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Estimation of Leachate Volume and Treatment Cost Avoidance Through Waste Segregation Programme in Malaysia

Josfirin Uding Rangga[1,2], Sharifah Norkhadijah Syed Ismail[1]*, Irniza Rasdi[1] and Karmegam Karuppiah[1]

[1]*Department of Environmental and Occupational Health, Faculty of Medicine and Health Sciences, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia*
[2]*Department of Health Sciences, Faculty of Humanities and Health Sciences, Curtin University Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia*

ABSTRACT

This study aims to calculate the avoided leachate volume and treatment cost from waste segregation practices compared to the existing waste disposal methods of landfilling. The mathematical equations were used to analyse the waste segregation rate, leachate volume and treatment cost. The study findings reveal that 99.4% of mixed waste was disposed of in landfills, resulting in an annual generation of 565 thousand cubic meters (m^3) of leachate with an estimated treatment cost of MYR 19.82 million (USD 4.36 million). The segregated waste, which accounts for only 0.06%, reduces 354 m^3 in leachate volume and a cost-saving of MYR 12.42 thousand (USD 2.73 thousand) in the treatment expenses per year. The findings concluded that waste segregation practice could reduce waste management costs by reducing leachate production and treatment costs and environmental impacts.

Keywords: Environment, health, leachate generation, recycling, waste

INTRODUCTION

Globally, 2.01 billion tonnes of municipal solid waste are generated annually, and this figure is projected to increase to 3.04 billion tonnes by 2050. The worldwide waste generation per capita ranges from 0.11 to 4.54 kg per day. It is estimated that waste generation will increase by 19% in high-income countries, while low- and middle-income countries are expected to experience

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E-mail addresses:
josfirin@curtin.edu.my (Josfirin Uding Rangga)
norkhadijah@upm.edu.my (Sharifah Norkhadijah Syed Ismail)
irniza@upm.edu.my (Irniza Rasdi)
megam@upm.edu.my (Karmegam Karuppiah)
* Corresponding author

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a growth of over 40% by 2050 (Kaza et al., 2018). In Malaysia, the available data showed a significant increase in daily waste generation in recent years, from 36,843 tonnes in 2018 to 39,936 tonnes in 2022 (Bernama, 2022). In a year, the country generates about 12,840,000 million t/yr. Of waste (Jain, 2017). A Malaysian generates about 1.03 kg of waste per day, which is higher than Japan (0.98 kg/capita/day), China (0.63 kg/capita/day), and India (0.5 kg/capita/day) (Hoornweg & Perinaz, 2012). The Malaysian recycling rate has increased from 24.6% in 2018 to 31.5% in 2021; by 2025, the government will achieve a 40% recycling rate (Jamliah, 2022; Kamel, 2021). Other countries, such as Germany, South Korea, and Austria, have a higher recycling rate than Malaysia, which are 67.1%, 59.7%, and 59%, respectively (Tiseo, 2022).

Approximately 37% of global waste is disposed of in landfills, 31% is dumped in open sites, 19% is recycled and composted, and 11% is disposed of through incineration. The remaining 8% of waste is disposed of in sanitary landfills with landfill gas collection systems (Kaza et al., 2018). About 65% of waste in Malaysia comes from households, 28% from commercial and institutions, and 7% from industrial waste (National Solid Waste Management Department, 2013). The country disposes of 69% of waste in landfills, which does not include illegal or open dumping waste where the amount may be higher than reported (Jamliah, 2022). There are 158 active landfills throughout the country, with 141 non-sanitary and 17 sanitary landfills (National Solid Waste Management Department, 2021). Landfilling is the primary waste disposal method in the country due to its low maintenance cost and ease of operation (Imran et al., 2019). However, it is not the best solution for waste management, as landfills cause environmental degradation. One of the landfills' problems is leachate generation and uncontrolled discharging into the environment. A recent study indicated that an effective solid waste management system should encompass environmentally friendly and cost-effective solutions while requiring collaboration among government, non-governmental agencies, and the community. The study emphasised that this can be accomplished by implementing waste segregation using the 4Rs approach: reduce, reuse, recycle, and recover (Mor & Ravindra, 2023).

Landfill leachate is the liquid formed when rainwater filters through waste in a landfill. When this liquid encounters buried waste, it leaches or draws out chemicals or constituents from it (USEPA, 2023). The volume of leachate and its compositions depend on the waste compositions, moisture availability, age of landfill sites, rainfall intensity, and land area. Organic waste and construction and demolition debris contribute to organic and inorganic constituents in leachate; for example, disposal of lead batteries, cans, steel scrap, electronic devices, thermometers, fluorescent lights, and other products in a landfill will generate leachate containing heavy metals (Maiti et al., 2016). The high moisture of the waste or landfill causes a high volume of leachate due to the moisture in the stabilisation rate and supports the methanogenic fermentation of solid waste (Adhikari et al., 2014). In terms of landfill age, leachate generation decreases over time due to waste stabilisation and reduced filtration rate (Aziz et al., 2012). Even a closed landfill produces some leachate (Ibrahim et al., 2017). Rainfall intensity influences leachate generation because intensive precipitation increases the volume of leachate (Aziz et al., 2012). A large landfill area also generates a high volume of leachate (Ibrahim et al., 2017). Its compositions are categorised into three groups: organic matters (i.e., biochemical oxygen demand, chemical oxygen demand), inorganic matters (i.e., phosphates, sulphates, ammonia, nitrate, nitrogen, and chlorides), and heavy metals (i.e., cadmium, chromium, lead, nickel, zinc, mercury, copper) (Maiti et al., 2016; Magda & Gaber, 2015).

Leachate generation in landfills has become a concern as improper landfills and leachate management will lead to environmental pollution, such as groundwater and soil pollution. For instance, a study conducted by Suratman et al. (2011) in Malaysia reported that leachate quality from most non-sanitary landfills exceeded the standard limits, and water sources were polluted. Non-sanitary landfills in Malaysia have a more severe impact on surface and groundwater contamination than sanitary landfills (Taha et al., 2011). For example, a study in Nigeria determined a high concentration of heavy metals in landfill leachate and water samples (Aderemi et al., 2011). A study by Sharifah et al. (2015) also reported a high concentration of heavy metals in Malaysia's topsoil of non-sanitary landfills. The contaminated groundwater with heavy metals that serve as a source of drinking water, as well as the accumulation of heavy metals in soil and vegetables in high amounts, can cause adverse health effects to both animals and human beings (Foufou et al., 2017; Khaled & Muhammad, 2016).

