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Review

Municipal Solid Waste Management in Laos: Comparative Analysis of Environmental Impact, Practices, and Technologies with ASEAN Regions and Japan

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Abstract: Municipal solid waste management in developing countries faces limitations, especially concerning technologies for treatment and disposal, which is crucial for achieving environmental and economic sustainability goals. This paper investigates municipal solid waste management in Laos, compared with the ASEAN-Japan regions, focusing on background information, waste characteristics, environmental impact, and treatment technologies for resource utilization. The findings indicate a continuous rise in municipal waste generation in Laos, particularly in the capital Vientiane, from 0.21 million tons in 2012 to 0.37 million tons in 2021. Treatment methods include unsanitary landfilling, basic recycling, and open dumping, as well as burning or discharge into rivers, posing potential risks to the environment and human health. Japan and Singapore have shown decreasing trends, with Japan reducing from 45.23 million tons in 2012 to 40.95 million tons in 2021 and Singapore from 7.27 million tons in 2021 to 6.94 million tons in 2021. Laos encounters challenges in managing municipal waste, especially in waste recovery and waste-to-energy practices, crucial elements of integrated solid waste management aimed at promoting environmental and economic sustainability. Enhancing waste management in Laos involves developing a waste management act with segregation, recycling, and extended producer responsibility policies. Implementing mechanical biological treatment facilities, waste-to-energy plants, and upgraded landfills is crucial. Capacity building and public awareness campaigns on waste management will improve sustainability, reduce environmental impacts, and advance sustainable development goals for sustainable cities and communities.

Keywords: municipal solid waste; environmental concern; management; Laos; ASEAN-Japan regions

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1. Introduction

Municipal solid waste (MSW) has emerged as a significant environmental concern due to global population growth, economic development, and urbanization trends [1]. The generation of MSW has been consistently increasing over the years; the global MSW generation ranges from approximately 2.3 to 3.1 billion tons, with an average of 2.7 billion tons in 2019. It has projected to further escalate to approximately 2.87 to 4.5 billion tones by the year 2050 [2]. Globally, 37% of waste goes to landfills, 33% is openly dumped, 19% undergoes recycling, and 11% is incinerated. High-income countries use controlled landfills, while 93% of waste in low-income countries is openly dumped. Upper-middle-income countries lead in landfilling (54%), with high-income countries prioritizing recycling (35%)

and incineration (22%) [3]. The lower capacity of MSW management, characterized by improper disposal in urban centers or open dumps, results from inadequate infrastructure, planning, funding, expertise, and public awareness. The lack of capacity leads to an increase in various environmental and health-related issues [4–6]. Despite its potential risks, MSW is now recognized as a valuable renewable resource with the ability to be converted into energy, materials, fuels, and higher-value byproducts [7,8]. However, low-income countries have lagged high/upper-middle-income countries in waste management practices. For instance, in the Association of Southeast Asian Nations (ASEAN), predominant practices for managing MSW still involve open dumping and landfilling, while incineration plants are commonly employed in developed nations [9]. The dominant technologies for resource recovery and mitigating issues in ASEAN countries involve mixed levels of technology. Except for Singapore and Malaysia, which have modern facilities, other countries rely more on landfill and basic recycling. Japan, on the other hand, is a global leader in advanced waste treatment technology, featuring sophisticated recycling facilities, incineration plants with energy recovery, and anaerobic digestion [10,11]. This highlights the importance of efficient MSW utilization and minimizing its harmful impacts. The implementation of a systematic waste management strategy, along with advanced technologies for treatment and resource utilization is crucial for ASEAN regions.

Among the ASEAN countries, Laos produces the lowest quantity of MSW, primarily due to its smaller population size. In contrast, Indonesia ranks first in waste generation, followed by Thailand, Vietnam, the Philippines, Malaysia, Singapore, Cambodia, Myanmar, and Brunei Darussalam, respectively [9]. The amount of solid waste in Laos has been steadily increasing each year. As per the World Bank, the estimated quantity of solid waste was approximately 910,000 tons/year in 2020. Projections indicate that this figure is expected to rise to 1.4 million tons by 2035, taking into account the water content within the waste [12]. The four major cities in the country, including the capital Vientiane (VT), Luang Prabang, Kaysone Phomvihane, and Champassak Cities, contribute to the high amount of MSW generated nationwide (Ministry of Natural Resources and Environment, 2020). The generation of MSW varies among cities within provinces, mainly due to differences in urbanization levels. Additionally, the composition and characteristics of MSW are complex, reflecting regional habits and needs [13]. Nationwide, the primary methods used for MSW treatment in Laos are mostly treatment and disposal through landfilling, open dumping, and illegal dumpsites [14].

In response to the complex challenge of the increasing MSW generation, Laos has made efforts in both MSW management and technology application. Several legislations and regulations have been implemented such as the "Environmental Protection Law No. 29/MA/2012" [15] and "Decree on Waste Management from Health Care Facilities (Ministry of Health, 2004)" [16]. Recently, there have been improvements in the application of sanitary landfill, resource utilization, and incinerator technology for healthcare waste for MSW treatment in some major cities in Laos [13,17]. These advancements reflect efforts to enhance waste management practices and promote the utilization of resources in an efficient and sustainable manner. Compared to developed countries like Japan with the extensive experience in waste management, the enactment of laws such as the Public Cleaning Act (1954), Waste Management Act (1970), Revision of the Waste Management Act (1976), and related legislations [18], shows that Laos' waste management framework is less established. In Japan, over 80% of waste is incinerated through waste-to-energy (WtE) processes, with a total of 1188 waste incineration plants [19,20]. However, in ASEAN regions such as Singapore, exemplary waste management practices, including strong promotion of integrated solid waste management systems via waste minimization and recycling, or the 3Rs (reduce, reuse, recycle), and advanced WtE incineration technologies, are implemented to reduce waste volume by 90% and minimize the need for landfill space [21]. These practices could serve as a model for other countries, similar to Japan. By 2025, it is projected that the total volume of waste produced in the ASEAN region will increase by approximately 150% compared to the levels recorded in 1995. This surge is attributed to rapid urban growth, increased consumption, and the rising complexity of waste streams, notably electronic and plastic waste. Additionally, cities face challenges in effectively regulating recycling, segregation, and safe disposal methods. Poorly managed waste, especially when illegally dumped in waterways or incinerated, poses significant risks to local environments and public health [22]. While numerous studies have explored MSW management in developed regions, there is a paucity of research focusing on developing countries like Laos. This study addresses the gap by proving a comparative analysis with the ASEAN-Japan regions, highlighting specific challenges and potential technological advancements for Laos. This paper aims to conduct a review of MSW management in Laos, focusing on aspects such as waste generation, environmental impacts, management practices, and treatment technologies. The major urban centers in Laos, particularly VT, are considered representative for comparative analysis with ASEAN-Japan regions.

2. Literature Framework

This work employed a mixed-methods approach, utilizing both qualitative and quantitative methods. The research involved a literature review using multiple academic and non-academic databases. These databases include Scopus, Web of Science, and Google Scholar for peer-reviewed articles, as well as documents released on Google and government and institutional repositories for grey literature. Specific search strings with logical operators were used in Scopus and Web of Science. For instance, the search string used was: “municipal solid waste management” AND (“Laos” OR “ASEAN” OR “ASEAN” OR “Japan”) AND (“environmental impact” OR “technology adoption”). The inclusion criteria for review encompassed publications from 2000 to 2024, focused on MSW management within Laos, ASEAN, or Japan, and written in English. The exclusion criteria included studies not proving empirical data, articles focused solely on unrelated environmental issues, and not written in English. Additionally, semi-structured field interviews (landfill site) were conducted in Laos, and quantitative data such as gross domestic product (GDP) and population figures were incorporated for comparative analysis, as depicted in Figure 1. Statistical differences among countries in waste generation, composition, population, and GDP were collected and evaluated by using Excel (Microsoft® for Microsoft 360 MSO, Version 2312 Build 16.0.17126.20132, Japan), developed by Microsoft Corporation, USA.

