Investigating the Temporal Variations in Leachate Contamination Risk Assessment at Kerawalapitiya Waste Park within Muthurajawela Wetland, Sri Lanka: An LPI-Based Investigation

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***Abstract*— This research examines temporal fluctuations in leachate contamination potential at Kerawalapitiya Waste Park, Sri Lanka's largest open waste disposal facility situated within the ecologically significant Muthurajawela wetland ecosystem. Using the Leachate Pollution Index methodology across three distinct seasonal periods over a comprehensive three-year monitoring campaign from 2022 to 2024, the study assessed multiple physicochemical parameters encompassing organic pollutants, inorganic components, heavy metals, major ions, and nutrient indicators to determine environmental contamination threats to the adjacent wetland system. Results revealed substantial seasonal and annual variability in contamination potential, with total LPI values fluctuating around 10.0 during the 2023 wet season and 37.2 during the 2024 dry season. Organic matter emerged as the primary pollution contributor, peaking at 80.0 during the 2024 intermediate season, while heavy metal contamination exhibited erratic behavior with maximum levels of 43.8 recorded during the 2024 dry season. The year 2024 represented the most environmentally hazardous period, with all measured components demonstrating elevated contamination levels. Seasonal analysis throughout the monitoring period revealed irregular patterns, suggesting that conventional seasonal management approaches are inadequate for addressing the complex interactions between climatic factors, waste composition, and leachate generation processes. These findings underscore the urgent need for enhanced monitoring protocols and adaptive pollution management strategies that can respond to temporal variations in contamination composition, while contributing valuable insights into leachate contamination dynamics in tropical wetland environments and informing targeted environmental protection measures for sensitive coastal ecosystems.**

I. Introduction

Muthurajawela wetland is the largest saline wetland of Sri Lanka and is located in between the Negombo lagoon and the Kelani River, covering 3,068 hectares by creating an integrated coastal wetland ecosystem [1]. According to the National Wetland Directory of Sri Lanka (2006), thirteen inter-connected canals that have been connected Hamilton and Dutch canals by creating a network for water transportation. The wetland faces significant anthropogenic pressures, including waste disposal and effluent discharge from surrounding urban and industrial activities [2].

Wetlands, especially floodplain areas become wastelands due to the lack of proper solid waste disposal facilities in Sri Lanka; some industrial and clinical waste is also dumped illegally at those dumping sites. Solid waste pollution and industrial waste disposal in the wetlands, create enormous negative impacts on the environment, human health as same as biodiversity by emitting greenhouse gases, toxic fumes, particulate matter as well as generating toxic leachate. Kerawalapitiya Waste Park is the largest open waste dump, located adjacent to the Environmental Protected Zone declared by CEA. Furthermore, the open dump site operates with a compost processing facility and is spread over 20 acres of Muthurajawela Development Zone. As per the waste records and inventory of the Kerawalapitiya Waste Park, it has been received approximately 350 MT per day as segregated biodegradables.

The lack of organized baseline metrics regarding physical and chemical characteristics blocks detailed assessment of threats in wetland water contamination and current water quality studies have not been included in patterns of leachate contamination and saltwater intrusion effects on freshwater environments. The essential knowledge gap requires swift action through the adoption of standard methods including Leachate Pollution Index (LPI) assessments that measure pollution variations across seasons to create essential scientific data for protecting this internationally important coastal ecosystem from permanent environmental harm.

The objectives of the study are to;

1. Identification of baseline physical and chemical parameters of landfill leachate of Kerawalapitiya Waste Park.
2. Calculate Leachate Pollution Index (LPI) by using sub- sub-indices of LPI
3. Identify seasonal variability of landfill leachate dynamics through LPI
4. Analyze possible environmental contaminations by landfill leachate with the Leachate Pollution Index

II. METHODOLOGY

The research methodology follows established protocols for wetland water quality assessment while incorporating spatial sampling strategies to evaluate the extent of pollution dispersion from point sources [2,3]. The selected study area receives direct impact from an unregulated waste disposal site which borders the Environmental Protected Zone and serves as the main pollution origin for this research study. The dump site is operated since 2017 while causing water and soil degradation.

A. Selection of Parameters

The selected physicochemical parameters provide a robust foundation for understanding water chemistry dynamics, with pH, electrical conductivity, and total dissolved solids offering baseline water characteristics, while BOD_5 and COD serve as critical indicators of organic pollution loading that are essential for assessing anthropogenic impacts on aquatic systems [4]. Those water quality parameters provide a comprehensive evaluation of possible pollution from the Kerawalapitiya Waste Park through different contamination pathways and environmental receptors.