Thus, it is necessary to design the engineering control of leachate pollution properly and build treatment facilities to reduce these adverse environmental impacts. For example, properly lining landfill cells and leachate ponds can minimise groundwater contamination (Magda & Gaber, 2015). A combination of conventional (i.e., nitrification and denitrification process) and advanced technologies (i.e., integrated method of physiochemical, biological, chemical, and physical treatment) provide a sustainable, cost-effective, and environmentally friendly (Aziz & Ramli, 2018; Show et al., 2019). Despite this, developing countries like Malaysia face barriers to these good facilities, such as budget constraints and trained operators (Aziz & Ramli, 2018). On average, the Malaysian government requires USD5 billion per year to manage waste in the country (Utusan Online, 2017). The fee for leachate treatment alone is about 35 Malaysian Ringgit (MYR) per cubic meter (m^3) (Ministry of Housing and Local Government, 2015).

Waste minimisation and recycling are proven to be the best methods to reduce the amount of waste being dumped in landfills as well as reduce the generation of leachate. Under the Solid Waste and Public Cleansing Management Act, 2007 (Act 672), waste segregation at the source is mandatory, as stated in Section 74 (1) and (2). Households need to segregate their waste into food, paper, plastic, miscellaneous, and non-recyclable waste, and noncompliance may result in a fine of no more than RM 1000. It is crucial to enhance waste segregation programmes to facilitate the separation of recyclable materials, organic waste, and hazardous waste for recycling, composting, or treatment. These approaches will aid in reducing the overall volume of waste being disposed of in landfills, thus promoting resource conservation and minimising the environmental impacts associated with waste generation (Coelho & Lange, 2018; Slagstad & Brattebø, 2012).

Proper waste segregation enables effective recycling and resource recovery, which helps conserve natural resources, save energy, reduce the demand for raw materials, and mitigate emissions (Liikanen et al., 2018). The programmes also promote the separate collection and treatment of organic waste, reducing the volume of waste in landfills and contributing to renewable energy generation in the form of biogas through anaerobic digestion treatment (Liu et al., 2017). Diverting organic waste from landfills significantly reduces the generation of greenhouse gas emissions. The study by Turner et al. (2015) reports that recycling source-segregated materials can reduce 70% of GHG emissions and global warming potential. Similarly, achieving a source-separated collection efficiency of 25% for food waste and 17% for other wastes can help avoid 77% of GHG emissions (Jun et al., 2013). The government can implement this strategy as part of its efforts to mitigate climate change and achieve environmental goals in Malaysia.

Separating hazardous materials, such as batteries, chemicals, and electronic waste, at the source enables proper handling and disposal, thereby preventing environmental and human health harm (Kaya, 2016; Pathak et al., 2019). For example, increasing the source segregation intensity from 25% (74.6% residual MSW, 19.0% paper, 6.40% packaging) to 52% (51.9% residual MSW, 11.6% paper, 12.1% light packaging, 17.9% organic, 3.30% glass, 3.20% metals) could result in significant reductions in the potential for human toxicology, terrestrial eco-toxicity, GHG emissions, and leachate production (Maria & Micale, 2014). Environmental pollution, such as soil and water pollution, can be prevented if hazardous and non-hazardous are properly managed.

Promoting waste segregation practices has a positive impact on raising public awareness and education. It helps foster a sense of environmental responsibility and sustainability among individuals and communities. Increased awareness can drive long-term behaviour change and cultivate a culture of sustainable waste management practices (Debrah et al., 2021; Knickmeyer, 2020). In addition, waste segregation programmes support the principles of a circular economy by promoting the recovery of valuable resources from waste streams (Ministry of Economy, 2021). Separating recyclable materials to be recycled and reused reduces the demand for virgin resources. It conserves natural resources and reduces energy consumption and associated environmental impacts from resource extraction and manufacturing processes (Ministry of Economy, 2021). Thus, Malaysia needs to implement waste segregation effectively to aid the country in moving towards sustainable waste management practices as well as contributing to achieving national and international environmental goals (Ministry of Economy, 2021; Ministry of Housing and Local Government, 2015).

There are limited studies done to elucidate the contributions of waste segregation to the avoided leachate generation in landfills and the cost savings to the leachate treatment, especially in Malaysia. The available study by Abunama et al. (2018) only determined the elements that contribute to leachate production, such as waste volume, rainfall level, and emanated gases, using the developed model of adaptive neural fuzzy inference system (ANFIS). A previous study by Ibrahim et al. (2016) only estimated the volume of leachate generated by closed landfills in Selangor using simple mathematical models where rainfall level and landfill size were considered. Another study by Aziz et al. (2012) also analysed the leachate generation rate by applying the field measurements and the Water Balance Method (WBM). A recent study conducted in Malaysia has shown that the commercial and industrial sectors actively reuse and recycle end-of-life vehicles (ELVs) to reduce waste disposal. It is achieved through donating, selling, trading, and sending unused vehicle parts to workshops (Othman et al., 2021). Most studies did not focus on the cost estimation for the leachate treatment. Recent studies on waste management have reported the development of composites from plastic waste and the transformation of waste into green building materials (Soni et al., 2022; Soni et al., 2023). These approaches can reduce the volume of waste as well as leachate generation when waste segregation and recovery are effectively implemented.

Thus, the present study aims to estimate the volume of leachate generated from landfilled waste and the avoided volume from segregated waste. The study intended to estimate the cost of leachate treatment through waste landfilling and cost savings through waste segregation. Waste segregation efficiency is the key factor in estimating leachate volume in a waste segregation program in Malaysia. Efficient segregation methods help divert recyclable and biodegradable waste from landfills, reducing waste volume and potential leachate generation. The second factor is the waste generation rate. The volume of waste generated is a crucial factor in estimating leachate volume. The higher the amount of waste generated, the greater the potential for leachate production. In addition, the composition of the segregated waste plays a significant role in estimating leachate volume. The estimations will aid authorities in designing and operating effective treatment systems, determining treatment requirements such as the capacity of the leachate collection system, and facilitating financial planning by providing cost estimates for maintenance and operational budgeting. The waste volume (tonnes) data was obtained from SWCorp and analysed using the adapted mathematical models. Six states of Malaysia and two Federal states were selected as the study area as the waste segregation programme under

Act 672 has been imposed in these states since 2015. The study's findings are expected to aid the authorities in planning waste management strategies regarding waste reduction and environmental impact protection. A model of leachate quantification and treatment cost estimation could also serve as the baseline data expected to stimulate more research on waste management in Malaysia.

