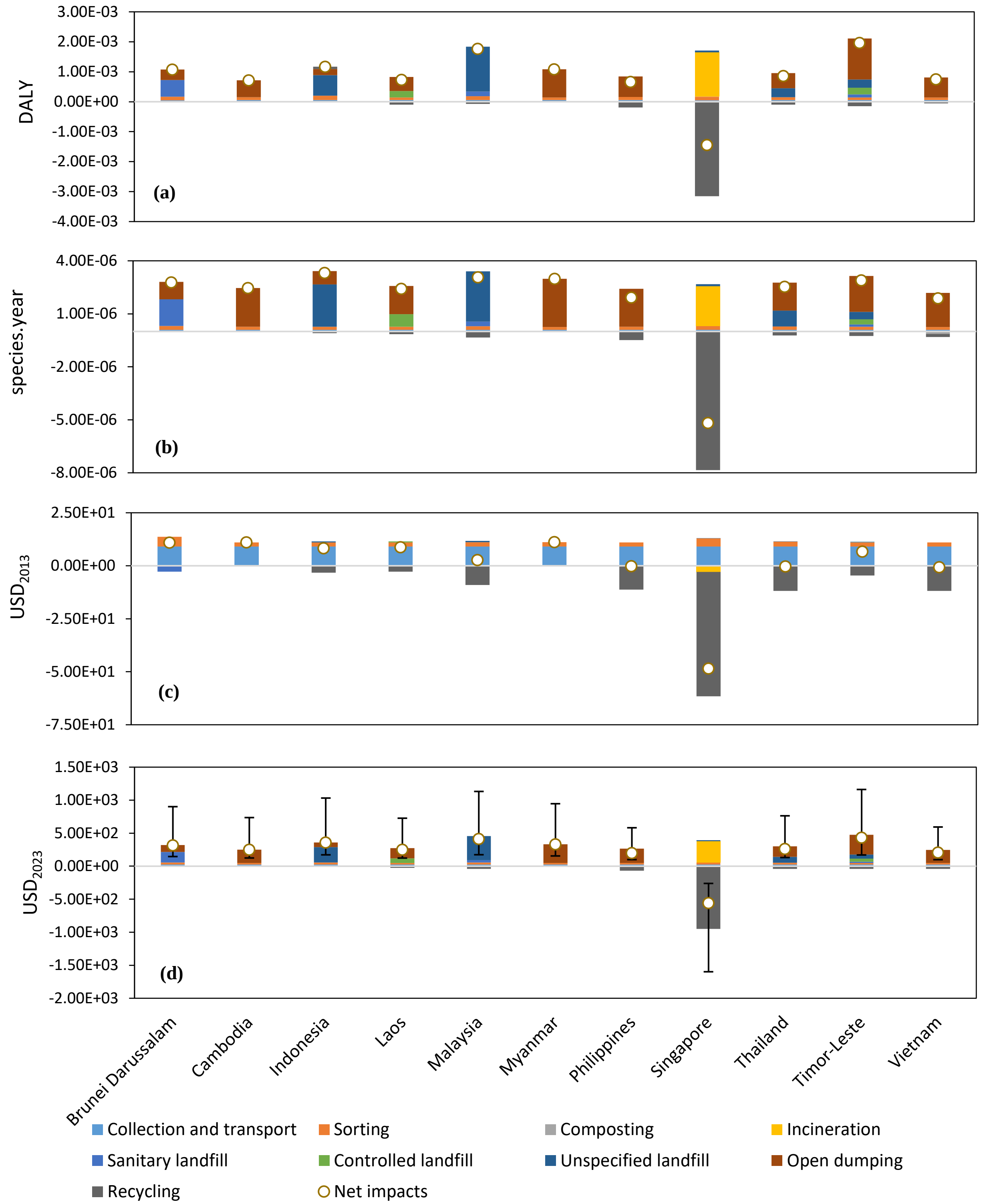

Fig. 2 Environmental impacts of one tonne of MSW management in ASEAN countries in 2024. (a) human health, (b) ecosystem quality, (c) natural resources, and (d) damage costs, the error bars denote the variation attributable to the monetary valuation.