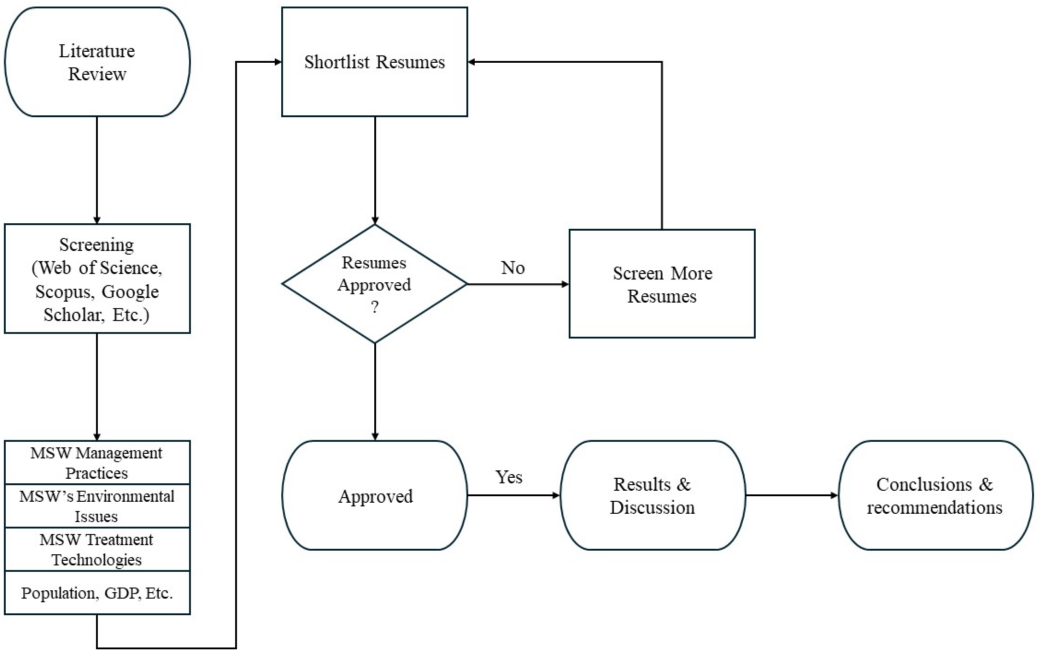

Figure 1. Main diagram of literature framework.

Data were collected, analyzed, and discussed regarding MSW generation, composition, and management practices, drawing on individual perspectives and expertise in this field. The study scrutinizes influential factors such as population, GDP, MSW distribution, characteristics, and available treatment infrastructure. Furthermore, it systematically assesses emerging technologies for MSW resource utilization, including WtE and waste-to-material (WtM) strategies. The paper will identify shortcomings in Laos' current MSW management system and provide insights for developing an optimal system that integrates waste management, transportation, and treatment facilities. The findings on MSW management in Laos, nine ASEAN countries, and Japan may offer guidance on addressing waste management challenges in other nations, thereby contributing to the achievement of Sustainable Development Goals (SDGs) by 2030.

3. The Municipal Solid Waste (MSW) Situation in Laos

3.1. MSW Situation

In recent years, the amount of waste in Laos has been increasing in tandem with economic growth. This increase in waste is believed to be accompanied by changes in waste quality, particularly an increase in plastic waste. These changes in waste composition can be attributed to shifts in people's lifestyles as well as an increase in tourist activities [23,24]. Laos comprises 17 provinces and one major capital city, Vientiane. The total population of the nation was approximately 7.338 million in 2021, with tourism reaching about 886,447 visitors in 2020 [25]. Based on demographic statistics and MSW generation per capita, the total waste generated by the population is estimated to be approximately 1.7 million tons per year [26]. This figure does not include waste generated by tourism. However, accurately identifying the amount of waste generation is challenging due to significant variations in waste production across different areas, particularly between big cities and rural areas [27–29]. In Laos, the composition of MSW, especially in the four major cities, comprises various components. Estimates suggest that the total waste composition in the cities consists of approximately 69% organic waste, 7% paper, 11% plastic, 4% glass, 1.5% metal, 1% textiles, and 6.75% other waste [30].

3.2. Policies and Regulations for MSW Management

The Environmental Protection Law, initially introduced in 1999 and subsequently revised in 2013, serves as a robust safeguard for the environment, resources, and public health, while promoting sustainable development. It sets rules for efficient resource use, pollution reduction, and strict compliance with construction standards to minimize nuisances like smoke, dust, noise, and waste [15]. The law categorized waste into general and toxic/hazardous types, requiring proper disposal through recycling, reuse, or elimination in designated areas. In tandem with legislative efforts, the governmental apparatus has orchestrated the formulation of the 8th National Socio-Economic Development Plan (NSEDP), constituting a strategic compass steering national progress. Of pertinence to waste management, the 8th NSEDP delineates overarching objectives, outcomes, and outputs geared towards nurturing ecologically sustainable rural expansion. A pivotal facet of this plan involves the institutionalization of a waste management system geared at reduction and control, encompassing toxic and hazardous substances, harmonized with the propagation of the 3Rs (reduce, reuse, and recycle) principles across provinces and VT [31]. Concurrently, to concretize the directives emanating from the 10th Party Congress and the 8th NSEDP, the government has promulgated the National Green Growth Strategy, charting a course until 2030. This strategic framework is built upon a tripartite foundation encompassing the economic, social, and environmental pillars. Of note, among its aspects is the establishment of quantifiable indices relevant to solid waste management, including the mean production of refuse per capita (Kg/capita/year), aiming for a reduction from 210 kg/capita/year to 180 kg/capita/year within the timeline of 2025–2030. Correspondingly, there is a targeted increase in the percentage of waste subjected to proper methods of reutilization or disposal, ranging from 65% to 80%, as projected [32].

In recent years, increased attention has been directed towards MSW management, particularly in urban areas of the nation. Notably, VT's waste collection service exhibited a contracted household rate of 27% for all households and 37% within the service area in 2020, a significant rise from the 2013 rate of 20.5%, with a target of 40% by 2020 [16]. Although the planned increase in waste collection rates has not been fully achieved, these figures reflect the authorities' commitment to enhancing waste management. The "Vision and Sustainable Solid Waste Management Strategy 2030" established by the Vientiane City Office for Management and Service (VCOMS) outlines specific targets. These include intermediate goals of a 70% waste collection rate between 2021 and 2025 and eventual full coverage at 100% by 2026–2030 [33]. Following the example set by a major urban center such as VT, other significant cities including Savannakhet, Luang Prabang, and Pakse have also embarked on the development of their own vision and strategy for MSW management, accompanied by specific regulations.

3.3. MSW Characteristics, Composition, Separation, and Collection

The Environmental Protection Law classifies waste into two main types: general waste and toxic/hazardous waste [15]. However, when developing guidelines for managing MSW, there are typically four primary classifications, with each type being collected separately and placed into designated collection containers (Table 1). Despite the development of these guidelines, the actual implementation often does not align with the guidelines due to inadequate classification and collection systems. For instance, in Vientiane, the MSW is collected by private companies operating under the supervision and contract of VCOMS. This waste management process involves a two-way approach: waste is transported from the municipality to either a landfill or a transfer station before reaching the landfill [34]. On the other hand, in Luang Prabang City, multiple waste collection services are provided by private companies in collaboration with the Urban Service Office of Luang Prabang City (USO). The collected waste from the municipality is then transferred to a landfill for disposal and recycling purposes [35].

Table 1. Types of MSW classified generally in waste management guidelines [36].

Types	MSW Components	Collecting Container
Compostable waste	Food waste, leftovers, vegetable scraps, plant leaves, fruit remnants, animal skeletal remains, etc.	Green
Recyclable	Paper, glass, metals, plastics, textiles, etc.	Yellow
General waste	Waste with characteristics that make it unsuitable for recycling due to its toughness and high costs that outweigh its recycling value. For instance, small plastic bags, foam, etc.	Blue
Hazardous waste	Industrial waste: containers containing chemicals, residual waste from processes, etc. Hospital waste: expired drugs, used needles, etc. Household waste: batteries, used electric products, fluorescent tubes, bulb waste, toilet cleaning containers, etc.	Red

The establishment of MSW systems is significantly influenced by the difference in waste characteristics and composition across various spatial attributes. MSW characteristics are primarily dominated by organic waste compositions, such as kitchen and garden wastes, which constitute approximately 60% of the total waste, alongside plastic, paper, glass, metal, textiles, and other wastes [37]. Moreover, it is important to note that waste composition percentages vary both spatially and temporally. In VT, as displayed in Figure 2A, the major components of MSW are organic waste, which covers 67% of the total, followed by plastic waste [33]. In secondary cities like Kaysone Phomvihane (Figure 2B), Luang Prabang (Figure 2C), and Pakse (Figure 2D), organic waste is also the highest proportion compared to other waste types [38,39].