METHODOLOGY

Study Area

The states under Act 672 were selected as the study area. The selected states were Kuala Lumpur (KUL), Putrajaya (PJY), Pahang (PHG), Perlis (PLS), Kedah (KDH), Negeri Sembilan (NSN), Melaka (MLK), and Johor (JHR) as shown in Figure 1. Pahang is the largest state, with around 35,965 square kilometres (km^2). The second-largest state is Johor (19,166 km^2), followed by Kedah (9,492 km^2), Negeri Sembilan (6,656 km^2), Melaka (1,720 km^2), Perlis (816 km^2), Kuala Lumpur (243 km^2) and Putrajaya (49 km^2) (Department of Statistics Malaysia, 2019b). Johor has the largest population (3,776.0 million), followed by Kedah (2,178.7 million), Kuala Lumpur (1,796.7 million), Pahang (1,679.7 million),

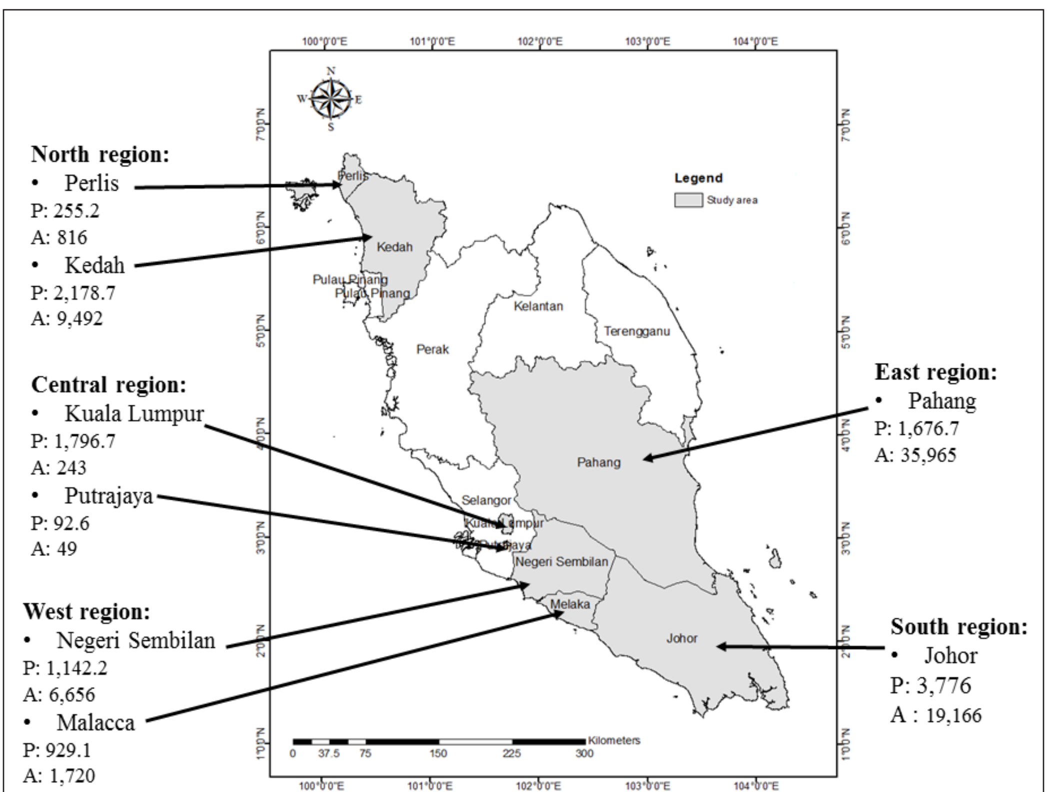


Figure 1. The selected study area (states) in west Malaysia: P: population ('000); A: area (km^2).

Negeri Sembilan (1,142.2 million), Perlis (255.2 million) and Putrajaya (92.6 million) (Department of Statistics Malaysia, 2019a).

The states were chosen because household waste segregation at source is mandatory under Act 672. Selangor, Perak, Penang, Terengganu, and Kelantan were excluded as they still did not conform to the Act when the study was conducted. The Act only applied to Peninsular Malaysia. Thus, the Borneo regions of Malaysia (Sabah and Sarawak) were excluded from the study as both states have their law and regulations.

Study Variables and Mathematical Models

Segregation Rate (SR). The segregation rate (%) was determined using Equation 1, adapted from the National Solid Waste Management Department (2013). Waste segregation rate (SR) is defined as the total segregated waste (SegW) volume divided by total solid waste volume (tSW) multiplied by one hundred. The tSW is the total volume of landfilled and segregated waste (tonne).

$$SR = \sum \left[\frac{SegW}{tSW} \right] \times 100 \qquad (1)$$

The Volume of Leachate (VL). The mathematical model of Equation 2 was used to estimate the volume of leachate generated in landfills. It was adapted based on the reported value by the KPKT (2015). Where the volume (m^3) of leachate (VL) is equal to the volume (tonne) of solid waste (SW) multiplied by 0.21 cubic meters (m^3t^{-1}), a tonne (t) of waste could generate 0.21 cubic meters (m^3) of leachate (KPKT, 2015).

$$VL = \sum SW \times 0.21 \qquad (2)$$

Leachate Treatment Cost (LTC). The leachate treatment cost (LTC) was calculated using Equation 3. The costs were estimated based on the volume (m^3) of leachate (VL) from Equation 2 multiplied by the treatment price (TP). In Malaysia, the TP is RM35/m^3 of leachate (KPKT, 2015).

$$LTC = \sum VL \times TP \qquad (3)$$

The mathematical models are summarised in Table 1.