Table 3 Net environmental impacts and damage costs per tonne of MSW management in ASEAN countries in 2024

Country	Human health (DALY)	Ecosystem damage (species.yr)	Resource scarcity (USD_{2013})	Damage costs (USD_{2023})
Brunei Darussalam	1.07E-03	2.78E-06	10.94	317.78
Cambodia	7.13E-04	2.46E-06	10.99	252.36
Indonesia	1.17E-03	3.31E-06	8.28	358.32
Laos	7.29E-04	2.42E-06	8.70	249.23
Malaysia	1.77E-03	3.07E-06	2.67	413.95
Myanmar	1.08E-03	2.98E-06	11.08	331.02
Philippines	6.60E-04	1.93E-06	-0.25	199.49
Singapore	-1.44E-03	-5.18E-06	-48.53	-555.88
Thailand	8.59E-04	2.54E-06	-0.37	261.15
Timor-Leste	1.97E-03	2.89E-06	6.70	434.88
Vietnam	7.47E-04	1.87E-06	-0.77	206.83

The assessment of environmental impacts to human health from managing one tonne of MSW in ASEAN countries ranges from 6.60×10^{-4} to 19.68×10^{-4} DALY, with the exception of Singapore, which exhibits a value of -1.44×10^{-3} DALY. Singapore is the only country that achieves substantial environmental benefits as a result of the significant proportion of MSW managed through recycling. It not only leads the region in recycling rates but also contains the highest metal fraction within its MSW, as detailed in ESM, section S1-1 [12], which contributes to environmental benefits by substituting for virgin metal production. Timor-Leste has the highest damage to human health within the region, followed in a descending order by Malaysia, Indonesia, Myanmar, Brunei Darussalam, Thailand, Vietnam, Laos, Cambodia, Philippines, and Singapore. Open dumping of MSW in ASEAN countries is the most significant contributor to human health impacts. Although higher rates of open dumping are observed in Cambodia, Myanmar, and the Philippines, Timor-Leste registers the highest impact at 1.97×10^{-3} DALY from managing one tonne of MSW. Following Timor-Leste, Malaysia records the second-highest impact in the region, with 1.77×10^{-3} DALY resulting from the unspecified landfilling of MSW. The higher impacts on human health observed in both countries are attributable to the considerable fraction of rubber waste in the MSW, which contributes to increased environmental impacts through the release of heavy metals, particularly zinc. Smolders and Degryse [30] have indicated that zinc emissions from rubber waste pose potential toxic effects on human health and aquatic ecosystems. Wik [31] has also identified zinc from waste tyres as a cause of toxicity to plants and microorganisms, which could lead to bioaccumulation and biomagnification.

The assessment of environmental impacts to ecosystem quality from managing one tonne of MSW in ASEAN countries ranges from 1.87×10^{-6} to 3.31×10^{-6} species.yr with the exception of Singapore, which exhibits a value of -5.18×10^{-6} species.yr. Indonesia has the most significant environmental impacts, followed in a decreasing order by Malaysia, Myanmar, Timor-Leste, Brunei Darussalam, Thailand, Cambodia, Laos, Philippines, Vietnam, and Singapore. The practice of unspecified landfilling within MSW management systems significantly impacts ecosystem quality in Indonesia and Malaysia, which exhibit the highest rates of unspecified landfilling practices in the region. The lack of specificity in landfill management leads to significant ecological degradation, with leachates accounting for approximately 20% of the total impacts and uncontrolled emissions of methane and carbon dioxide constituting over 70% of the total impacts, thereby adversely affecting local ecosystems. Conversely, for other ASEAN countries, with the exception of Singapore, impacts on ecosystem quality predominantly arise from open dumping practices. Open dumping, characterised by the absence of containment measures and limited regulatory oversight, exacerbates the release of pollutants into the environment, which could impact ecosystem quality. The incineration of MSW with energy recovery in Singapore results in considerable environmental impacts on ecosystems within the MSW management system. This is particularly attributable to the emissions resulting from the incineration of the plastic fraction of MSW, which accounts for over 35% of the total impacts, and the rubber fraction of MSW, which contributes approximately 20% of the total impacts. The major contributor to environmental impacts on ecosystems resulting from MSW incineration is carbon dioxide emissions, which account for approximately 50% of the total impacts.

The assessment of environmental impacts to resource scarcity from managing one tonne of MSW in ASEAN countries ranges from -0.77 to 11.08 USD_{2013} with the exception of Singapore, which exhibits a value of -48.53 USD_{2013}. Myanmar experiences the most significant impacts, followed by Cambodia, Brunei Darussalam, Laos, Indonesia, Timor-Leste, Malaysia, Philippines, Thailand, Vietnam, and Singapore, in decreasing order. The significant impacts on resource scarcity observed in the region are associated with the consumption of fossil fuels during the collection and transport of MSW and its sorting. Some ASEAN countries benefit from the byproducts generated from MSW management systems, including recycling, composting, incineration, and sanitary landfilling. For instance, Thailand and Philippines derive higher benefits from recycling within the region, following Singapore. Brunei Darussalam benefits predominantly from energy recovery through sanitary landfilling, supported by the highest sanitary landfill rate in the region. Additionally, Vietnam derives greater benefits from composting, reflecting its highest composting rate within the region. These systems facilitate resource conservation by reclaiming valuable materials and energy, thereby mitigating the impacts associated with resource scarcity. For example, recycling MSW in these countries can decrease the demand for virgin material extraction, while energy recovery from incineration reduces dependence on non-renewable energy sources.