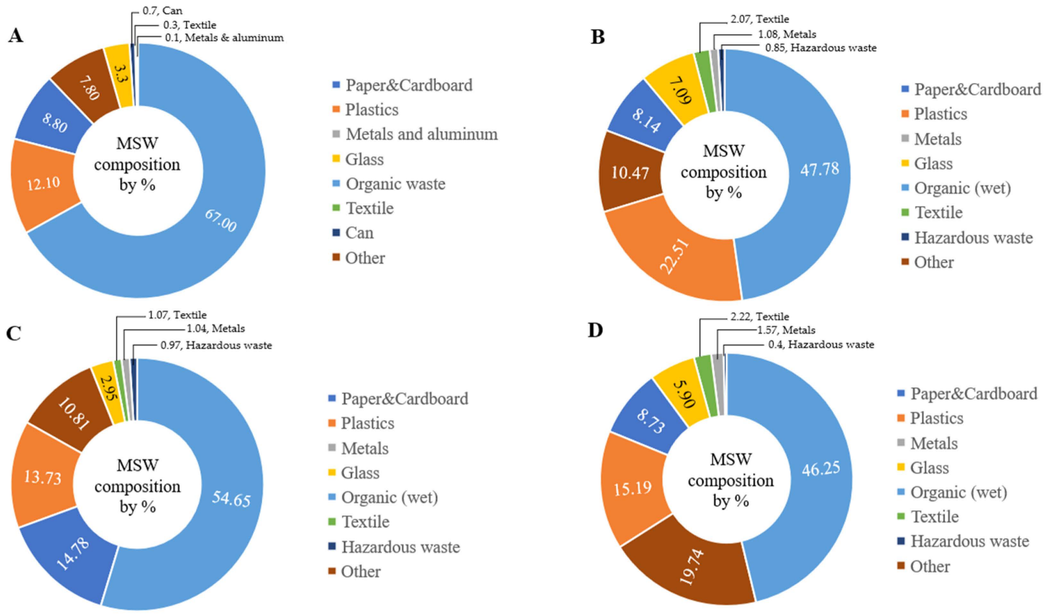

Figure 2. Solid waste composition in four cities in Laos.

3.4. Environmental Impact and Treatment Technologies

Given the complex challenges of increasing MSW generation and waste composition, Laos is making efforts in technological development for treatment and resource utilization as the volume of waste disposed has increased. The waste transported to landfills in the four cities amounted to about 265 tons/day in 2008 and, between 2019 and 2021, rose to approximately 557.1 tons/day [39], marking a twofold increase. It is worth noting that the waste disposed of in municipal landfills in Laos includes both commercial and domestic waste originating from municipal or designated areas, presented in solid or semi-solid forms. This excludes hazardous industrial waste but includes treated biomedical waste. These wastes are classified into accepted and non-accepted waste within municipal landfills [13]. When considering residual MSW not covered by disposal contracts, two alternatives arise: on-site recycling and self-disposal. However, accurate data on the volume of waste to be managed, particularly self-disposal, remains lacking. Predominantly, self-disposal methods such as open burning, open dumping, and discharge into rivers are prevalent in both urban and rural areas. In VT, the MSW amounted to 1004 tons/day in 2019, with only half of the waste being properly disposed of, as shown in Figure 3 [16]. The survey conducted in six cities identified approximately 60 hotspots of illegal dumpsites near rivers and 88 dumpsites inland. The total plastic waste flow was found to be approximately 151 tons/year in the survey [14]. Plastic debris, including occasional small waste fragments, hooks, and soap, were observed in fish at Luang Prabang's morning market. Fishers noted that net entanglement was the primary impact of this debris. Currently, there is no research on the influence of plastic pollution on Mekong migratory species [40]. Additionally, various research studies conducted downstream of Laos in the Mekong River have identified microplastics, including polypropylene, polyethylene, polystyrene, polyamide, and others, contaminating the river. These studies have highlighted local pollution that may affect the ecosystem [41–43]. On the other hand, the open burning of MSW has been a common practice, especially for household waste. According to a random survey conducted in VT by the World Bank, 32% of the total sample mentioned that waste was generally burned in their homes for those who do not have waste collection services [44]. In this context, it is one of the factors contributing to environmental and human health risks, with outdoor $PM_{2.5}$ ambient air pollution accounting for 27% of these effects [45].

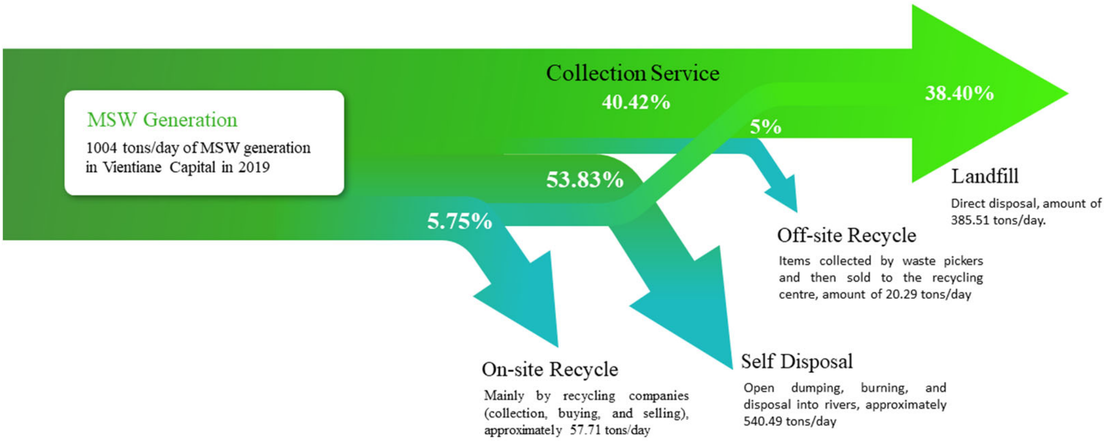

Figure 3. Flow of municipal solid waste in Vientiane.

MSW management technologies encompasses various practices in developing countries. The most common methods include landfilling, recycling, composting, and incineration. However, the actual implementation of these practices in each country depend on their respective policies and economic growth trajectories [9,46]. Laos is among the countries that have adopted waste management technologies, although these systems are not yet comprehensive. Starting from 1992, the management of MSW received financial support from the Japan International Cooperation Agency (JICA). The focus was on collection, transportation, and disposal at the landfill site in VT, overseen by the VUDAA [47]. Over the past decade, there has been a prominent trend of involvement from development partners. Organizations such as the JICA, the Asian Development Bank (ADB), the World Bank, the Global Green Growth Institute (GGGI), and the European Union (EU) have played a major role in encouraging waste management initiatives [16]. This support involves conducting preliminary data surveys, formulating policies and legislation, building human capacity, and providing financial assistance for constructing treatment facilities such as landfills, recycling centers, composting facilities, and incinerators. However, it is worth noting that waste incineration still primarily focuses on healthcare waste incinerators.

4. The Municipal Waste Situation in ASEAN-Japan Regions

4.1. ASEAN Regions

4.1.1. Situation and MSW Management

The volume of MSW in the ASEAN region has emerged as a significant concern due to an increasing trend driven by factors such as rapid urbanization, industrialization, population expansion, and enhanced living standards. The main contributors to MSW are households, including waste generated by offices, hotels, shops, schools, institutions, and municipal services [9]. In 2025, it is projected that the total urban waste generation in ASEAN nations will reach 529,430 tons/day, with generation rates ranging from 0.45 to 1.1 kg/capita/day [46]. Each country has different characteristics, volumes, and treatment methods for waste management. As shown in Figure 4, the management of waste varies depending on policy and economic income, leading to different situations in high-income, middle-income, and low-income countries.

High-income countries: Despite having a smaller population compared to other ASEAN countries, Brunei has seen a significant increase in waste generation. The management of MSW primarily involves disposal in landfills, with a small portion used for composting and the remainder disposed of using conventional techniques [48,49]. To address environmental concerns and improve waste management practices, the government has enacted the Environmental Protection and Management Order 2016 (EPMO) and the Hazardous Waste Order 2013 (HWO), which regulate waste management activities and mandate waste segregation at the source [48,50]. A developed ASEAN country like Singapore has witnessed a substantial increase in MSW, propelled by rapid population expansion and economic advancement [51]. Non-segregated waste undergoes collection and is then transported to waste-to-energy facilities for incineration, significantly reducing the solid waste volume [52–54]. The fundamental regulatory framework overseeing SWM in Singapore is governed by the Environmental Public Health Act 1987 (EPHA), which underwent a revision in 2002, encompassing provisions concerning household solid waste recycling [55,56].

