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Estimating Heavy Metal Concentrations in Landfill Leachate and the Impact of Waste Segregation in Malaysia

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ABSTRACT: Estimation of heavy metal concentrations in leachate was crucial for effective landfill management and pollution mitigation. The study aimed to estimate the volume of landfill leachate, the heavy metal content in the leachate, and their reduction through waste segregation practices. It was conducted in Malaysia and utilised municipal solid waste volume data from six states and two federal territories. A mathematical empirical model was applied to estimate the concentrations of heavy metals in the leachate. Based on the volume of landfilled waste, an estimated 565,000 cubic metres (m^3) of leachate were discharged annually. Among the heavy metals analysed, Pb and Zn exhibited the highest concentrations (8.49 kg/yr). Waste segregation practices reduced heavy metal discharge in leachate, preventing approximately 7.09×10^{-4} to 5.32×10^{-3} kg/yr. Through mathematical modelling, this research provided a cost-effective approach for estimating heavy metal concentrations and supported strategies for addressing environmental and health impacts.

KEYWORDS: Landfill leachate; heavy metals; mathematical modelling; waste segregation; environmental risk.

1. Introduction

The global generation of municipal solid waste (MSW) was estimated at 1.3 billion tonnes annually (t/yr), with projections indicating an increase to 2.2 billion t/yr by 2025, accompanied by a rise in per capita waste generation from 1.2 to 1.4 kg/capita/day [1]. In Malaysia, daily solid waste generation reached 38,000 tonnes (t/day), corresponding to an average of 1.17 kg/capita/day [2, 3]. This figure exceeded that of several other Asian nations, including Thailand (1.0 kg/capita/day), South Korea (0.99 kg/capita/day), Japan (0.98 kg/capita/day), Indonesia (0.70 kg/capita/day), China (0.63 kg/capita/day), and India (0.5 kg/capita/day) [1].

Landfilling remained the most commonly used method for waste disposal among developing countries, owing to its low operational and maintenance costs [4–6]. Waste deposited in landfills produced leachate containing heavy metals that could infiltrate and contaminate soil, surface water, and groundwater [7]. The deposition of residual waste, including mixed organic, inorganic, and electronic materials, led to the production of leachate enriched with heavy metals such as cadmium (Cd), copper (Cu), zinc (Zn), and lead (Pb) [8, 9].

Leachate percolating from landfills transported these toxic elements into the soil and subsequently into groundwater [10]. Previous studies reported the presence of heavy metals in both soil and groundwater near landfill sites in Malaysia [11–13]. Groundwater contaminated with heavy metals posed significant health risks when used as a source of drinking water [14]. Furthermore, the accumulation of heavy metals in soil and vegetables in substantial amounts could result in adverse health effects for both humans and fauna [15]. The present study aimed to estimate the volume of landfill leachate and the heavy metal content within it, as well as to evaluate the reduction of heavy metal discharge through waste segregation practices. The findings were expected to contribute to scientific knowledge through the application of mathematical models, providing a cost-effective and reliable approach to predict leachate contamination without relying entirely on resource-intensive laboratory analyses. This approach could support policymakers and landfill operators in implementing improved waste management strategies, optimizing leachate treatment processes, and reinforcing environmental regulations to minimize contamination risks.

2. Materials and Methods

2.1. Study area.

This study selected Kuala Lumpur, Putrajaya, Pahang, Perlis, Kedah, Negeri Sembilan, Malacca, and Johor as study areas because these states had implemented a waste segregation programme under the Solid Waste and Public Cleansing Management Act 2007 (Act 672). They were also categorised according to the Human Development Index (HDI), with Kuala Lumpur and Putrajaya (0.839), Malacca (0.822), Negeri Sembilan (0.820), and Pahang (0.801) classified as very high HDI, while Johor (0.796), Kedah (0.770), and Perlis (0.770) were classified as high HDI [16]. According to the United Nations Development Programme (UNDP), the HDI is a summary measure of average achievement in key dimensions of human development, including a long and healthy life, knowledge, and a decent standard of living. In accordance with Act 672, Part VIII, Section 74 (1) and (2), waste segregation at the source was mandatory, requiring households to separate waste into food waste, paper, plastic, miscellaneous, and non-recyclable categories. Non-compliance could result in a fine not exceeding RM1,000 [17].