The assessment of environmental impacts in terms of environmental damage costs from managing one tonne of MSW in ASEAN countries varies from 199.49 to 434.88 USD_{2023} with the exception of Singapore, which exhibits a value of -555.88 USD_{2023}. Timor-Leste has the highest environmental management costs per tonne of MSW management in the region, followed in a descending order by Malaysia, Indonesia, Myanmar, Brunei Darussalam, Thailand, Cambodia, Lao, Vietnam, Philippines, and Singapore. Notably, the prevalent practice of open dumping of MSW in Timor-Leste, particularly in cases where rubber waste with elevated levels of heavy metals, such as zinc, constitutes a substantial fraction of MSW, contributes significantly to increased environmental damage costs. This is primarily driven by the adverse impacts on human health resulting from the leaching and dissemination of toxic substances into the surrounding environment. Singapore is the only country in the region that avoids the environmental impacts of the MSW management sector, primarily due to its highest recycling rates in the region and the absence of landfilling of MSW.

2. Future status of environmental impacts from the municipal solid waste management sector in ASEAN countries

The environmental costs of the MSW management sector in ASEAN countries for the year 2024 range from approximately 29 million to 24 billion USD_{2023}, depending on MSW composition, management systems and annual generation rates in each country, apart from Singapore, which avoids the environmental damage costs of about 5 billion USD_{2023}. Without the implementation of improvements or reforms in current MSW management systems, these costs are projected to escalate, ranging from 40 million to 28 billion USD_{2023} in 2030 and from 71 million to 38 billion USD_{2023} in 2050, as shown in **Fig. 3.** Indonesia suffers the highest environmental costs from the MSW management sector among ASEAN countries, despite ranking the third highest in costs per tonne of MSW. This result can be explained by the fact that Indonesia has the highest population among ASEAN countries, as shown in **Table 1**, which primarily drives its substantial MSW generation volume and amplifies the overall environmental impacts despite relatively moderate per-tonne costs. The annual MSW generation in Indonesia accounts for over 40% of the region's total, significantly contributing to its elevated environmental costs.

Timor-Leste has the lowest environmental costs from the MSW management sector among ASEAN countries, despite having the highest environmental costs per tonne of managed MSW within the region. This result is primarily due to its low annual MSW generation rate, as Timor-Leste has the second lowest population among ASEAN countries. MSW generation rate in Timor-Leste is the lowest in the region, accounting for less than 1% of the total MSW generated regionally. Brunei Darussalam has the lowest population in the region; however, its annual MSW generation rate is approximately 3.5 times higher than that of Timor-Leste, as shown in **Table 1**. This highlights the critical importance of MSW reduction strategies to mitigate the environmental damage costs associated with high MSW volumes, despite treatment costs per tonne. Implementing effective MSW reduction strategies is essential for reducing the overall environmental damage costs across the region.

Singapore is the only country in the region that avoids significant environmental impacts from its MSW management sector, primarily due to its high recycling rate, with 61% of collected MSW being recycled and 37% processed through energy recovery via incineration. The landfilling of only 2% of the total collected MSW results in minimal environmental impacts typically associated with landfilling, such as methane emissions and leachate production. This integrated approach allows Singapore to achieve environmental benefits through resource recovery and waste diversion.

3. Mitigation potential of environmental impacts from the municipal solid waste management sector in ASEAN countries in 2030 and 2050

The mitigation potential of total environmental damage costs from MSW management systems in ASEAN countries in 2030 and 2050 were assessed through improvement potentials and a circular economy scenario as shown in **Fig. 4**. The potential reductions in the total percentage of environmental costs associated with MSW management systems are also presented in **Fig. 5**. According to scenarios S1.1 and S1.2, increasing the waste collection rate alone does not inherently lead to a reduction in environmental damage costs, primarily due to the continued prevalence of unsanitary landfilling and open dumping practices within the current MSW management systems of ASEAN countries. These unmanaged disposal methods, along with increased exhaust emissions generated from MSW collection and transport and its sorting, significantly contribute to higher environmental impacts. Such impacts frequently outweigh the environmental benefits associated with merely increasing MSW collection efforts. This underscores the necessity of adopting more comprehensive MSW management strategies that focus not only on collection but also on reducing disposal impacts through proper treatment, resource recovery, and waste minimisation initiatives, in order to achieve environmental sustainability.

The environmental costs associated primarily with MSW collection and transport processes are also influenced by the type of fuel used in each country. High-income countries employing higher-quality fuels, such as Euro 6, can mitigate environmental impacts. In contrast, lower-income countries experience high environmental costs due to the use of lower-quality fuels, such as Euro 4. Therefore, transitioning to better fuel quality through supportive policies and international collaboration is essential for enhancing the environmental sustainability of the MSW collection and transport sector, thereby achieving broader environmental and public health benefits.