Data Collection and Calculation

The solid waste data (tonnes) of the selected states were obtained from SWCorp as presented in Table 2, as first published in the Journal of Material Cycles and Waste Management,

Table 1
The summary of mathematical models

Parameter	Mathematical models	Source
Segregation rates (%)	$SR = \sum \left[\frac{SegW}{tSW} \right] \times 100$ (1) SR = segregation rates (%) $SegW$ = volume of segregated waste (tonne) tSW = total solid waste volume (tonne) 100 = to obtain the percentage (%)	(Ministry of Housing and Local Government, 2015)
Leachate production (m^3)	$VL = \sum SW \times 0.21$ (2) VL = volume of leachate (m^3). SW = volume of solid waste (tonne). 0.21 = volume of leachate per tonne of waste.	(Ministry of Housing and Local Government, 2015)
Leachate treatment (MYR (USD))	$LTC = \sum VL \times TP$ (3) LTC = leachate treatment cost (MYR (USD)). VL = estimated volume of leachate (m^3) using Equation 2. TP = leachate Treatment Price (RM35 m^{-3}).	(Ministry of Housing and Local Government, 2015)

Table 2
The volume of landfilled (L) and segregated (S) waste

Waste (tonnes)		KUL	PJY	PHG	PLS	KDH	NSN	MLK	JHR
2014	L	680,806.63	26,193.53	302,233.41	49,440.65	309,494.57	218,617.04	360,734.76	810,829.75
2015	L	613,561.50	28,649.16	308,009.50	63,792.00	433,996.39	233,137.48	313,950.85	818,515.73
	S	140.02	16.26	134.72	4.29	50.57	45.54	46.41	60.52
2016	L	614,357.93	29,360.29	247,664.08	41,269.00	424,287.45	245,802.71	214,688.00	912,033.82
	S	429.38	89.79	385.50	6.25	178.07	231.41	238.55	426.11
2017	L	610,849.75	28,903.84	242,309.86	30,366.10	345,456.08	242,538.16	218,275.08	839,252.11
	S	342.75	168.18	353.16	23.40	134.95	283.70	284.43	667.50
2018	L	610,068.90	29,360.29	229,811.12	30,118.21	388,397.00	252,529.82	203,308.89	869,692.81
	S	272.90	94.18	212.59	28.35	131.48	216.38	261.41	795.16

2022 by Springer Nature (Rangga et al., 2023). The MSW (in tonne) was categorised as landfilled waste (i.e., MWS that had been disposed of in landfills) and segregated waste (i.e., separated waste or materials for recycling purposes). The available data at the time of the study was only from 2014 to 2018. Microsoft Excel 2016 was used to calculate the parameters of the study. The mathematical models were inserted and programmed in the Excel "function formula" to avoid any errors during the analysis.

RESULTS AND DISCUSSION

The present study reported that the country's overall waste segregation rate was 0.06% (Figure 2). It was analysed based on the segregated waste volume divided by the total volume of waste. The waste segregation rate increased from 0.02% in 2015 to 0.06% in 2018 after the government made it compulsory by implementing the Act 672. Still, enormous amounts of waste were deposited in landfills, averaging 99.94% annually. Based on the reported data, the amount of waste generated and disposed of in the country's landfills increased from 33 thousand tonnes per day in 2012 to 39 thousand tonnes per day in 2022 (Hassan et al., 2022).

Low segregation practices in the country were influenced by knowledge, attitude, awareness, facilities, and incentives (Irina et al., 2014; Azilah et al., 2015; Low et al., 2016; Malik et al., 2015).

The findings in Figure 3 show that the volume of leachate was reduced from 579 thousand cubic metres (m^3) in 2014 to 548 thousand m^3 in 2018, which parallels the reduction in the volume of waste disposed of in landfills through waste segregation. About 565 thousand m^3 per year (m^3/yr.) of leachate is generated in landfills. The waste segregation practice increased the avoided volume of leachate discharge into the environment from 104 m^3 in 2015 to 422 m^3 in 2018. On average, 354 m^3/yr of leachate was avoided.

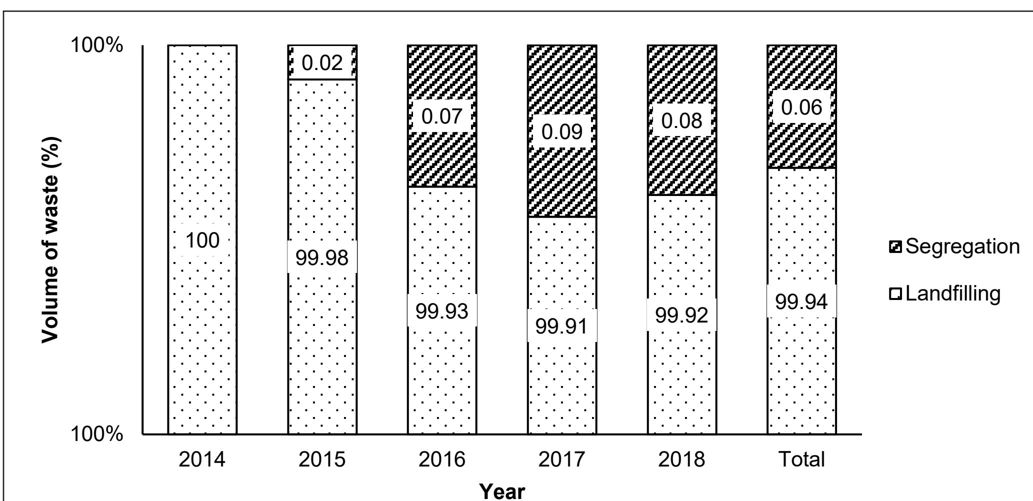
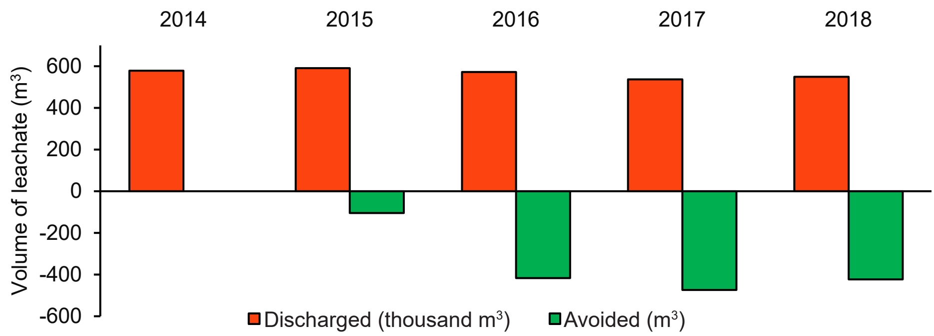