2.2. Data Collection.

Table 1 shows the volume of landfilled waste from the states under Act 672. These secondary datasets were obtained from the Domestic Waste and Public Cleansing Division of the Solid Waste and Public Cleansing Corporation (SWCorp) and Alam Flora Sdn. Bhd., covering the years 2014 to 2018. The data were provided in Microsoft Excel and categorised by state, year, and waste type. In this study, the collected waste included domestic waste, bulky and garden waste, public cleansing waste, and segregated waste. The segregated waste was further classified into plastic, paper, metal, aluminium, glass, e-waste, and other types. Commercial, institutional, industrial, public cleansing, and bulky and garden waste were excluded from the analysis. The estimation of heavy metal concentrations incorporated only the volume of domestic waste (i.e., landfilled domestic waste) and segregated waste, measured in tonnes. These categories were included because 80–90% of collected domestic waste originated from households and was disposed of in landfills [18]. Since the waste segregation programme was officially implemented in 2015, data on segregated waste from 2015 to 2018 were used, representing the most recent available at the time of data collection. Mathematical models were developed and executed in Excel, with the relevant data transferred into the model for analysis. The study specifically analysed the volumes of landfilled domestic waste and segregated waste.

Table 1. Volume of landfilled waste from the state under Act 672 (in tonne) [19].

State	2014	2015	2016	2017	2018	Average
Kuala Lumpur	922,667.03	845,053.88	824,140.28	775,083.24	761,455.28	825,679.94
Putrajaya	57,239.80	43,507.45	44,260.24	47,745.10	51,990.47	48,948.61
Pahang	384,074.79	366,346.62	311,363.47	302,659.55	289,524.44	330,793.77
Perlis	58,614.33	79,934.59	56,500.25	41,917.05	42,207.90	55,834.82
Kedah	378,086.39	549,736.26	564,123.97	456,316.91	500,974.84	489,847.67
Negeri Sembilan	250,227.64	250,623.90	285,230.26	278,980.48	291,382.68	271,288.99
Malacca	420,719.20	335,516.87	228,629.19	233,832.73	248,210.25	293,381.65
Johor	931,436.32	1,028,948.80	1,028,583.37	933,161.39	912,907.16	967,007.41
Average	3,403,065.50	3,499,668.37	3,342,831.03	3,069,696.45	3,098,653.02	3,282,782.87

2.2. Mathematical models.

The mathematical model for estimating the volume of leachate generated in landfills was developed based on data reported by the Ministry of Local Government Development (KPKT) [20], which states that one tonne of municipal solid waste generates approximately 0.21 cubic metres (m^3) of leachate. The volume of landfill leachate (VL) was calculated using the following equation:

$$VL = \sum (MSWT \times 0.21) \quad (1)$$

The volume of leachate generated (VL) in cubic metres per year was calculated based on the mass of municipal solid waste (MSWT) disposed of in landfills, expressed in tonnes per year. A conversion factor of 0.21 was applied to translate the mass of waste into the corresponding leachate volume, as referenced in [20]. To estimate the volume of heavy metals in the landfill leachate, the following equation was applied:

$$HM\_h = VL \times C\_h \quad (2)$$

The quantity of a specific heavy metal (HM_h) in the leachate, expressed in kilograms per year, was determined by multiplying the volume of landfill leachate generated (VL, in cubic metres per year) by the concentration of that heavy metal (C_h, in kilograms per cubic metre) in the leachate, as shown in Table 2. The analysis focused on selected heavy metals, including cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), and zinc (Zn).