In the food waste reduction scenarios S2.1 and S2.2, environmental damage costs in the ASEAN countries could be reduced by up to 23% with a 50% reduction in food waste (S2.1), and by about 18% with a 40% reduction in food waste (S2.2). Environmental costs per tonne of MSW management in ASEAN countries could be reduced by approximately 5% to 21% with S2.1, and by 4% to over 16% with S2.2, depending on the proportion of food waste fraction in the MSW. Cambodia could achieve the highest reduction due to its substantial food waste fraction in the MSW stream in the region. Conversely, Singapore could attain an approximately 1% reduction in environmental costs per tonne of MSW under both the current global waste management target and the alternative scenario, reflecting its low proportion of food waste in the overall MSW composition.

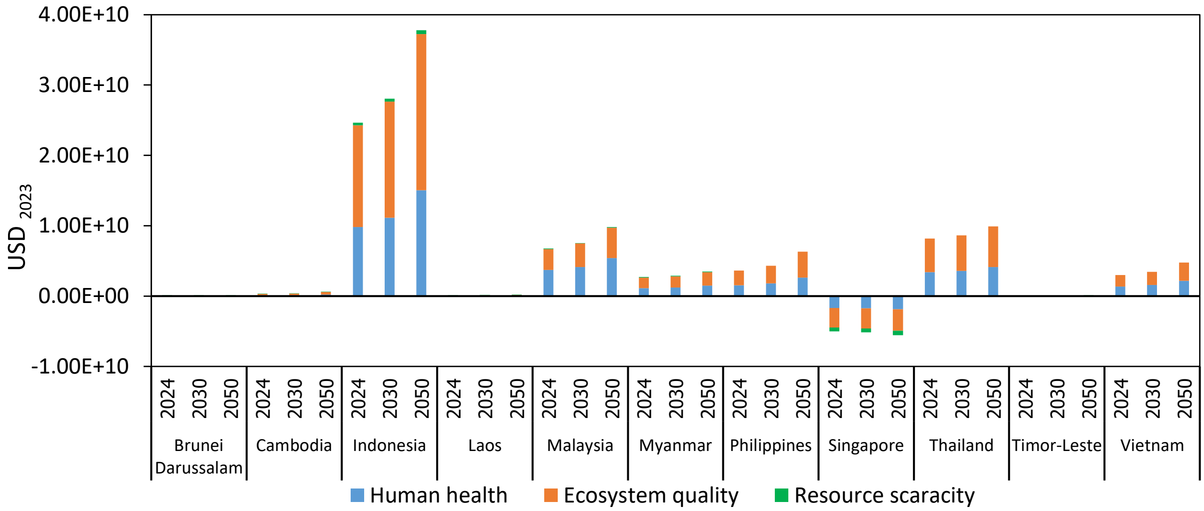

Fig. 3 Projected environmental costs associated with MSW management in ASEAN countries for 2024, 2030 and 2050

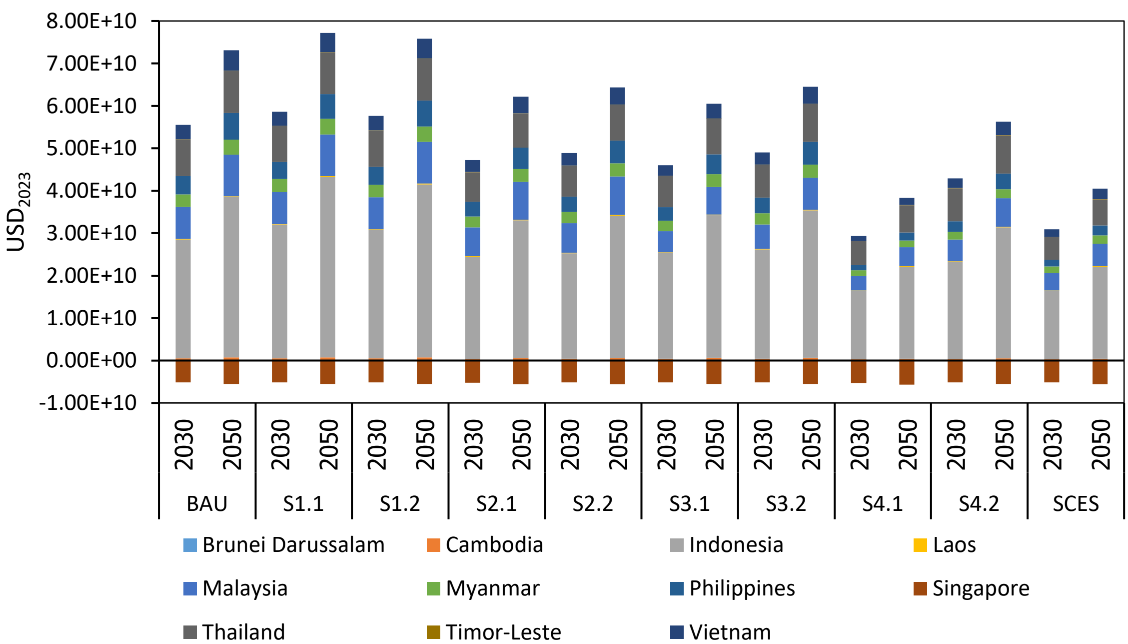

Fig. 4 Improvement potentials of MSW management systems in ASEAN countries in the year 2030 and 2050