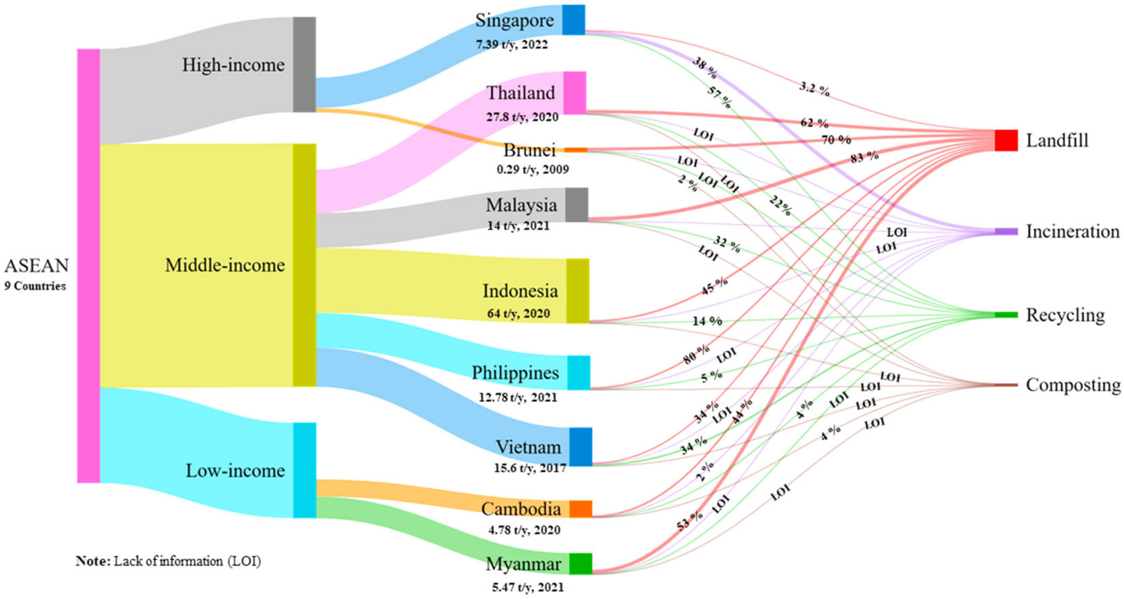

Figure 4. Municipal solid waste management flows (million tons) in nine ASEAN countries.

Middle-income countries: In Malaysia, the MSW includes household solid waste, commercial and institutional waste, and industrial waste. Currently, landfilling is the most common method of waste disposal in the country. Incineration is the second most widely used method, followed by material recovery facilities [57,58]. The National Strategic Plan for solid waste management was established in 2006 to develop a comprehensive MSW management system and promote waste minimization through the principles of the 3Rs (reduce, reuse, recycle) [59,60]. The Solid Waste Management and Public Cleaning Act 672 was enacted in 2007, with enforcement implemented in six states in Malaysia, focusing on collection, disposal of controlled solid waste, and public cleaning [61,62]. In Thailand, the MSW has been increasing annually, particularly in Bangkok [63,64]. However, waste collection, transportation services, and sanitary facilities remain limited, leading to illegal waste dumping and open burning [65]. The country has implemented policies, legislation, and specific regulations on solid waste management, such as the National Economic and Social Development Plan (2017–2021) and the National Waste Management Master Plan 2016–2021 [66]. Vietnam generates a substantial amount of solid waste annually, with this amount increasing each year. A significant portion of the MSW is recycled at treatment plants [67,68]. The government has updated the Law on Environmental Protection and issued Decree No. 08/2022/ND-CP [69], aimed at strengthening the legal framework for waste management. This provides guidance for the development of specific regulations, guidelines, and strategies for comprehensive MSW management [70]. Indonesia, with one of the highest populations among ASEAN nations, faces significant waste management challenges. The recycling rate relies primarily on informal waste sorting, with a substantial portion of waste disposed of in landfills, while the remaining portion was either illegally dumped or openly burnt [71]. Despite long-standing efforts to address the waste issue through national policies and legislation, such as the Law on Solid Waste Management (UU No. 18/2008) and the Law on Environmental Protection and Management (UU No. 32/2009) [72], based on these legislations, the government has been developing specific policies and regulations to tackle waste pollution issues [73]. In the Philippines, a substantial amount of MSW is produced daily, with a significant portion remaining uncollected [74]. The Ecological Solid Waste Management Act No. 9003 was enacted in 2000 to enhance waste management systems, mandating enforcement for segregation at the source, segregated transportation, storage, transfer, processing, treatment, disposal, and the prevention of activities that could harm the environment [75,76].

Low-income countries: Waste management in Cambodia primarily involves treatment and disposal by landfill, with small portions recycled, incinerated, and composted [77]. The government has developed and enacted sub-decree No. 36/1999 on Solid Waste Management [78] and a specific Sub-decree No. 113/2015 on Municipal Solid Waste Management [79]. In urban areas of Myanmar, a significant amount of MSW is generated daily, with an estimated portion of inorganic waste being recycled. Only Yangon and Mandalay exhibit high rates of waste collection [80,81]. The situation regarding MSW management in Myanmar mirrors that of other developing countries, focusing primarily on waste collection, disposal, and recycling. The Environmental Conservation Law No. 9/2021 [82], along with rules and regulations, has been developed. However, enforcement remains weak and the implementation of 3Rs activities is limited [83,84].

4.1.2. MSW Characteristics, Composition, Separation, and Collection

The global MSW classification system varies significantly, contingent upon the underlying framework and prerequisites for effective waste management [85]. In ASEAN countries, MSW primarily emanates from households, commercial activities, and similar sources such as offices, hotels, shops, markets, schools, institutions, and municipal services [46]. As depicted in Table 2, the waste in those countries shows differences in composition, generation rate, and treatment methods.

Table 2. The MSW characteristics and management practices of nine ASEAN nations.

Country	Composition	Generation Rate	Recycling	Collection	Reference
Brunei	Food waste 36% Paper 18% Plastic 16% Glass 3% Textiles 2% Metals 4% Yard waste 6% Rubber 1% Wood 1% E-Waste 1% Other 12%	1.4 kg/capita/day	11.3% (plastic, paper, aluminum)	70% goes directly to landfills by private companies through door-to-door.	[86,87]
Cambodia	Food waste 55% Paper 3% Plastic 10% Glass 8% Metals 7% Other 17%	0.78	4% recycled, 2% composted	About 86% of MSW in cities.	[77,88,89]
Indonesia	Food waste 42.38% Paper 12.24% Plastic 16.03% Glass 5.98% Metals 6.23% Fabric 6.18% Rubber/leather 3.27% Other 7.60%	0.8	7% through composting	About 69% goes directly to open landfill.	[90,91]

Table 2. *Cont.*

Country	Composition	Generation Rate	Recycling	Collection	Reference
Malaysia	Food waste 36% Paper 9% Plastic 24% Glass 2% Garden waste 4% Metals 2% Other 23%	1.17	31.5% recycled	82.5% disposed of in landfill.	[57,92]
Myanmar	Organic waste 77% Plastic 13% Paper 7% Other 3%	0.44–0.53	Recycled: 5% in cities and only 2% in the country.	80% in major cities and around 45% in the country.	[9,93–95]
Philippines	Biodegradable waste 52% Residual waste 18% Special waste 2% Other waste 28%	0.69	5% recycled	40–80% collected nationwide.	[9,75,96]
Singapore	Food/organic waste 10.5% Paper 16.5% Plastic 11.6% Glass 1.1% Textiles 2.1% Metals 20.8% Grass/wood, etc. waste 8.6% Construction debris 17% Other 11.9%	3.8	19% is recycled, the remaining is burned to generate electricity.	>90% collected nationwide, about 50% of waste is collected by private enterprises.	[9,97]
Thailand	Organic waste 64% Paper 8% Plastic 17.6% Glass 3% Textiles 1.4% Metals 2% Other 4%	1.05	16% recycled before collection, 16% recycled before disposal.	78% collected.	[9,98,99]
Vietnam	Food/organic waste 55% Plastic 10% Paper 5% Metals 5% Rubber 4% Glass 3% Other 18%	0.84	Approximately 11% is recycled in nationwide.	The nationwide average is approximately 75%.	[9,100,101]

The waste composition in nine ASEAN nations shows organic waste ranging from 10.5% to 77%, which is higher than other compositions, followed by plastic ranging from 10% to 24%. However, this waste is still underutilized, with most being disposed of in landfills, incinerators, or through uncontrolled means. Additionally, there are a lower number of collection services for waste treatment and disposal, as well as for recycling.

4.1.3. Environmental Impact and Treatment Technologies

The complex challenge of increasing MSW generation and the high composition of organic and plastic wastes, commonly managed in developing countries through improper methods such as landfilling, open burning, and illegal dumping [102–104], exacerbates environmental concerns. Waste materials from MSW contain complex chemical components that can release substances and pathogens into the environment upon decomposition, leading to pollution [105,106]. The release of pollutants from waste into the environment occurs through air, soil, and water, resulting in significant environmental and health impacts, as shown in Table 3 [107,108]. ASEAN nations rank among the top 10 countries globally in plastic waste emission into the ocean, including the Philippines, Malaysia, Indonesia, Myanmar, Vietnam, and Thailand, respectively [109,110]. Researchers have been developing technologies to address these issues and simultaneously recover waste materials for environmentally friendly utilization [111–113]. However, despite the availability of innovative treatment, disposal, and recovery technologies, considerations of residual waste from operations, such as fly ash and bottom ash, must still be addressed. Proper management of these residuals is crucial, as they can have adverse effects on the environment and public health, necessitating high operational and maintenance costs in the process [114–116].