In this study, the volume of landfill leachate generated (VL) was obtained from a previous study conducted by Agamuthu and Fauziah [21], as presented in Table 2. The average concentrations of heavy metals were derived from data collected at two disposal sites in Malaysia, including one active and one closed non-sanitary landfill. For each site, three sampling points were selected. Soil samples were taken from landfill boreholes at various depths and analysed for heavy metal content using an Inductively Coupled Plasma (ICP) Spectrophotometer [21].

Table 2. The average concentration of heavy metals in landfills [21].

Heavy Metal (HM)	Average concentration (kg/m^3)
Cadmium (Cd)	2.00E-06
Chromium (Cr)	6.00E-06
Copper (Cu)	5.00E-06
Lead (Pb)	1.50E-05
Zinc (Zn)	1.50E-05

3. Results and Discussion

3.1. Type of solid waste.

The collected waste in the study areas was classified into four main types: (i) domestic waste, (ii) bulky and garden waste, (iii) public cleansing waste, and (iv) segregated waste, as shown in Figure 1. Domestic waste dominated, comprising 82% of the total waste generated between 2014 and 2018 (1,684,083.03 tonnes per year (t/yr)), followed by bulky and garden waste (13%, 266,527.96 t/yr) and public cleansing waste (5%, 100,284.07 t/yr). Segregated waste accounted for only 0.05% (1,688.48 t/yr). This finding aligned with national reports, which indicated that more than 90% of domestic waste was generated annually and disposed of in landfills [18, 22]. Even in developed countries, such as Austria, Germany, and Singapore, domestic waste remained the primary contributor to total waste volume [23–25]. The high volume of domestic waste was attributed to both household and commercial activities [26].

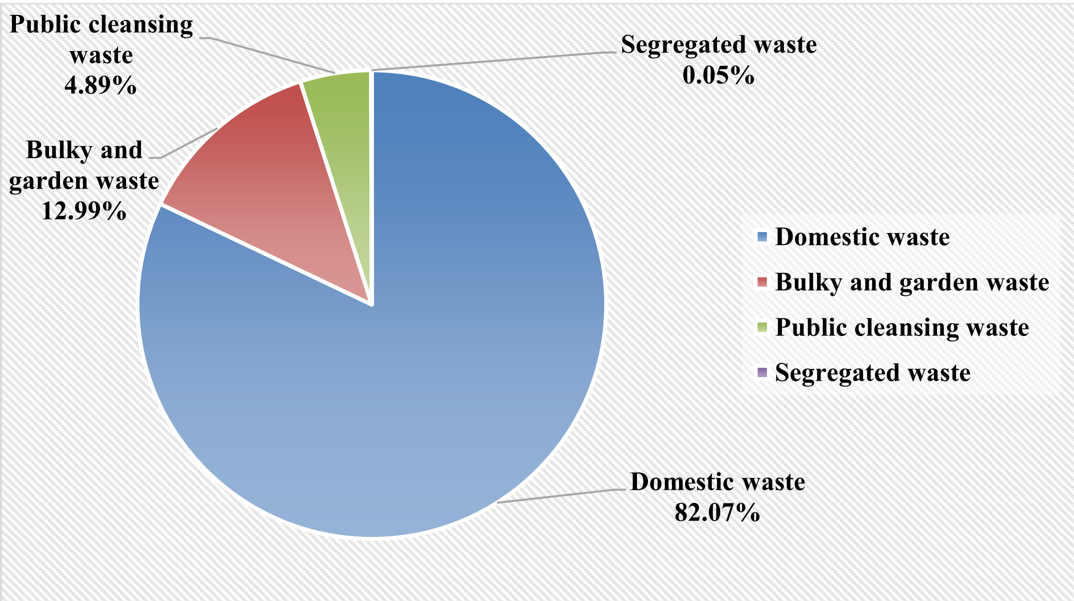

Figure 1. Category of solid waste.