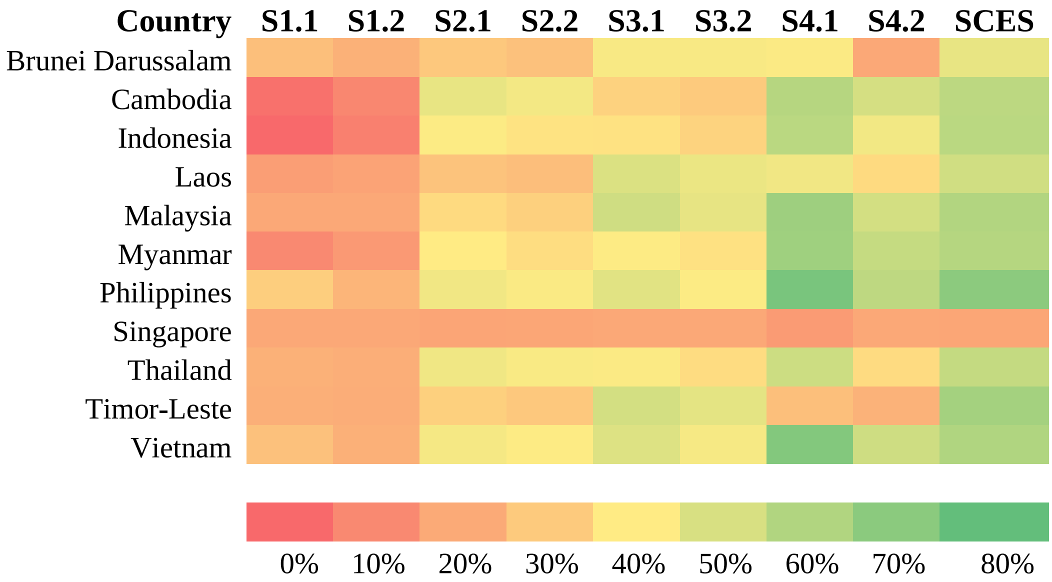

Fig. 5 Potential reductions in the total percentage of environmental costs associated with MSW management systems in ASEAN countries

In the scenarios with increased recycling rates, S3.1 and S3.2, the total environmental damage costs in the ASEAN countries, excluding Singapore, could be reduced by up to 23% and 34% by increasing recycling to 40% (S3.2) and 50% (S3.1), respectively. Singapore could not gain additional environmental benefits under scenarios S3.1 and S3.2, as its existing BAU recycling rate of 61% already exceeds the proposed targets in these scenarios. Environmental costs per tonne of MSW management in ASEAN countries, excluding Singapore, could be reduced by approximately 15% to 77% with S3.1, and from 12% to 60% with S3.2, depending on the initial composition of recyclable materials. Timor-Leste could achieve the highest environmental cost reduction due to the higher percentage of recyclable fractions in its MSW, particularly the metal waste fraction, which is the second highest in the region after Singapore.

In the scenarios of diverting uncontrolled dumping, S4.1 and S4.2, environmental damage costs in the ASEAN countries could be reduced by up to 71% by diverting all uncontrolled dumping of MSW to controlled disposal (S4.1), and by about 41% by redirecting over 30% of uncontrolled dumping from the BAU level to controlled disposal (S4.2). Environmental costs per tonne of MSW management in ASEAN countries, excluding Singapore, could be reduced by approximately 11% to over 82% with S4.1, and by 4% to over 64% with S4.2. Singapore may not gain additional environmental benefits under scenarios S4.1 and S4.2 and Brunei Darussalam under S4.2, as their existing BAU levels of uncontrolled dumping, at 2% and 28% respectively, have already met the proposed targets in these scenarios. The Philippines with the second highest recycling rate in the ASEAN region after Singapore, could achieve the most significant reduction in environmental costs.