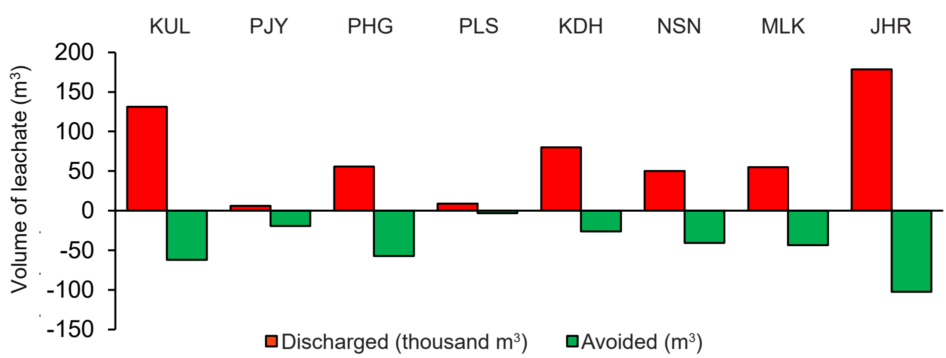
Figure 2. Waste segregation rates

Among the states under Act 672, Johor produced the highest volume of leachate (about 178 thousand m^3/yr.) as the state disposed of the highest volume of waste in the landfills. It was followed by Kuala Lumpur (104 thousand m^3/yr.), Kedah (79 thousand m^3/yr.), Pahang (55 thousand m^3/yr.), Negeri Sembilan (50 thousand m^3/yr.), Melaka (55 thousand m^3/yr.), Perlis (nine thousand m^3/yr.) and Putrajaya (five thousand m^3/yr.), as shown in Figure 3. Johor avoided a high volume of leachate discharge into the environment (102 m^3/yr.). Waste segregation practices in other states also avoided the production of leachate, for example, Kuala Lumpur (62 m^3/yr.), Pahang (57 m^3/yr.), Melaka (43 m^3/yr.), Negeri Sembilan (40 m^3/yr.), Kedah (25 m^3/yr.), Putrajaya (19 m^3/yr.), and Perlis (3.27 m^3/yr.).



State	KUL	PJY	PHG	PLS	KDH	NSN	MLK	JHR
Discharged (thousand m^3/yr.)	131.45	5.98	55.86	9.03	79.87	50.10	55.06	178.51
Avoided (m^3/yr.)	- 62.21	-19.34	-57.01	-3.27	-25.99	-40.79	-43.62	-102.34

(a)



State	KUL	PJY	PHG	PLS	KDH	NSN	MLK	JHR
Discharged (thousand m^3/yr.)	131.45	5.98	55.86	9.03	79.87	50.10	55.06	178.51
Avoided (m^3/yr.)	- 62.21	-19.34	-57.01	-3.27	-25.99	-40.79	-43.62	-102.34

(b)

Figure 3. The estimated volume of leachate (m^3) generated (a) from 2014 to 2018 and (b) among the states under Act 672. Negative (-) indicates the avoided volume of leachate discharged in landfills

A previous study by Ibrahim et al. (2017) reported that six Selangor landfills produced an average of 3,936 m^3/yr of leachate by considering the factors of rainfall intensity and landfill area. The present study used the mathematical models from the literature in which one tonne of waste could generate 0.21 cubic meters (m^3) of leachate (Ministry of Housing and Local Government, 2015). The study estimated the volume of leachate based on the volume of waste generated. Similarly, a study in Jordan proved that 30 kilograms of waste (52% organic waste, 13% paper, 17% plastic, 3% glass, 1% metals, and 14% others) generated about 15.7 litres of leachate (i.e., equivalent to 1 tonne of waste generates 0.52 m^3 of leachate) after 200 days of decomposition (Aljaradin & Persson, 2016). Therefore, the present study's findings can be used as the baseline data to improve the waste management strategy. It shows that waste segregation can increase the recovery of recyclable materials and waste deviation from landfills and reduce leachate generation in landfills.

Improper waste segregation leads to a high generation of landfill leachate volume but also causes adverse impacts on the environment and human health. Landfill leachate contains heavy metals (such as cadmium, copper, lead, and zinc), organic matter, and inorganic matter, resulting from the disposal of mixed waste in landfills (Maiti et al., 2016; Magda & Gaber, 2015), which leads to contamination of soil and water bodies. A recent study reported that heavy metal concentrations in leachate from Ethiopia's dump site exceeded the permissible limits set by WHO standards, with nearby stream water highly polluted with chemicals, having chemical oxygen demand (COD) values ranging from 10 mg/l to 61 mg/l in all water samples (Mekonnen et al., 2020). A study in Saudi Arabia also revealed high concentrations of heavy metals in leachate, soil, and waste samples. They found that 59.3% of water samples were contaminated, rendering the groundwater unsafe for drinking (Alghamdi et al., 2021).

In Malaysia, a recent study reported that the leachate from the Simpang Renggang landfill had high volumes of COD (1712–1633 mg/l), biological oxygen demand (137–138 mg/l), ammonia (405 mg/l), and suspended solids (341–359 mg/l), exceeding Malaysian standards (Detho et al., 2020; Zaini et al., 2022). The disposal of a large volume of mixed waste in landfills also contributes to the emission of greenhouse gases (GHGs) and other toxic pollutants such as non-methane organic compounds (NMVOCs) (Wu et al., 2018; Cheng et al., 2019). People living near landfill sites are exposed to landfill pollutants through inhalation, ingestion, and dermal contact, resulting in a higher risk of carcinogenic and non-carcinogenic health issues, especially among children, who are a vulnerable group, compared to adults (Nai et al., 2021; Obiri-Nyarko et al., 2021; Yao et al., 2019).

Therefore, comprehensive mitigation strategies are necessary to ensure proper waste segregation practices and minimise the risks associated with waste management. One such strategy is encouraging and mandating waste segregation at the source. The community must be aware of and actively participate in waste segregation, particularly when it comes to food waste, which accounts for 45% of the total waste generated (National Solid Waste Management Department, 2013). In Malaysia, approximately 17,000 tonnes of food waste are generated daily (Noor, 2022). Malaysian waste composition shows a high moisture content, with 59.45% being a mix of 45% food waste, 13% plastic, 9% paper, 12% diapers, 6% garden waste, and 16% other materials (e.g., glass, metal, leather, wood & rubber textiles). The high moisture content of the waste contributes to increased degradation and leachate production in landfills (Aljaradin & Persson, 2016). Waste segregation helps reduce the moisture content and the amount of waste disposed of in landfills. Waste segregation alone is insufficient; it must be integrated with other strategies to achieve sustainable waste management. An effective combination of recycling, composting, anaerobic digestion, and incineration, supported by efficient separate waste collection, is considered the best option for integrated solid waste management (Coelho & Lange, 2018). A study by Yong et al. (2015) stated that a combination of waste separation at the source with other approaches has a significant environmental impact, saving on global warming (30%), acidification (18%), nutrient enrichment (28%), and photochemical ozone formation (29%).