3.2. Volume of leachate discharged.

Figure 2 shows the estimated volume of leachate. The findings indicated a gradual decline in leachate production at landfills, from 579,253.57 m³ in 2014 to 548,790.28 m³ in 2018. On average, approximately 565,851.90 m³ of leachate was discharged annually. This reduction suggested improvements in waste management practices, such as increased recycling and waste segregation efforts in the study area [27]. The implementation of waste segregation policies under the Solid Waste and Public Cleansing Management Act 2007 (Act 672) may have contributed to diverting recyclable materials and organic waste away from landfills, thereby reducing the total volume of municipal solid waste (MSW) disposed. Initiatives such as composting and energy recovery from waste gained traction in Malaysia, as 89% of collected waste ended up in landfills and had significant potential for energy recovery through waste-to-energy (WTE) technologies [28]. These initiatives could further decrease the amount of biodegradable waste contributing to leachate generation.

Comparing these results with global trends, developed nations such as Germany and Sweden successfully minimized landfill leachate production through WTE technologies and stringent landfill regulations [23, 24]. In contrast, Malaysia still relied heavily on landfilling as the primary waste disposal method [28]. The current act (Act 672) may remain ineffective in some areas, as it focuses more on waste management services and facilities and lacks supporting regulations related to recycling [29]. Other factors influencing waste segregation among Malaysians included knowledge, attitude, awareness, facilities, and incentives [30–33]. Based on the solid waste management hierarchy, the most preferred option was waste minimization [34]. Therefore, the government should focus on strategies that reduce the volume of waste generated, such as strengthening the 3R programme (reduce, reuse, and recycle) and encouraging household participation.

Moreover, advanced leachate treatment systems should be improved to mitigate the environmental and health impacts associated with landfills [35]. Integrating circular economy principles into Malaysia's waste management framework could further reduce landfill dependency [36, 37]. Encouraging industries and households to adopt sustainable waste reduction strategies, including extended producer responsibility (EPR) schemes, could significantly curb the volume of waste reaching landfills [38], ultimately decreasing leachate production.

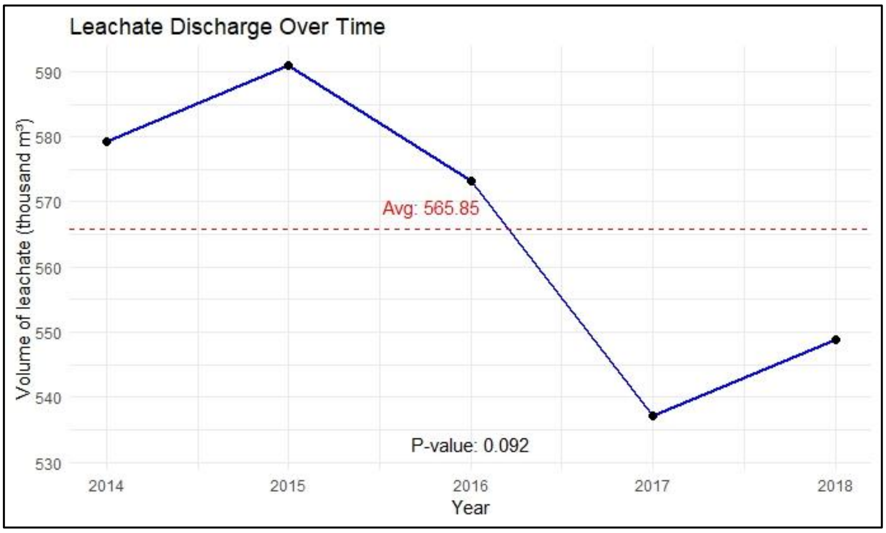

Figure 2. The estimated volume of leachate (m^3).

3.2. Estimation of heavy metals volume in leachate.

Figure 3 presents the estimated volume of heavy metals, Cd), Cr), Cu, Pb, and Zn), in landfill leachate under conventional landfilling and waste segregation practices. These estimations were derived from the average annual volume of leachate discharged. Among the heavy metals analyzed, Pb and Zn exhibited the highest estimated concentrations, each at 8.49 kg per year, followed by Cr at 3.40 kg/yr, Cu at 2.83 kg/yr, and Cd at 1.13 kg/yr. Similarly, a study in Nigeria using a finite element model to simulate the migration of heavy metals (Pb and Cd) through dumpsite soil found significant contamination and potential risks to the environment and human health [39]. While that model focused on transport dynamics, the present study contributed to early estimation using input-based empirical modelling. Likewise, a study in Vietnam demonstrated the spread of heavy metals in landfill soil using mathematical modelling [40]. Another study in Colombia reported high concentrations of Pb in landfill leachate, estimated using ARIMA modelling [41]. Compared to previous studies in developing countries, the use of empirical mathematical methods to estimate heavy metals in leachate is relevant, particularly in settings with limited real-time monitoring systems.