In the circular economy scenario (SCES), environmental costs in the ASEAN countries could be reduced by up to 62% by increasing the MSW collection rate from the BAU level to 80%, reducing food waste from the BAU level to 40%, increasing recycling from the BAU level to 40%, and decreasing uncontrolled dumping from the BAU level to 30%. By implementing the circular economy scenario, environmental costs in ASEAN countries, excluding Singapore, for the years 2030 and 2050 can be reduced by approximately 23% to 62%, depending on existing MSW systems. Singapore, having already met all the proposed targets in this scenario, would not experience additional environmental benefits. Singapore, with high recycling rates, minimal landfilling, and a low proportion of food waste in its overall MSW composition, could serve as a role model for other ASEAN countries aiming to mitigate the environmental costs associated with MSW management. However, its replicability in the region is impeded by factors such as weaker regulatory capacity, limited enforcement, financial constraints, and larger land areas. These challenges often result in landfilling or open dumping, leading to diminishing incentives for investments in alternative treatment systems. Timor-Leste, which has the highest environmental costs per tonne of MSW in the region, could achieve over 60% reduction in environmental costs by implementing SCES in its MSW management systems.

4. Sensitivity analysis

The sensitivity analysis examined variations in the minimum and maximum MSW collection and transport distances (SS1.1 and SS1.2) and demonstrated that the environmental costs per tonne of MSW management fluctuate by approximately 4% to 10%, depending on these distances (**Fig. 6, a**). Therefore, optimising the MSW collection and transport distances is important for reducing the overall environmental costs of the waste sector. One potential approach to further enhance the MSW management sector is the electrification of MSW collection and transport, which would not only lead to substantial improvements in operational efficiency, such as reduced fuel consumption and lower operational costs, but also contribute to significant reductions in environmental costs. By effectively managing MSW collection and transport processes, ASEAN countries can achieve more sustainable MSW management practices, minimising environmental impact and fostering environmental responsibility.

When applying future renewable energy mixes for the years 2030 and 2050 (scenarios SS2.1 and SS2.2), it is estimated that the environmental costs per tonne of MSW management could be reduced by approximately 1% to 28% in 2030 and 2% to 30% in 2050, depending on the existing energy mix in each country (**Fig. 6, b**). Countries like Myanmar would experience the smallest reductions in environmental costs with the adoption of future renewable energy mixes, given that its current electricity mix is already significantly composed of hydroelectric power (54%) and natural gas (33%) [23]. Indonesia stands to achieve the highest reductions in environmental costs through the adoption of renewable energy mixes, as its current electricity mix is heavily reliant on lignite-fired power plants at 64% [23]. The transition to a renewable energy mix can lead to a substantial decrease in greenhouse gas emissions and other environmental impacts associated with MSW management. The shift from lignite to renewable sources in Indonesia promises substantial environmental benefits, highlighting the critical role of energy source in national waste management strategies. Such shifts not only address climate change mitigation but also foster cleaner air and more resilient energy systems, aligning with broader sustainability goals across ASEAN countries.

5. Limitations of the study

National data on MSW collection and transport vehicles are sparse across the ASEAN region. Therefore, the limited information available from Thailand, Laos, and the Philippines was applied across the ASEAN region. This approach constitutes a study limitation, as country-specific vehicle data for the region were unavailable for most of the countries in the region. To address this limitation, consistent and representative national vehicle data on MSW collection and transport from all ASEAN countries are required for the analysis.