Another mitigation strategy to minimise the environmental impact of landfill leachate is the utilisation of effective and efficient leachate treatment methods prior to discharging it into the environment. Various leachate treatment technologies, such as photocatalysis, advanced oxidation processes (AOPs), electrooxidation (EO), electrocoagulation, and bio-granulation, can be practised, and improvement is required to increase the efficiency in leachate management (Bandala et al., 2021). Previous studies have shown that photocatalysis can remove 61% to 85% of COD and 52% of phthalates in leachate (Azadi et al., 2021; Eslami et al., 2021). AOPs, specifically using supercritical water oxidation (ScWO) as a reagent, can remove 96% of phosphorus, 70% of nitrate, 94% of total dissolved solids, and 87% of true colour (Martins et al., 2020). EO can effectively remove 68% of COD and 40% of total organic carbon (Yan et al., 2021). Electrocoagulation, as indicated in a study by Dia et al. (2018), can reduce turbidity by 82% and Zn content by 95% in leachate. Moreover, bio-granulation can eliminate nearly 100% of ammonia and 90% of COD in leachate (Moa et al., 2021). Thus, treating landfill leachate before its discharge into the environment is crucial, albeit incurring some costs to operate the treatment facilities.

Table 3 indicates the estimated costs of leachate treatment for different regions. Johor is projected to have the highest cost of leachate treatment, requiring MYR 6.25 million (USD 1.38 million) annually. Kuala Lumpur follows with MYR 4.60 million (USD 1.01 million) yearly, and Pahang with MYR 1.96 million (USD 0.43 million) yearly. On average, the total annual cost for leachate treatment amounts to approximately MYR 19.82 million (USD 4.36 million). Implementing waste segregation practices that divert waste from landfills can help avoid these leachate treatment costs, saving about MYR 12.42 thousand (USD 2.73 thousand) annually. Among the regions, Johor shows

Table 3
The estimated cost of leachate treatment, MYR (USD)

VARIABLE	STATE	Leachate treatment cost	
		MYR	USD
Landfilled waste (million/year)	KUL	4.60	1.01
	PJY	0.21	0.05
	PHG	1.96	0.43
	PLS	0.32	0.07
	KDH	2.80	0.62
	NSN	1.75	0.39
	MLK	1.93	0.42
	JHR	6.25	1.38
	TOTAL	**19.82**	4.36
Segregated waste (thousand /year)	KUL	2.18	0.48
	PJY	0.68	0.15
	PHG	2.00	0.44
	PLS	0.11	0.02
	KDH	0.91	0.20
	NSN	1.43	0.31
	MLK	1.53	0.34
	JHR	3.58	0.79
	TOTAL	**12.42**	2.73

the highest savings in leachate treatment costs, amounting to MYR 2.18 thousand (USD 3.58 thousand) per year, which is attributed to its high volume of waste segregation. Kuala Lumpur follows with MYR 2.18 thousand (USD 0.48 thousand) per year, and Pahang with MYR 2 thousand (USD 0.44 thousand) per year. The economic benefits of waste segregation programs include avoiding costs associated with leachate treatment, such as construction, operation, and maintenance.

The operational process involved in leachate treatment, which incurs ongoing costs like energy consumption, labour expenses, and chemical usage (Almeida et al., 2020; Cingolani et al., 2016), can be reduced by minimising leachate generation through waste segregation practices. In addition to cost savings in leachate treatment, waste segregation contributes to savings in developing new landfill sites. Treating 60% of waste can help save up to 40% of landfill area requirements (Pujara et al., 2019). Leachate contaminants can potentially degrade the quality of landfill liners (Özçoban et al., 2022). Controlling the amount of leachate discharged into landfills minimises landfill liner degradation, thus extending the lifespan of the landfills and reducing the costs of landfill construction. In Malaysia, constructing a new landfill requires approximately USD 7.75 million (Zaipul & Ahmad, 2017). Avoiding leachate treatment costs also helps to prevent or reduce clean-up and remediation expenses associated with environmental liabilities, as the volume of leachate discharge in landfills is decreased. For instance, the costs associated with environmental clean-up resulting from leachate leakage in landfills can be avoided.

The estimated costs in the present study were based on the estimated volume of leachate generated in landfills. The study used the cost of leachate treatment in Malaysia, which was MYR 35 m^{-3} (USD 7.41 m^{-3}) multiplied by the estimated volume of leachate (m^3). According to Almeida et al. (2020), in Brazil, the estimated cost of leachate treatment for the reverse osmosis (RO) process was USD 8.58 m^{-3} for 20 years of the RO unit operation after landfill closure. In Italy and China, the estimated cost of leachate treatment for the RO process was USD 2.7 m^{-3} and USD 3.86 m^{-3}, respectively (Cingolani et al., 2016; Sato et al., 2021). It indicates that the leachate treatment cost used in this study aligns with the estimated costs from previous studies, showing little difference. Therefore, the method and estimated treatment cost based on the leachate volume presented in this study can be utilised by the authorities for conducting cost analyses and budget planning for waste management, even though specific treatment methods and other factors such as operating and capital costs were not analysed.

The treatment costs depend on the methods and technologies used to treat leachate in a landfill. For example, the conventional leachate treatment method, such as denitrification and nitrification, requires a high operation cost because the method requires high oxygen and carbon, respectively (Show et al., 2019). An integrated method of leachate treatment, which combines conventional and advanced processes, should be practised as it is cost-effective, sustainable, and acceptable to the community (Show et al., 2019). There are some constraints in implementing an integrated treatment technology, especially for developing countries like Malaysia. High costs of operation and maintenance and well-trained operators are required. As the treatment costs can be avoided through segregation and the deviation of waste from landfills, the best options for the country are waste reduction, recycling, and segregation strategies that are inexpensive and environmentally friendly.