The study also estimated the volume of heavy metals avoided in landfill leachate through waste segregation practices. Based on the average reduction in leachate discharge, waste segregation helped prevent the release of 5.32×10^{-3} kg/yr of Pb and Zn, 2.13×10^{-3} kg/yr of Cr, 1.77×10^{-3} kg/yr of Cu, and 7.09×10^{-4} kg/yr of Cd into the environment. These findings underscore the potential of waste segregation as a mitigation strategy to reduce hazardous heavy metals in landfill leachate. However, the avoided volume of heavy metals remained relatively low, suggesting that enhanced segregation efforts and improved recycling initiatives could further reduce heavy metal contamination. A previous study by Abubakar et al. reported that sustainable solid waste management, including improved recycling and segregation, as well as reduced dumping in landfills, can help prevent environmental pollution, including leachate emissions [42].

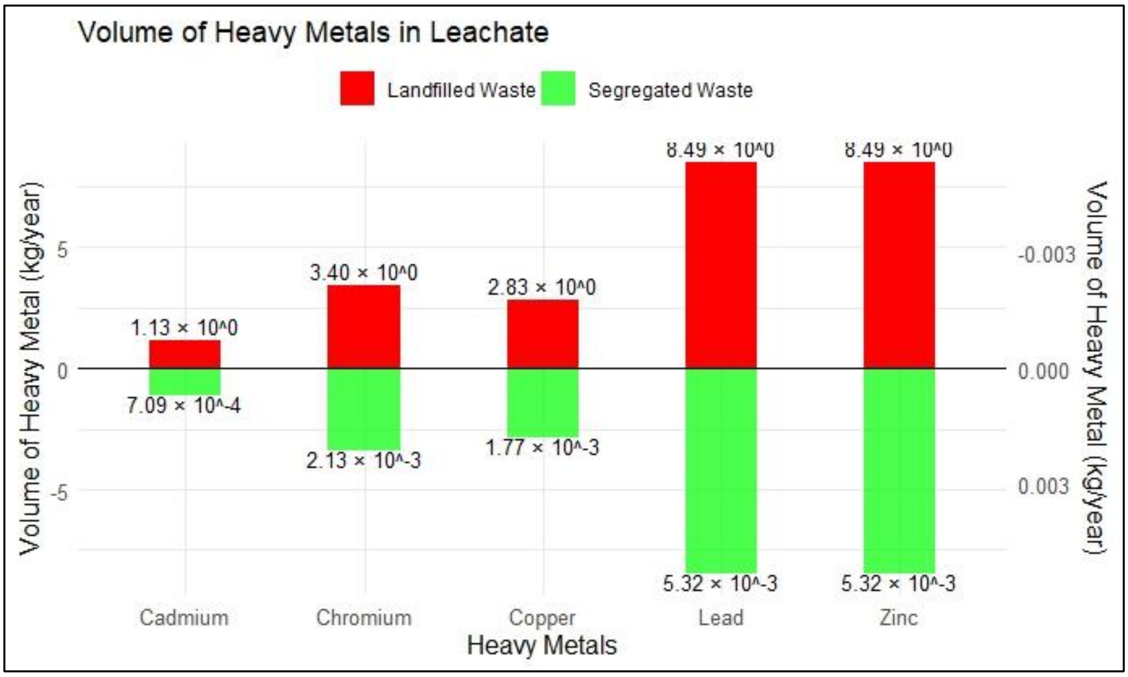

Figure 3. The estimated volume of heavy metals in leachate (kg/year).