Table 3. Impact of municipal waste on pollution and health [5,108,117].

Pollution Type	Sources from MSW	Health Impacts
Water pollution	Leachate from landfills, improper disposal of chemicals, sewage overflow	Gastrointestinal diseases, skin infections
Soil pollution	Improper disposal of hazardous waste, landfill leakage, use of untreated sludge as fertilizer	Cancer, neurological disorders, reproductive issues
Air pollution	Incineration of waste, decomposition of organic waste releasing methane, open burning of trash	Respiratory issues, cardiovascular diseases, asthma
Biological pollution	Organic waste attracting pests, accumulation of waste leading to bacterial growth	Infectious diseases (e.g., cholera, malaria), allergic reactions

Singapore, Malaysia, Thailand, and Indonesia serve as exemplary models for waste material recovery through WtE initiatives, a trend gaining momentum across ASEAN nations. For example, Singapore boasts four WtE plants (the Tuas, Senoko, Tuas South, and Keppel Seghers Tuas plants) alongside one landfill (Semakau), collectively generating approximately 256.8 MW of power [118,119]. Embracing the principles of the 3 Rs (reduce, reuse, recycle), Singapore minimizes solid waste, with the remaining waste directed to WtE plants, reducing waste volume by around 90% in landfill [21,120]. In Malaysia, landfilling remains a common method for MSW management, with 141 operational landfills, of which only 21 are sanitary landfills. Additionally, there are approximately 11 biogas plants with a total installed capacity of around 25.47 MW [57,121]. Incineration serves as the second most utilized method, particularly for healthcare waste. The WtE plant in Kajang is a notable facility converting MSW into refuse-derived fuel (RDF) for electricity generation at a rate of 8 MW per day. Furthermore, there are four small-scale incinerators, with Langkawi island standing out for its ability to generate electricity from MSW, producing 1 MW from 100 tons of MSW per day [122]. In Thailand, while landfilling remains the primary disposal method, emerging technologies such as semi-aerobic methods (like the Fukuoka landfill method) and incineration plants are gaining traction. For instance, the Phuket incineration plant has a capacity of 2.5 MW [123,124]. Moreover, mechanical biological treatment (MBT) is employed to enhance the MSW properties for its utilization as RDF, with several full-scale MBT facilities currently operational [125,126]. In Indonesia, MSW treatment primarily involves landfill disposal, burning, and recycling [127]. WtE plants utilizing incinerator technology with RDF have emerged as the most suitable option, demonstrating positive economic indicators. The government has strategically planned to develop 12 WtE projects with a combined capacity of 234 MW [128,129]. Similarly, the Philippines and Vietnam have been active in pursuing waste management solutions. In Vietnam, several WtE plants are operational, notably the Can Tho plant with a generating capacity of 7.5 MW, the Soc Son plant with a capacity of 15 MW, and three high-tech WtE projects with a total capacity of 29 MW [130]. In the Philippines, approximately 13 WtE plants are registered with the Philippine Department of Energy (DOE), ranging from 100 kW to 12 MW in capacity. These plants utilize various technologies including anaerobic digestion/bio-methanation, landfill methane recovery, gasification, RDF production, and direct combustion [96,131].

Brunei, Cambodia, Laos, and Myanmar still lack efficient WtE recovery technology and comprehensive policies, programs, and plans for MSW management. The predominant method of MSW disposal in these countries is landfilling or open dumping, with limited source segregation focused only on plastic, metal, and paper waste for recycling [9]. Brunei currently lags behind other ASEAN nations in terms of MSW recovery for WtE purposes. However, plans are underway to construct a waste incineration plant capable of processing up to 100 tons of waste/day to generate electricity [132]. In Cambodia, the final MSW treatment or disposal methods are similar to those in neighboring countries, primarily involving landfilling and small-scale incinerators without energy recovery. Nevertheless, the government is actively encouraging private sector investment in WtE to harness electricity from waste [77,133]. Similarly, Myanmar predominantly relies on open dumping or uncontrolled landfilling as the primary method of waste disposal, covering approximately 83% of MSW disposal. Other methods, including recycling, anaerobic digestion, and incineration, contribute to a smaller percentage [95]. One notable incineration plant with a capacity of 60 tons of waste/day has been established for WtE purposes in Yangon, with a power generation capacity of about 760 kW [134].

4.2. Japan

4.2.1. Situation and MSW Management

Japan is undoubtedly a global leader in MSW management, boasting a comprehensive system characterized by meticulous planning and sustainable practices across waste disposal, treatment, and material recovery. According to the Ministry of Environment, waste generation in Japan in 2023 amounted to 40,950 million tons, marking a 1.7% decrease from 41,670 million tons in 2020 [135,136]. The waste management flow in Japan primarily involves intermediate treatment, accounting for approximately 94.4% of waste, with 4.6% directly recycled, and around 1.0% undergoing direct final disposal. The country's commitment to proper waste treatment and the promotion of recycling is underscored by laws, as shown in Figure 5, which collectively form a comprehensive framework for managing waste, promoting recycling, and ensuring the sustainable use of resources.

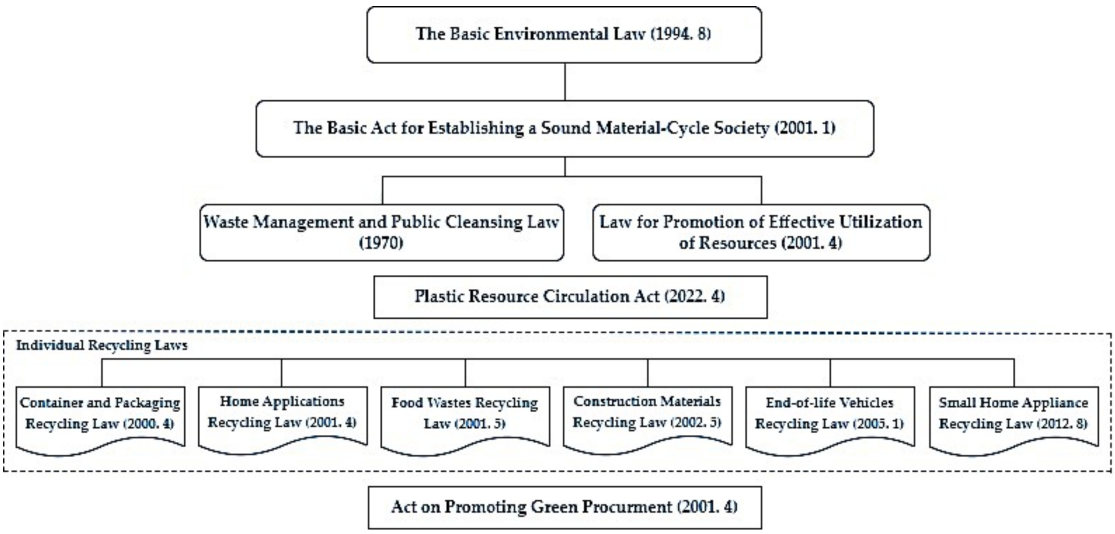

Figure 5. Legal framework for waste management and recycling in Japan [137–141].

These laws collectively aim to manage waste products in a manner that prioritizes safety and environmental sustainability. In Japan, waste management operates at three levels: the central government formulates policies and standards, prefectures oversee plans and facilities, and municipalities implement strategies and guide waste reduction efforts [142]. Efforts to reduce the consumption of natural resources and minimize waste are facilitated through the promotion of the 3Rs (reduce, reuse, recycle) policies and sustainable development initiatives. The endeavor to establish a sound material-cycle society is emphasized through the Basic Act for Establishing a Sound Material-Cycle Society, enacted in 2000 and enforced in April 2001 (2001.4) [143,144]. To effectively promote the 3Rs and achieve synergistic outcomes, five key implementation strategies are considered necessary: increasing awareness, fostering partnerships among relevant bodies, facilitating information sharing, conducting technological research and development, and providing incentives [145]. These approaches collectively contribute to Japan's commitment to waste reduction and sustainable resource management.

4.2.2. MSW Characteristics, Composition, Separation, and Collection

Waste in Japan is classified into two main types, industrial waste and municipal waste, as defined by the Waste Management Act [18]. The MSW category mainly consists of waste, raw sewage, and specially controlled municipal waste sourced from households and businesses. Specially controlled waste is further categorized based on hazardous properties, such as those containing PCB, dust, or infectious materials [85,146]. According to a 2019 survey on MSW, the waste generation rate is 0.90 kg/person/day, with the waste composition in the country consisting of 48% paper and cloth, 24% plastics, synthetic resins, rubber, and leather, 10% wood, bamboo, and straw, 12% kitchen waste, 3% non-combustible material, and 3% other [18,147]. This waste composition makes it suitable for introduction into incineration facilities for WtE implementation, as the low percentage of kitchen waste results in a lower moisture content and higher heating potential [148,149].