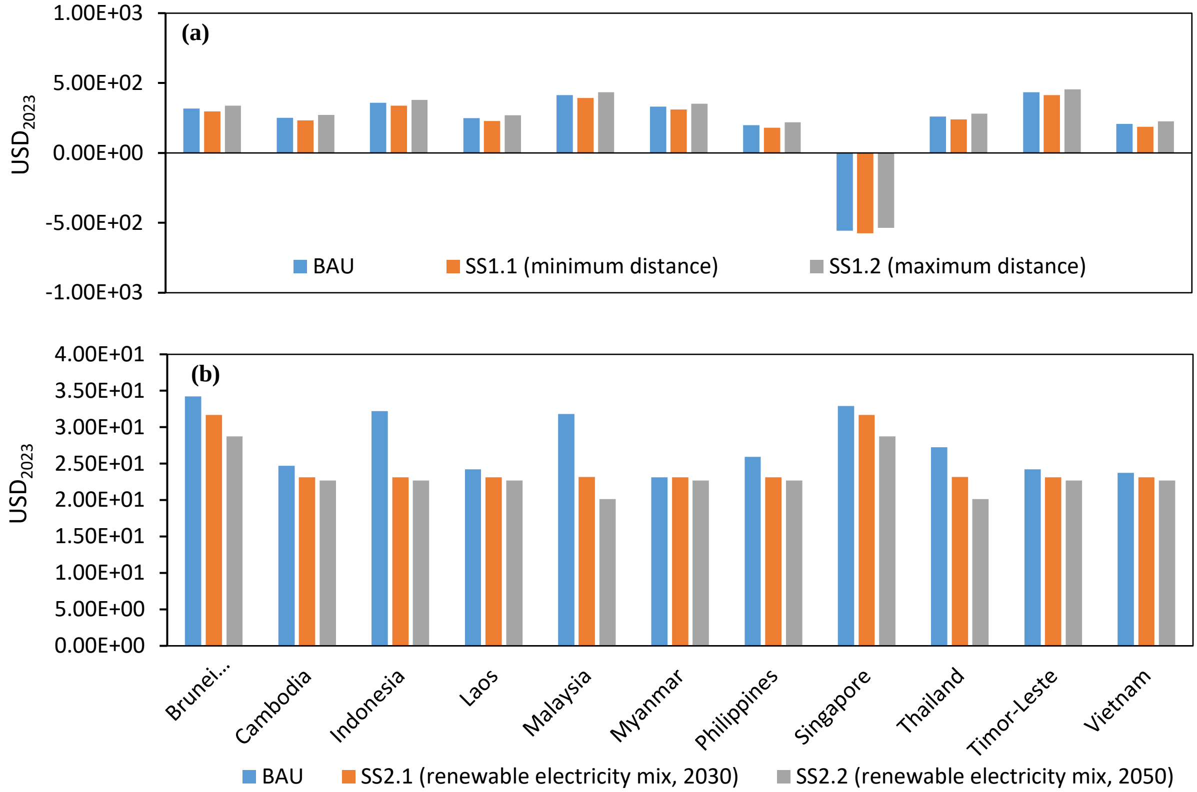

Fig. 6 Environmental costs per tonne of MSW management sector based on the BAU and sensitivity scenarios (a) minimum and maximum waste collection and transport distances, (b) electricity consumption in MSW sorting with BAU and the future global renewable electricity generation mix data in 2030 and 2050.

The monetary valuations of DALY and BAHY were derived from global estimates expressed in euros. These figures were adjusted using the average inflation rate for the European region and subsequently converted to USD. This conversion was performed to present environmental impacts of MSW management systems at the national level across ASEAN. It was implemented because USD is widely used in ASEAN countries, serving as the principal currency for international trade, cross-border financial transactions, and foreign reserve holdings across the region [32]. This approach aims to facilitate the presentation of environmental impacts from the waste sector at the regional level. However, it introduces a limitation to the study, as it may misrepresent region-specific economic conditions in ASEAN countries by relying on European inflation dynamics, which differ from ASEAN inflation trends and exchange-rate volatility. Nonetheless, this study remains comprehensive, incorporating mitigation potential through the integration of circular economy practices to provide a holistic LCA of the MSW management systems across ASEAN and enhancing interpretability and supporting informed decision-making.

6. Policy recommendations

Based on the improvement scenarios, most ASEAN countries require comprehensive MSW management reforms, including the development and enforcement of stringent regulations for landfill diversion and incentivising recycling initiatives to reduce dependency on open dumping. Implementing such measures could mitigate over 60% of environmental costs, enhance ecosystem quality and promote sustainable development within the region. The adoption of environmentally sound MSW strategies that suit to local MSW composition, alongside economic and environmental factors, is crucial.

High-income countries in ASEAN, such as Brunei Darussalam and Singapore, possess greater financial resources for advanced MSW treatment and the capacity to implement gradual landfill taxes to encourage landfill diversion. We recommend establishing suitable infrastructure and legislation, including investment in advanced MSW management systems, landfill diversion targets, and integrated landfill taxes and bans, which have been effective in reducing landfill rates in the European Union [33]. Other ASEAN countries face budget constraints, limited technical capacity for advanced MSW treatment, and prevalent open dumping with weak enforcement. Uncontrolled open dumping of MSW, particularly with a high fraction of food waste, poses significant environmental and health risks. Therefore, prioritising investments in transitioning from open dumps to sanitary or controlled landfills is essential. A step-by-step approach can achieve progressive improvements, transitioning from open dumps to controlled landfills and, ultimately, sanitary landfills. Landfill mining is an alternative strategy that may be implemented once the waste within a landfill achieves physical, chemical, and biological stability. This approach has the potential to extend the operational lifespan of landfills and aligns with sustainable development goals. Landfill mining contributes to environmental benefits by enabling the recovery of valuable materials and reducing greenhouse gas emissions from landfills [34].

The recycling scenarios (S3.1 and S3.2) provide environmental benefits by substituting virgin material production. Therefore, ASEAN countries should establish national recycling targets to improve recycling rates. The ambitious targets have been shown to enhance recycling performance significantly, while additional standards for recycled materials are critical for maintaining quality, safety, and supply chain confidence within the European Union. High-income ASEAN countries possess the capacity to design, implement, and enforce economic policies such as deposit-return schemes and extended producer responsibility (EPR) regulations and to coordinate regionally. We recommend mandating EPR for key packaging sectors, ensuring robust monitoring, and harmonising standards across the region to enhance effectiveness and efficiency. Conversely, other ASEAN countries face limited industry structures, weak enforcement, and insufficient recycling infrastructure. Therefore, a phased approach involving voluntary EPR, data collection, and pilot collection schemes for materials such as plastics and beverage containers integrated with industry is recommended. This foundation can be progressively expanded toward mandatory EPR systems, supported by regional cooperation and donor funding. International aid and cooperation can support infrastructure development and capacity building in the region. Partnerships with international organisations, such as the Asian Development Bank and the World Bank, and engagements with high-income countries as co-investors and donors can mobilise investments and grants to support regional research and pilot projects.