3.3. Environmental and health implications.

The estimated concentrations of heavy metals in landfill leachate carry important implications for environmental contamination and human health. In this study, the annual estimated releases of Pb, Zn, and Cr (converted to mg/l) exceeded the U.S. EPA regulatory thresholds under the Resource Conservation and Recovery Act (RCRA), where the maximum permissible leachate concentrations for Pb, Cr, and Cd are 5.0, 5.0, and 1.0 mg/L, respectively [43]. Although Cu and Zn are not specifically regulated, they remain a concern due to their potential toxicity. Heavy metals are persistent pollutants that can accumulate in soil and water bodies, causing long-term ecological damage [44]. Leachate containing heavy metals can infiltrate groundwater or surface water, posing serious health risks to nearby communities through inhalation, dermal absorption, and consumption of contaminated food and water [45]. Acute exposure can lead to kidney injury, while chronic exposure contributes to Alzheimer's disease [46] and cancer development [47].

Estimating heavy metal volumes in leachate allows landfill operators and policymakers to develop effective mitigation strategies. Mathematical modelling offers a cost-efficient approach for predicting heavy metal levels while reducing the need for extensive field sampling and laboratory analyses. Similarly, Benítez et al. reported that mathematical models can predict residential solid waste generation, helping authorities plan and manage waste more efficiently [48]. Identifying specific concentrations of toxic metals supports determining the required level of treatment before discharge [49] and informs environmental impact assessments, regulatory compliance, and the design of waste management policies to reduce hazardous emissions. For example, in the Republic of Ireland, implementation of European Union (EU) Directives significantly improved landfill leachate management, reducing leachate volume per tonne of landfilled waste [50].

The study also shows that waste segregation practices can reduce heavy metal levels in leachate. Expanding source separation initiatives for recyclables, such as metals, plastics, and electronic waste, can prevent these pollutants from reaching landfills. Public awareness programs should encourage household participation in waste segregation and the proper disposal of hazardous materials, including batteries, electronics, and industrial by-products [31, 51, 52]. Overall, practicing waste segregation and recycling enhances sustainability in waste management while protecting ecosystems and human health [53, 54].

4. Conclusions

The study showed that domestic waste accounted for 82% of the total waste generated between 2014 and 2018, followed by bulky and garden waste at 13% and public cleansing waste at 5%, while segregated waste represented only 0.05% of the total. On average, approximately 565,000 cubic meters (m^3) of leachate were discharged annually. Pb and Zn had the highest concentrations in landfill leachate, each at 8.49 kg per year (kg/yr), followed by Cr at 3.40 kg/yr, Cu at 2.83 kg/yr, and Cd at 1.13 kg/yr. Waste segregation practices reduced the discharge of heavy metals, preventing approximately 7.09×10^{-4} to 5.32×10^{-3} kg/yr from entering the environment. These findings provide valuable insights into the environmental and health risks associated with heavy metal contamination in landfill leachate. The study acknowledges several limitations. The estimation of heavy metal concentrations relied on assumptions such as uniform waste composition and average leachate discharge volumes. In reality, waste composition varies due to seasonal changes, local generation patterns, and landfill operational practices. The study used data from states under Act 672, which may not fully represent all Malaysian landfills. Additionally, the heavy metal content in leachate is influenced by municipal solid waste composition, which can differ substantially between urban and rural areas. Industrial waste, which was not included in the analysis, could also contribute to higher heavy metal levels. Given these constraints, further research using multiple estimation methods is recommended to refine the accuracy of predictions and provide a more comprehensive evaluation of landfill leachate contamination.

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Author Contribution

Conceptualization, Formal analysis, Investigation, Methodology, Writing – Original draft: Josfirin Uding Rangga; Methodology, Supervision, Validation, Writing – review & editing: Sharifah Norkhadijah Syed Ismail; Supervision, Writing – review & editing: Karmegam Karuppiah and Irniza Rasdi.

Competing Interest

All authors declare no competing interest from any other party influence this research.

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