Municipal waste separation methods in Japan vary depending on the disposal systems implemented by cities, towns, and villages. These systems often involve designated plastic bags and specific rules set by local municipalities for waste separation and disposal [150,151]. The primary categories for separating regular MSW typically include combustible waste, non-combustible waste, recyclable waste, oversized waste, and hazardous waste [152]. For instance, in Hiroshima City, household waste is divided into eight categories, including combustible waste, PET bottles, recycling plastics, non-combustible waste, recyclable waste, hazardous waste, and oversized waste [153]. MSW generation sources are broadly categorized into residential waste from individual homes and commercial waste from larger establishments such as offices, hotels, and schools. Residential waste is typically collected by municipalities, organizations, and private companies, while commercial waste is managed by authorized waste collection companies [154].

4.2.3. Environmental Impact and Treatment Technologies

During the period from 1945 to the 1950s, Japan primarily disposed of waste by dumping it into rivers, oceans, or open lots, leading to public health issues such as fly and mosquito infestations and the spread of infectious diseases [155,156]. In the 1950s, the Japanese government began focusing on addressing social conditions by implementing policy responses and applying technologies to manage the increasing waste and resolve waste-related problems. Efforts included improved waste collection and disposal methods, along with the promotion of technological solutions such as incineration. Despite the crucial role played by incineration technology, issues arose with air pollution due to emissions of dioxins and polychlorinated biphenyls (PCBs) from burning plastics in both domestic and industrial waste [157–159]. Furthermore, incineration posed risks associated with heavy metal leaching from fly ash and bottom ash, exceeding Japanese risk levels, particularly for metals like Pb, Cr, Cd, and Se [160]. Additionally, the discharge of plastic waste into rivers and seas has become a critical issue and challenge for Japan's marine environment. Research by Kataoka et al. [161] demonstrated the presence of microplastics in Japanese river environments, with plastics breaking down into small fragments before entering the ocean. The identified sources of microplastic pollution include both point sources, such as wastewater treatment plants (WWTPs), and non-point sources. WWTPs are significant contributors to ecological risks in rivers, creating pollution hotspots downstream by releasing high numbers of microplastics and toxic polymers [162,163]. Japan has experienced challenges regarding the environmental impact of waste. However, ASEAN regions face a higher number of issues compared to Japan, including the impact of waste on air, water, and soil pollution, as shown in Table 4.

Due to Japan's limited land area and scarcity of landfill space, waste undergoes intermediary treatments such as incineration before being carefully deposited in sanitary landfills; this represents the primary waste management method in the country [164]. MSW incineration technology has been utilized since the 1960s in Japan, with 1243 incineration facilities operating by 2009. These facilities boast high-level environmental conservation technology, including pollution prevention measures and high-efficiency power generation capacities [165]. Although the number of plants has decreased to about 1028, power generation facilities have increased to encompass 38.5% of all plants, with a total power generating capacity of 2149 million kilowatts. Concurrently, the amount of available sanitary landfill space has also decreased, with a remaining capacity of 98.45 million m^3 in 2022 compared to 99.84 million m^3 in 2020 [135]. To optimize waste incineration plants, integrating the MBT system is a significant option. This system allows for the utilization of food waste and sewage sludge from waste incineration plants, sewage treatment plants, and industrial facilities, mixing them to produce methane gas for energy while simultaneously reducing CO_2 emissions [166,167].

Table 4. Previous issues and treatment technologies on MSW in ASEAN-Japan nations.

Country	Environmental Concern (Published)	Treatment and Disposal	Reference
Japan	- Heavy metals in bottom ash. - CO_2, SO_x, NO_x, and PM emission. Cost recycling and transport from disaster waste treatment.	- Intermediate treatment (94.4%). - Recycled (4.6%). - Landfilled (1.0%).	[18,168–170]
Singapore	- Heavy metals in bottom ash. - Effects of particle size on chemical compositions of incineration bottom ash.	- Recycled (58%). - Incinerated (40%). - Landfilled (2%).	[171–173]
Brunei	- Climate change and water pollution from construction waste.	- Landfilled (85%). - Recycled (15%).	[9,171,174]
Cambodia	- GHG emissions from landfill sites. - Heavy metal contamination in leachate and sediments. - Leaking of microplastic to soil.	- Landfilled (44%). - Incinerated (4%). - Recycled (4%). - Composted (2%).	[77,171,175–177]
Indonesia	- Leaking of microplastic to soil. - Marine plastic pollution. - Particulate matter ($PM_{2.5}$) risk to workers in landfill sites. - Toxic heavy metals contaminated the sediment and rivers.	- Landfilled (68.64%). - Dumped (9.47%). - Composted (7.10%). - Burned (4.73%). - Discharged into rivers (3.55%). - Others (6.51%).	[110,171,177–180]
Laos	- Leaking of microplastics to the soil and water environments. - Heavy metal accumulation in leachate, soil, and plants in the landfill environment. - GHG emissions from landfill sites.	- Landfilled (<50%). - Recycled (<50%). - Composted (n.d.). - Burned and discharge into rivers (n.d.).	[9,171,177,181–183]
Malaysia	- CO_2, SO_x, NO_x, HCl, and HF are emitted during the incineration. - Leaking of leachate to rivers. - Microplastics in the water environment.	- Landfilled (53.2%). - Recycled (22%). - Incinerated (16.8%). - Composed (8%).	[184–187]

Table 4. *Cont.*

Country	Environmental Concern (Published)	Treatment and Disposal	Reference
Myanmar	- GHG emissions. - Air pollution (PM, TSPM). - Leachate.	- Landfilled (83%). - Recycled (13%). - Incinerated (1%). - Other methods (3%).	[95,171,188,189]
Philippine	- Leaking of microplastics to soil. - Short-lived climate pollutants. - Plastic emissions into rivers. - Toxic heavy metals.	- Improperly disposed or littered (10–60%). - Recycled (21%). - Composted (n.d.). - Sanitary landfill (4%).	[75,109,171,177,190,191]
Thailand	- Leaking of microplastics to soil. - Microplastic-contaminated leachate, surface, and groundwater. - Heavy metals contaminated in leachate and a high concentration of air pollution.	- Landfilled and incinerated (36%). - Sorting and recycling (33%). - Open dumping and open burning (31%).	[171,192–194]
Vietnam	- GHG emissions. - Leaking of microplastics to soil. - High leachate pollution index (LPI) value.	- Landfilled (34%). - Recycled at treatment plant (42%). - Improperly disposed of (24%).	[67,171,177,195,196]

5. Laos' Municipal Solid Waste Analysis Based on Vientiane

This section presents a comparative analysis of MSW management between VT, a representative municipality in Laos, and international regions of ASEAN-Japan. The comparison focuses on solid waste generation and composition, environmental and health impacts, treatment technology, and resource recovery. The objectives are: (1) to highlight differences and similarities and (2) to establish effective MSW management practices in VT by identifying good practices and recommended perspectives from international experiences.

5.1. Comparison of MSW Generation Based on Population and Gross Domestic Product

From 2010 to 2020, in VT, economic and population growth have influenced the quantity of MSW generated. The waste generation rate of 0.75 kg/capita/day has led to an increase in waste production in the Vientiane municipality. Based on waste disposal data in landfills, the amount rose from 86,023 tons in 2012 to 143,891 tons in 2020, marking a 67.3% increase and an average annual growth rate of approximately 6.7%. More than half of the solid waste generated in the city has been disposed of by residents themselves, primarily because the MSW collection service covers less than 40% of the city [33].

The population in VT had reached 948,477 by 2020, excluding the number of tourists. This figure is projected to increase to more than 1 million by 2023, representing a 5.43% increase over the last three years. The growth rate of the GDP also rose compared to the previous year, reaching 4.42% in 2022 [25]. Vientiane has projected MSW generation to increase from 1,115 tons/day in 2023 to 1,512 tons/day in 2030, marking a 35.6% increase [33]. When comparing the rates of increase, the results suggest that MSW generation is slightly closely related to population and GDP growth. The quantity of waste generated in VT has increased annually, paralleling population growth, even though the GDP has declined in the last two years (Figure 6A). In contrast, developed countries in ASEAN like Singapore, as shown in Figure 6B, experience fluctuations in MSW in line with the GDP trends, with slight decreases in some waste compositions. In upper-middle-income countries like Thailand and Malaysia, the MSW increases year by year in parallel with population growth, even though the GDP fluctuates (Figure 6C,D). Similarly, the lower-middle-income country of Vietnam shows a similar trend, as seen in Figure 6E. The population and GDP mostly experience continuous growth in ASEAN nations due to rapid urbanization, leading to a parallel increase in waste generation, although in some countries, GDP has fluctuated [197], exhibiting differences in the characteristics of the MSW, population, and GDP relationship [33,79,198–201]. However, it is not only GDP and population factors that influence waste increase or decrease but also policies in waste management and tourism development [202,203].