The physical and chemical variables of pH together with Electrical Conductivity (EC) and Total Dissolved Solids (TDS) function as critical screening tools for detecting deterioration of the water quality, especially in surface water bodies. Landfill leachate shows unfamiliar pH readings between 3.7 and 9.0 and high EC levels reaching 3,000 to 60,000 μS/cm which allows rapid identification of contamination in comparison to the natural waters that have conductivity below 1,000 μS/cm [5,6]. The organic pollution levels in surface waters can be determined by measuring Biochemical Oxygen Demand (BOD) along with Chemical Oxygen Demand (COD) which tracks oxygen consumption in the water body. Landfill leachate consists of substantial organic materials with BOD_5 levels between 2,000 and 30,000 mg/L and COD levels from 3,000 to 60,000 mg/L which leads to major aquatic ecosystems.

Heavy Metals including As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn represent priority pollutants due to persistence, bioaccumulation, and toxicity at trace concentrations. These metals are commonly elevated in landfill leachate through battery disposal, industrial waste co-disposal, and chemical mobilization under anaerobic conditions [7]. Fe and Mn are selected since they turn moveable when the landfill environment experiences the characteristic reduction of the conditions. The major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) along with anions (Cl^{-}, SO_4^{2-}) serve as hydrogeochemical fingerprints to identify contamination sources and track groundwater movement.

Ammonia, Nitrate and Phosphate ions (NH_3^{+}, NO_3^{-} and PO_4^{3-}) assess eutrophication potential in receiving waters. An accumulation of nutrients especially nitrogen and phosphorus in water starts a eutrophication process; algae feed on the nutrients, growing, spreading, and turning the water green [8]. Ammonia and nitrate, as forms of nitrogen, promote eutrophication [8], while 80% of lake and reservoir eutrophication is restricted by phosphorus. Ammonia concentrations in landfill leachate (500-2,200 mg/L) far exceed natural levels (< 0.2 mg/L), posing direct toxicity risks and accelerating eutrophication processes (Renou et al., 2008). Concentrations between 3 to 5 mg/L of nitrate-nitrogen and 0.03 to 0.1 mg/L of phosphate-phosphorus are considered high, with levels above these ranges considered eutrophication [9]. Major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (Cl^{-}, SO_4^{2-}) provide hydrogeochemical fingerprinting for contamination source identification and groundwater flow assessment. Chloride acts as a conservative tracer enabling contamination plume delineation [10]. NH_3^{+}, NO_3^{-} and PO_4^{3-} assess eutrophication potential in receiving waters. Ammonia concentrations in landfill leachate (500-2,200 mg/L) far exceed natural levels (< 0.2 mg/L), posing direct toxicity risks and accelerating eutrophication processes [6].

The ecological structure of Muthurajawela provides brackish wetland ecosystem, due to the saltwater intrusion from the Hamilton canal and it blends with fresh water flowing from inland canals. This brackish water environment supports an incredible variety of life, necessitating the application of aquatic life protection standards that account for the physiological requirements of diverse species assemblages [11,12]. The mixture of vegetation types and aquatic habitats in Muthurajawela has made it an ideal eco-zone for a variety of birds, with Herons, Egrets, Cormorants, Teal, Waders and Kingfishers found here, serving as a very important breeding habitat of many aquatic birds [1,3]. According to the baseline studies carried out in this study, agricultural activities have not been practiced due to the salinization of soil through the saltwater intrusion. Muthurajawela receives inputs from the heavily polluted Kelani River system and faces ongoing anthropogenic pressures, maintaining Category C water quality standards serves as a critical threshold for ecosystem resilience and long-term sustainability [13,14].

B. *Leachate Pollution Index*

The Leachate Pollution Index (LPI) is a quantitative tool for environmental evaluation, designed to measure and compare the contamination potential of leachate generated from municipal solid waste landfills. Developed as a standard method for quantifying leachate contamination potential, the LPI provides a unified system for the reporting of leachate pollution data from different landfill sites.

The original LPI was developed by Kumar and Alappat [15] based on feedback from 80 experts in the field of waste management, who selected 18 parameters from an initial list of 50 potential indicators, each with varying significance weights. The technique was initially developed in 2003 to quantify the contamination potential of landfill leachate, making it one of the pioneering comprehensive indices in this field. From the time of its initial creation, the LPI has been subjected to various revisions to account for evolving environmental statuses and improvements in technology. Many elements, such as technological development and long-term reliability issues of the indicators, have questioned the validity of the initial LPI, which prompted the creation of revised versions.