Increasing the intensity of waste segregation can enhance the recovery of recyclables and decrease the amount of waste dumped in landfills (Maria & Micale, 2014), leading to a reduction in leachate generation and a decrease in treatment costs. Malaysia must implement the best practices for waste segregation, focusing on achieving the maximum reduction in leachate volume and treatment costs. These practices should increase segregation and recycling rates by promoting public awareness and education (Otitoju & Lau, 2014; Knickmeyer, 2020). The best practice for waste segregation programmes in Malaysia to ensure maximum reduction of leachate volume and treatment cost avoidance is through law enforcement. Enforce mandatory waste segregation, not only at the residential level but also among industrial and commercial sectors, providing clear and consistent guidelines for implementation (Fauziah & Agamuthu, 2010; Yiing & Latifah, 2017).

The Malaysian government should ensure the availability of adequate infrastructure, such as separate bins, collection trucks, and recycling centres, to promote waste segregation (Ting et al., 2016). Previous studies indicate that incentives and rewards motivate individuals to participate actively and effectively in waste segregation programmes (Ali et al., 2015; Low et al., 2016). Continuous evaluation and active monitoring should be carried out to enhance the quality of waste management and reduce waste generation and disposal in landfills (Abas & Wee, 2014). Another approach is to identify new waste management techniques and technologies that can minimise leachate generation and improve the treatment process in terms of both costs and environmental impact (Bandala et al., 2021). It can be achieved through active research and development initiatives and stakeholder collaboration (Abas & Wee, 2014; Samsudin & Don, 2013). The goal of reducing leachate volume and treatment costs can be accomplished by exploring innovative solutions.

Waste Segregation Challenges in Malaysia

There are several challenges in implementing waste segregation programmes in Malaysia. One of the constraints is the level of public awareness and knowledge about waste segregation (Malik et al., 2015). Effective awareness campaigns and education programmes should be conducted through various platforms such as workshops, social media, and public outreach (Otitoju & Lau, 2014). While a high percentage of people have heard about waste segregation (86%), the actual participation in waste segregation practices is relatively low (42%), as reported in Sarawak (Otitoju & Lau, 2014). Previous studies have shown that people possess a high level of knowledge but only a moderate attitude and practice towards waste segregation (Al-Naggar et al., 2019; Mahat et al., 2019). Individual behaviour is one of the factors that influences waste segregation practices. For example, a study conducted in Putrajaya reported that 52% of the community practised waste segregation at the source, while 47% did not (Malik et al., 2015). Similarly, a study in Johor found that only 37% of the respondents claimed to practice waste segregation and recycling actively (Azilah et al., 2015). Thus, behaviour change strategies can be implemented in addition to awareness campaigns to overcome these challenges. For example, applying social norms strategies in the community, led by leaders and local influencers, can positively influence others and attract more people to participate (Knickmeyer, 2020).

The limited availability of segregation facilities, collection systems, and recycling centres for the public to participate in waste segregation programmes poses a challenge to good waste segregation practices in Malaysia. It has been reported that 48.37% of respondents in Selangor agreed to practice waste segregation and recycling if they had access to recycling bins (Ting et al., 2016). Similarly, in another state, 90% of households in Kuala Lumpur were willing to practice waste segregation if infrastructure and facilities were provided (Irina & Chamburi, 2015). Thus, the respective agencies of the local authority need to overcome this problem by investing in the development and expansion of waste management infrastructure. Previous studies have also reported that socioeconomic factors impact households' waste segregation practices. In Malaysia, most recyclers (84.2%) had a family income above MYR4000, higher education levels, lived in two-storey terraced houses, and most were Chinese. They were actively involved in recycling compared to those with lower income, lower education levels, and living in one-storey terraced houses(Irina et al., 2014).

The authorities need to ensure that waste management services are accessible and affordable for all segments of society and provide incentives to promote participation. People tend to refuse to participate in waste segregation and recycling programmes when they have limited access to them and no financial incentives, such as rewards or penalties, are provided (Ali et al., 2015; Low et al., 2016). The lack of stakeholder collaboration is also a challenge in implementing good waste segregation practices in Malaysia. More intensive collaboration between the government and non-governmental organisations (NGOs) is crucial in promoting and inspiring public participation in waste segregation activities (Abas & Wee, 2014; Mor & Ravindra, 2023; Samsudin & Don, 2013). Another challenge is Malaysia's lack of enforcement and monitoring of waste management. For example, although Act 672 was introduced in 2007, it was officially implemented in 2011 to improve the quality of waste management in the country (Abas & Wee, 2014). The impact of the Act on current waste management practices is still limited (Abas & Wee, 2014; Yahaya & Larsen, 2010) due to several factors, such as a lack of manpower and financial resources to effectively conduct enforcement and monitoring activities (Abas & Wee, 2014; Manaf et al., 2009). To mitigate regulations, fines for noncompliance and strict adherence to the law should be strengthened and implemented with a robust monitoring system.

The Role of Government Policies and Regulations

Government policies and regulations are crucial in promoting waste segregation programmes and reducing leachate volume in Malaysia. Their key role encompasses various aspects, such as establishing and developing legislation and frameworks, implementing waste management plans, enforcing mandatory waste segregation, developing infrastructure, fostering community awareness and education, facilitating enforcement measures, promoting collaboration and partnerships, and supporting research and development. For instance, in the 8th Malaysia Plan (2001-2005), the emphasis was placed on the 3Rs program (reduce, reuse, and recycle) to encourage participation. The program was relaunched, and the National Recycling Day was announced to be celebrated annually on November 11th.

The National Strategic Plan for Solid Waste Management (NSP) was also implemented in 2005 to enhance the efficiency of non-sanitary landfills and construct new sanitary landfills, promoting environmental sustainability in Malaysia (Sreenivasan et al., 2012). During the 9th Malaysia Plan (2006-2010), the Master Plan on National Waste Minimization was implemented to provide a clear vision, strategies, and stakeholder roles in minimising solid waste disposal (Yiing & Latifah, 2017). Establishing a national solid waste management policy aimed at building an integrated system that is comprehensive, sustainable, cost-effective, and protects the environment and human health (Agamuthu & Victor, 2010).