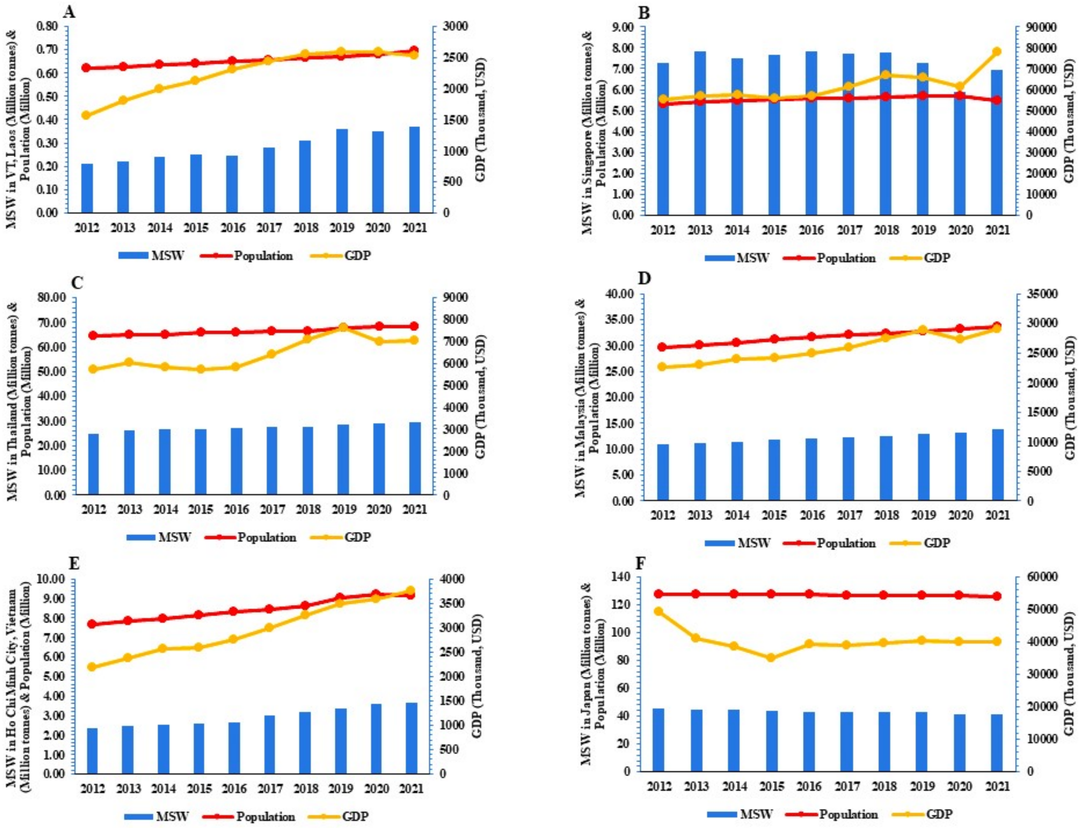

Figure 6. The relationship between MSW generation and influencing factors such as population and GDP in VT (**A**), Singapore (**B**), Thailand (**C**), Malaysia (**D**), Vietnam (**E**), and Japan (**F**), respectively.

Japan has shown a year-by-year decrease in MSW, as shown in Figure 6F. The trend is attributed to the development of comprehensive systems such as waste reduction initiatives, stringent regulations, advanced recycling systems, waste separation programs, public awareness and education, innovative technologies, and circular economy practices [18].

Other countries in ASEAN exhibit a trend of increasing MSW generation parallel to population and GDP growth, similar to other developing countries in the region. Although some countries, like Brunei, lack updated information on waste generation, recent research indicates an increase from 0.18 million tons in 2005 to 0.21 million tons in 2014, with a generation rate of 1.4 kg/capita/day [87]. However, the government has a strategy to reduce this to 1 kg/capita/day by 2035, focusing on waste separation and WtE technology options [204]. In Cambodia, MSW generation data show an increase of approximately 24.16% from 2010 to 2020 [77]. Indonesia has projected a waste increase of approximately 6.41% from 2019 to 2025 [205], while Myanmar predicts a total waste increase of about 61.54% from 2018 to 2025 [206]. The Philippines has experienced a trend of increasing waste generation at a rate of about 33.90% from 2010 to 2020 [207].

5.2. Comparison of MSW Composition

Due to rapid growth in their populations and economic activity, cities have become primary destinations for migration and habitation, resulting in heightened consumption, including food, lifestyle choices, travel, and increasing material needs. These factors contribute to a rise in MSW generation. This increase has, in turn, impacted the composition and characteristics of MSW, which now exhibits notable differences compared to earlier patterns. In ASEAN-Japan nations, the proportion of kitchen or organic waste averages about 46.09%, with households being the main sources. Specifically, the percentages are as follows: Myanmar 77%, Thailand 64%, Laos approximately 55.81% (four cities), Cambodia 55%, Vietnam 55%, the Philippines 52%, Indonesia 43.78%, Brunei 36%, Malaysia 36%, and Singapore 10.5%. Japan, as a developed country with extensive experience in waste management, has a lower amount of kitchen/organic waste at approximately 22%, which includes kitchen waste as well as wood, bamboo, and straw [18].

In the case of VT, Laos, the waste composition shows that organic waste covers 67% of total waste generation, followed by plastic at 12.1%, paper/cardboard at 8.8%, glass at 3.3%, and others, as shown in Figure 2A. At landfill, the waste composition reveals that organic waste comprises approximately 56%, plastic 27%, paper/cardboard 6%, textiles 3%, glass 2%, and other waste 6% [33]. This highlights that most waste generation is disposed of in unsanitary landfills, with a low rate of recycling or waste recovery compared to developed countries in the ASEAN and Japan nations (e.g., Singapore and Japan). In Singapore, MSW management involves collecting waste from homes and businesses, with non-segregated waste being transferred to WtE plants for incineration and recovery to generate electricity [51]. According to the National Environment Agency (NEA) in 2022, food waste generation is approximately 813,000 tons, with a recycling rate of about 18%. To encourage food waste reduction, the NEA has developed specific strategies and a guidebook on food waste management [208]. Japan has comprehensive systems for dealing with MSW, with only 9.3% of waste being disposed of in landfills, including direct disposal of 1.0% and final disposal after intermediate treatment of 8.3% [18]. The intermediate treatment includes incineration, composting, and MBT, with these methods significantly contributing to reducing municipal waste in Japan [209,210].

5.3. Comparison of Environmental Impact and Treatment Technologies

Landfilling is a prevalent method for managing MSW; however, landfill leakage into the environment is a crucial concern due to intricate composition and elevated pollutant levels. This issue has emerged as a significant global eco-environmental problem [108,211,212]. Particularly in developing countries, landfills have higher concentrations of chemical pollutants in ground and surface waters, and soil environments due to heavy metals [191,213]. Additionally, the microplastics from waste contribute to environmental contamination [214,215]. The open dumping and burning of waste is a major environmental issue in ASEAN regions, notably in lower-middle-income economies such as Indonesia, the Philippines, Vietnam, Cambodia, and Myanmar. For example, MSW landfill in Indonesia have released micro-mesoplastics into the aquatic environment through landfill leachate [216], while particulate matter (PM) from these landfill has impacted the health of workers. Additionally, open waste burning is linked to an increased risk of chronic diseases [179,217]. Similar issues exist in the Philippines, Vietnam, Cambodia, and Myanmar, where final disposal causes toxic chemical contamination in leachate, impacting ecological health [176,218–220]. Air pollution (e.g., CO_2, CH_4) also contributes to the environmental impact [221,222]. In upper-middle-income economies like Malaysia and Thailand, improper waste management leads to the presence of toxic chemicals in the environment, which could affect human health [223,224]. High-income economies like Singapore have assessed incineration as leading to air pollution and contributing to climate change, acidification, and ecotoxicity, harming both human health and the environment. Due to national policies limiting landfilling to only 10% of the total disposed waste, landfill gases and leachate generate minimal environmental damage [225,226]. The limited research on the MSW impact assessment in Brunei Darussalam generally identifies solid waste disposal as a cause of pollution to the air, water, and environment [227,228]. Japan has a lengthy history of environmental impact caused by the disposal of solid waste into rivers and oceans, resulting in public health problems such as infestations of flies and mosquitoes and the transmission of infectious diseases [18]. However, Japan currently serves as a model for global best practices in waste management. In Laos, there is limited specific research on pollutant issues from MSW, but a few studies have been conducted. For instance, toxic heavy metals have contaminated soil, plants, and groundwater near landfill sites [182]. Improper MSW management has led to the prevalence of microplastic polymers, which have contaminated urban surface water [181]. Additionally, toxic metals have been found in some fish species from landfill ponds/wetlands that are commonly consumed by local people living near these areas [229]. Currently, there is still a lack of attention and enforcement regarding specific plastic waste management, resulting in plastic waste being disposed of in waterways and main rivers in Laos [12]. These issues highlight that Laos still lags behind upper-middle-income and high-income economies in ASEAN and Japan.