The organic fraction, primarily composed of food waste, constitutes a significant portion of MSW in the region. This organic waste can be either composted or processed via anaerobic digestion to produce biogas. Despite the region's favourable climate for such biological treatments, these methods are not extensively implemented in most ASEAN countries. This limited application is mainly due to inadequate source separation and the contamination of MSW with hazardous waste, which impede efficient biological processing. To address these challenges, the introduction of source separation practices is required, accompanied by educational campaigns aimed at raising public awareness across diverse demographic groups. Furthermore, authorities should consider implementing market incentives and penalties, along with the appropriate allocation of financial resources, to enhance the effectiveness and sustainability of MSW management sector. Policies for MSW management in the region should include direct subsidies or tax incentives for commercial composting and anaerobic digestion and should promote compost utilisation in the agricultural sector. Household and community composting should be incentivised via small grants, technical assistance, and market development. Decentralised pilot facilities in densely populated urban areas, funded by donors or public-private partnerships, can enhance the efficiency and sustainability of MSW management systems. These measures are crucial for optimising the potential benefits of organic waste treatment and promoting environmentally sustainable MSW management systems within the region.

Conclusions

This study aims to quantify the life cycle environmental impacts of MSW management systems in ASEAN countries for the years 2024, 2030, and 2050, and explores mitigation potentials through the integration of circular economy practices. Environmental damage costs from managing one tonne of MSW in ASEAN countries, excluding Singapore, range from 199.49 to 434.88 USD_{2023}, with Timor-Leste incurring the highest management costs in the region. Singapore has the lowest environmental costs from managing one tonne of MSW among ASEAN countries, with total environmental damage costs of -555.88 USD_{2023}. The integrated approach with high recycling rates, significant energy recovery, and minimal landfilling allows Singapore to achieve environmental benefits through resource recovery and waste diversion. The estimated environmental damage costs from the MSW management sector in ASEAN countries range from 29 million to 24 billion USD_{2023} in 2024. If no improvements are made to existing systems, these costs are projected to increase, ranging from 40 million to 28 billion USD_{2023} in 2030 and from 71 million to 38 billion USD_{2023} in 2050. Indonesia incurs the highest overall environmental costs in the region, primarily due to its large MSW generation volume, which significantly amplifies total impacts despite moderate per-tonne costs.

According to the improvement scenarios, increasing MSW collection rates alone does not reduce environmental damage costs in ASEAN countries due to ongoing open dumping and landfilling. Food waste reduction scenarios could potentially decrease the environmental damage costs in ASEAN countries by approximately 18% to 23%, depending on the proportion of food waste fraction in the MSW. Increasing recycling scenarios could decrease environmental costs in ASEAN countries by approximately 23% to 34%, with Timor-Leste achieving the greatest benefits due to its high recyclable waste fractions. Diverting uncontrolled dumping scenarios could reduce the environmental costs in ASEAN countries by up to 41% to 71%, with the Philippines achieving notable reductions due to its high recycling rates. The circular economy scenario could reduce the environmental costs in ASEAN countries by approximately 62%.

Sensitivity analysis showed that optimising MSW collection and transport distances can reduce environmental costs by 4% to 10%. Therefore, reducing MSW collection and transport distances could enhance efficiency and environmental sustainability in the MSW management sector of ASEAN countries. Applying future renewable energy mixes could reduce environmental costs of MSW by 1% to 28% in 2030 and 2% to 30% in 2050. Transitioning to renewables addresses climate mitigation and promotes cleaner energy systems, vital for sustainable MSW management in ASEAN countries.

ASEAN countries need comprehensive reforms, including the implementation of stringent landfill regulations and the promotion of incentivised recycling practices, to reduce reliance on open dumping and potentially achieve over a 60% reduction in environmental costs. Transitioning from open dumping to controlled and sanitary landfills is essential to reduce health and environmental risks. Landfill mining offers a sustainable alternative, prolonging landfill lifespan, recovering valuable materials, and reducing greenhouse gas emissions. Although food waste constitutes a major component of MSW in the ASEAN region, its composting and anaerobic digestion are underutilised due to poor source separation and contamination with hazardous waste. Introducing source separation, public awareness campaigns, and market-based incentives, alongside adequate funding, are essential for improving organic waste management and advancing sustainable MSW management practices in the region. The findings of this study offer valuable insights for stakeholders, governments, and policymakers by providing detailed information on the environmental impacts and associated costs of MSW management systems in the ASEAN region, which facilitates the development of evidence-based policies.

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