Act 672 and the Solid Waste and Public Cleansing Management Corporation Act (Act 673) were gazetted as part of these efforts on August 30th, 2007. These acts aimed to improve service quality in waste collection, transportation, treatment, and disposal, protect the environment and human well-being, standardise solid waste management and public cleansing services, and ensure proper waste management throughout the country. The JPSPN and SWCorp were introduced to enhance waste management. JPSPN, established under Section 6(1) of Act 672, is responsible for formulating policies, plans, and strategies for waste management and public cleansing. SWCorp, under Section 17(1) of Act 673, is responsible for recommending and implementing policies, plans, and strategies for waste management and public cleansing (Anuar & Wahab, 2015).

Enforcement of Act 672 commenced on September 1st, 2011, during the 10th Malaysia Plan (2010-2015), as the federal government assumed full responsibility for solid waste management and privatisation of concessionaires from local authorities, aiming to improve waste management quality (Yiing & Latifah, 2017). Mandatory solid waste separation at source was introduced under Section 74(1) of Act 672, with a fine of up to one thousand ringgits imposed on individuals who fail to comply. Starting in 2016, solid waste segregation at source became mandatory in states governed by Act 672, aiming to increase the recovery of recyclables, reduce waste disposal in landfills, and ensure their long-term sustainability (Fauziah & Agamuthu, 2010; Yiing & Latifah, 2017). Part XI of Act 672 establishes the "Solid Waste and Public Cleansing Management Fund," which is used to finance solid waste and public cleansing activities, services, and research and development related to waste management in Malaysia (Fauziah & Agamuthu, 2010). The government also plans to implement an integrated waste management system nationwide. This system has already been initiated in Johor as a "test bed" and involves the combination of a sanitary landfill, waste-to-energy (WTE) facilities, anaerobic digestion, and a materials recycling facility (MRF) (Ministry of Housing and Local Government, 2015).

In the 11th Malaysia Plan (2016–2020), the government aims to manage various types of waste, including solid, agricultural, construction, radioactive, mining, sewage, and scheduled waste, more comprehensively through a life cycle approach. As part of this strategy, the government encourages the adoption of 3R practices among the community to increase recycling rates and invests in converting waste into electricity through energy recovery. Since 2016, other strategies have been implemented, such as enforcing Government Green

Procurement (GGP) to promote product recycling in public procurement, implementing a media strategy to raise awareness and provide public education, establishing a code of practice for construction and demolition (C&D) waste management, and fostering smart partnerships between NGOs, private sectors, academic institutions, and communities in 3R activities (Ministry of Housing and Local Government, 2015).

The pay-polluter principle (PPP), also known as Pay-As-You-Throw (PAYT), was introduced in 2018 as part of the key initiative under Thrust 1. It aims to enforce waste reduction and separation at the source, encourage recycling activities among the community, and promote cost control, equality, and environmental quality. Polluters will be charged based on the volume, weight, or hybrid waste disposal system. The Take Back System, launched in 2018, aims to boost recycling demand among manufacturers, producers, importers, and retailers to increase the recycling rate in the industrial sector (Ministry of Housing and Local Government, 2015). Under the 12th Malaysia Plan (2021–2025), the government targets a recycling rate of 40% by 2025. Therefore, there will be intensified enforcement of waste segregation at the source and the implementation of 3R initiatives, particularly in urban areas. More waste collection, segregation, and recycling facilities will be introduced, especially in residential, institutional, and commercial areas.

The government has also introduced a sustainable economy cycle that emphasises the restoration of resources through reuse and recycling initiatives. This approach follows the principles of the 3Rs, aiming to minimise resource consumption, maximise product reuse, and recycle materials back into the manufacturing cycle. The economic cycle is expected to reduce waste generation and disposal, as well as minimise the environmental and health impacts associated with solid waste management in Malaysia (Ministry of Economy, 2021). Thus, the effective implementation of these approaches is expected to encourage waste segregation practices, reduce waste volume, and minimise leachate generation in Malaysia's landfills.

CONCLUSION

The present study reports that many mixed wastes are sent to landfills, resulting in a high volume of landfill leachate generated in a year. Discharging untreated leachate can cause environmental problems such as soil pollution and surface and groundwater contamination, as well as impact human health. The treatment is crucial, with the high costs required to operate the treatment facilities. The waste segregation practices showed they potentially avoid leachate production and benefit leachate treatment cost savings. The savings cost can be used and allocated for sustainable approaches such as conducting awareness programmes and improving recycling facilities in the country. It is expected that the government in Malaysia can use the model described in this study to plan waste management strategies, create legislation, and support segregation and recycling efforts. The findings of the study are summarised as follows:

- 99.94% of waste is disposed of in the landfills.
- 0.06% waste segregation rate in the country.
- 565 thousand m^3 of leachate generated by landfilled waste per year.
- 354 m^3 per year of leachate can be avoided through waste segregation practices.
- USD 4.36 million per year is required for landfill leachate treatment.
- Waste segregation practices can prevent USD 2.73 thousand per year leachate treatment costs.

However, the waste segregation rate was reported as low. Thus, promoting community engagement and education is important to encourage waste segregation practices and reduce landfill leachate in Malaysia. One approach that can be taken to raise community awareness is through an educational campaign that utilises various mediums such as social media, posters, pamphlets, and community meetings to disseminate information effectively. At the school level, for example, waste management and segregation can be introduced in the curriculum as an early step to educate and encourage students to practice waste segregation. Authorities should also establish community waste segregation centres or recycling stations that provide convenience for households to drop off their segregated waste. It can be achieved by ensuring the availability of proper waste segregation infrastructure, such as separate bins for different waste. Another approach to encourage community engagement and education is the establishment of public-private partnerships, which can contribute resources, expertise, and infrastructure to strengthen waste segregation initiatives. By combining these approaches, community engagement and education can effectively promote waste segregation practices and minimise leachate volume in landfills.

The Limitations of the Study

There are a few limitations to this study. First, the study's findings only represent the states implementing Act 672. However, other states can use this result as a baseline data for improving their waste management strategies. Second, the secondary data were analysed using mathematical models adapted from the literature where the estimated value may be under- or over-estimated. Nonetheless, the values used in the equations of the volume of leachate per tonne of waste and leachate treatment price were compared and were within the values from previous field studies. The study recommends that some factors in the analysis must be considered to estimate the quantity of the leachate. For example, the analysis of leachate production must consider other factors such as waste composition, waste moisture availability, landfills' age, rainfall intensity, and land area in a region. Capital expenses (CAPEX) and operational expenses (OPEX) should be included in estimating leachate treatment costs by determining economical methods or processes based on the country settings that should be performed in future studies.

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