In the ASEAN regions, landfilling remains the primary method for managing MSW, except in Singapore, as shown in Figure 7. There is a growing trend towards WtE solutions as an alternative to direct waste disposal, employing various techniques and technologies. Singapore is a leader in ASEAN countries in waste treatment technologies, advancing towards a circular economy (CE). The CE strategy implemented in 2019 aims to reduce consumption by increasing reuse and recycling and adopting the 10R strategy to achieve zero waste (reducing landfill usage by 30%) by 2030 [230]. The nation aims to improve the recycling rate to 70% by 2030, driven by two priorities: waste minimization and recycling. This effort includes utilizing WtE plants to efficiently reduce waste volume and generate electricity [231]. The Tuas Nexus plant is a state-of-the-art facility integrating various waste treatment processes with a capacity of 5800 tons/day for WtE, 250 tons/day for materials recovery facility (MRF), 400 tons/day for a food waste treatment facility, and 800 tons/day for a sludge incineration facility [232]. Thailand, Malaysia, Vietnam, Indonesia, and Myanmar have also adopted technologies to transition towards a CE within their own countries. While this signifies progress, there are still issues such as public perception, public–private partnerships, financial constraints, and climate factors [95,118,233–237]. Meanwhile, Cambodia, Brunei, and the Philippines continue to rely on conventional methods, utilizing sanitary landfilling and dumping. Although there are small-scale pilot WtE facilities, there have yet to be a commercial WtE plants producing electricity in these countries [77,118,131]. Japan embarked on the adoption of a CE as early as 1870 and implemented recycling legislation in 1991 [238]. The country has 1028 WtE facilities, representing a decrease of 2.7% from 1056 in 2020 but with highly improved advanced environmental conservation measures. The total power generating capacity stands at 2,149,000 kilowatts, marking a 3.3% increase from 2,079,000 kilowatts in 2020 [135]. In recent years, Japan has significantly improved waste management, achieving a 20% increase in recycling rates alongside a corresponding decrease in incinerator numbers. Embracing circular design principles has propelled the development of WtE and heat-recovery technologies. Consequently, the government prioritizes three key objectives: reducing incinerators, increasing recycling rates, and lowering total costs [239]. In contrast, Laos continues to rely on conventional methods such as landfilling and open dumping; currently, there is no WtE plant [16,118].

5.4. Trend and Perspectives

The integrated solid waste management (ISWM) systems must leverage state-of-the-art technological advancements and advanced methods to maximize resource utilization and minimize environmental and health impacts. Methodological concepts in MSW management, including operation, treatment, disposal, and resource utilization, as presented in various sections, are increasingly being adopted by developing countries, inspired by practices in developed nations like Japan and Singapore. Particularly, the development of technologies for WtE conversion and the transition towards a CE will be significant trends in Laos in the coming years. Semi-landfill could be employed to generate biogas and biomaterials, contributing to environmental protection. Additionally, the utilization of waste materials can be effectively implemented across the entire country. Incineration plants are likely to become the mainstream application for waste management. However, a major challenge will be efficiently converting MSW into energy/fuel, given the diverse characteristics of waste. Addressing the high moisture content of MSW in Laos is a crucial factor for enhancing WtE efficiency.

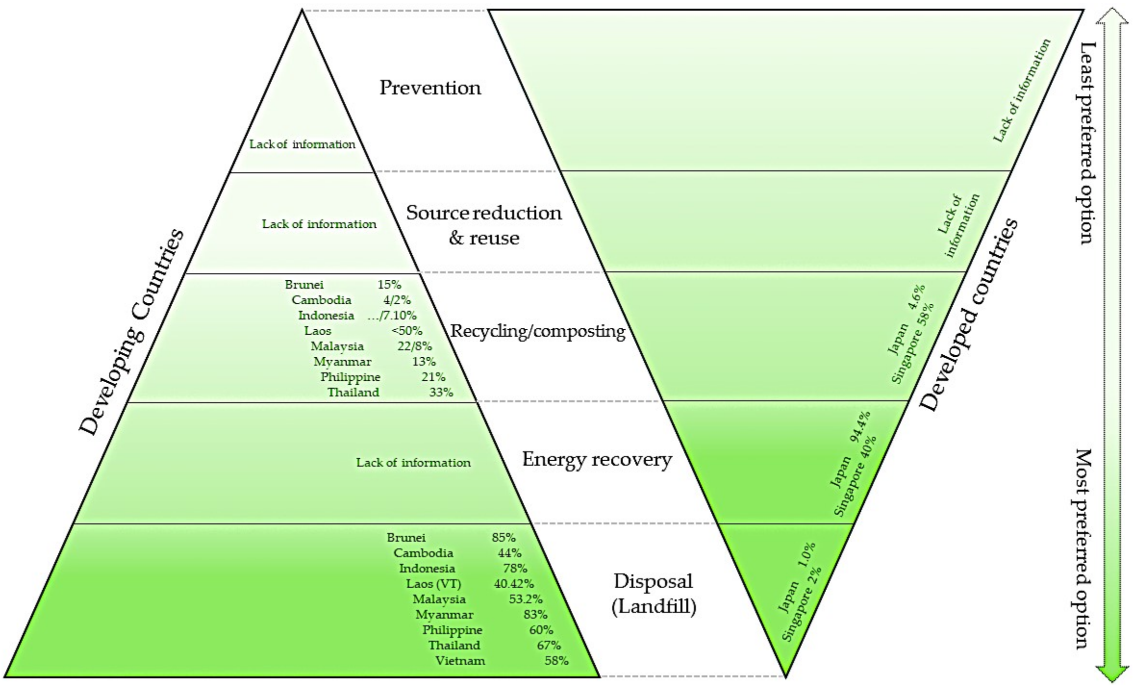

Figure 7. Hierarchy in MSW management between developing and developed countries.

To control MSW generation and mitigate environmental issues, the government should regulate and enforce nationwide implementation of MSW classification and collection, drawing lessons from developed countries. This includes adopting advanced technologies for waste material recovery through WtE practices, such as incineration plants and the utilization of sanitary landfill gas. Furthermore, the legal and regulatory framework for waste management in Laos must be clearly defined, with individual articles integrated into national policy and strategy. The implementation of the 3Rs strategy (reduce, reuse, and recycle) should be intensified for greater efficiency. Additionally, a carefully crafted policy should enhance prevention, reuse, and recycling, while simultaneously promoting WtE and WtM conversion for the waste produced.

6. Conclusions

The MSW in VT, along with nine ASEAN nations and Japan, has been analyzed in terms of background information, characteristics, environmental issues, and technologies for treatment and disposal. The findings indicate a continuous rise in MSW generation in nine ASEAN nations (excluding Singapore), with VT's total annual generation increasing from 0.21 Mt in 2012 to 0.37 Mt in 2021. In contrast, developed countries like Japan and Singapore have experienced a decreasing trend in MSW generation, declining from 45.23 Mt in 2012 to 40.95 Mt in 2021 in Japan and from 7.27 Mt in 2012 to 6.94 Mt in 2021 in Singapore. The composition of MSW is complex, with organic waste comprising the majority of components, ranging from approximately 36% to 77%, except in Japan and Singapore. Lower-middle-income ASEAN countries generally exhibit low rates of domestic waste recycling and waste recovery. Common practices include the use of unsanitary landfills and open dumping methods for MSW management, leading to environmental issues such as soil, water, and air pollution and resulting in bioaccumulation and adverse effects on human health. Developed countries like Japan and Singapore have implemented comprehensive waste management systems, incorporating advanced technologies for WtE practices, such as incineration plant and sanitary landfill gas utilization. Additionally, specific laws, acts, regulations, and policies provide guidance for enforcement and support on MSW management. In conclusion, Laos faces limitations in MSW management, particularly in waste recovery and WtE practices, which are key factors in ISWM and contribute to environmental and economic sustainability. To enhance MSW management in Laos, the following measures are essential: (1) Developing a waste management act that includes waste segregation, recycling strategies, and extended producer responsibility (EPR) policies is crucial. (2) Technological advancements such as MBT facilities for waste separation, WtE plants for energy generation, and upgraded landfills are vital for sustainability. (3) Capacity building through training programs for municipal staff and public awareness campaigns on waste segregation and recycling foster community support. These measures will significantly improve Laos's MSW management, reduce environmental impacts, and enhance public health, contributing directly to the SDGs, particularly in advancing sustainable cities and communities.

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