The development of LPI follows four key steps:

1. Selection of pollutant variables: Eighteen critical leachate quality parameters were selected using the Delphi method, involving expert opinions [15,16].
2. Derivation of parameter weights: Each parameter was assigned a relative weight based on its environmental significance ($\Sigma w_i = 1$) [15,16].
3. Sub-index formulation: Rating curves were generated for each parameter to convert concentration values into dimensionless sub-index scores (p_i) on a scale of 5–100 [15,16].
4. Aggregation: The weighted linear sum aggregation function was chosen as the most appropriate method for computing LPI, minimizing both underestimation and overestimation errors [15,16].

When data for all parameters are available:

$$LPI = \frac{\sum_{i=1}^{n} w_i \cdot p_i}{\sum_{i=1}^{n} w_i} \quad (1)$$

w_i = weight of the i[th] pollutant variable
p_i = sub-index score of the i[th] variable
n = number of variables

III. Results and Discussion

The results of the Leachate Pollution Index (LPI) for three years (2022-2024) covering three different seasonal periods (dry, wet, and intermediate) show significant temporal and seasonal variations in the potential of leachate contamination. This relationship is aligned with current research that demonstrates the generation of highly toxic leachate due to waste decomposition in landfills, which has the potential to migrate and percolate through the soil and thus cause contamination of nearby aquatic bodies [17]. A comprehensive analysis involving organic, inorganic, and heavy metal components is shown, providing critical information on the dynamics of leachate pollution in landfills. These results are consistent with the original formulation of the LPI by Kumar and Alappat [15,16], which was derived from the knowledge of 80 waste management experts.

Significant annual variability with clear seasonal trends is exhibited by the overall LPI values, varying from 10.0 in the wet season of 2023 to 37.2 in the dry season of 2024 (Fig 1). This variability is supported by recent research showing that LPI values in active and closed dumping sites are 34.02 and 31.80 respectively, indicating similar potentials for contamination [18]. It is inferred that concentrated leachate conditions are represented by the maximum contamination potential observed during the dry season of 2024, whilst optimal dilution effects or efficient leachate management strategies during this season are represented by the minimum value during the wet season of 2023. This agrees with the LPI being used as a quantitative measure for standardized reporting of leachate pollution data [15,16]. Seasonal analysis reveals erratic patterns during the study period, highlighting the complex dynamics between climatic conditions and leachate generation. During 2024, the highest pollution potential (LPI = 37.2) is due to conditions during the dry season (Table 1), followed by the wet season (29.0) and the intermediate season (25.6). However, this pattern is not consistently followed in previous years; the wet season had the highest figures (30.5) in 2022, whereas the intermediate season had its highest figures (23.2) in 2023 (Table 1). These fluctuations highlight the imperative requirement for continuous monitoring since leachates from municipal landfills are known to be a source of toxic heavy metals that have devastating impacts on human health and the environment, with the dynamics changing during wet and dry seasons.

The organic component displays the strongest seasonal changes and represents the main part of the LPI values for most of the measurement period. Peak organic pollution at LPI = 80.0 was detected in 2024's intermediate season which marked the highest single component value across all measurements while indicating severe biodegradation activity. The wet season of 2023 experienced exceptionally low organic pollution (10.0) which contrasted strongly with the dry (60.2) and intermediate (67.1) seasons indicating possible treatment impacts or climatic anomalies. The dry and intermediate seasons in 2022 and 2024 showed consistently high levels which indicates predictable seasonal biodegradation patterns that need specific management approaches.

The inorganic pollution elements demonstrate more consistent patterns compared to organic components because their values remain between 13.6 and 34.5 throughout all monitoring periods. The wet season of 2024 experienced the highest inorganic contribution at 34.5 while 2022 and 2023 maintained stable readings which mostly fell between 22.6 and 25.3. The significant increase observed in 2024 especially during the wet season points to changes in waste composition or leachate management practices which need additional examination to determine the root causes.

According to the LPI classification schemes the recorded values throughout the study period demonstrate moderate to high pollution potential with most total LPI values exceeding 25 showing concerning contamination levels. According to research LPIs that exceed 7.5 represent unsuitable environmental states that require immediate intervention thus placing the majority of recorded values above critical levels. The data indicate that the 2024 dry season poses the greatest environmental threat due to increased organic and heavy metal contributions that demand enhanced monitoring and treatment during dry periods when concentrations tend to peak.

IV. Conclusion

This research examines how seasonal changes affect landfill leachate contamination through the analysis of Leachate Pollution Index data spanning from 2022 to 2024. The study reveals that leachate pollution potential changes considerably throughout time because total LPI values fluctuate between 10.0 and 37.2. The research demonstrates that leachate contamination levels range between moderate and high levels which consistently surpass environmental standards set by Kumar and Alappat [15,16]. The yearly data reveal that 2024 presents the worst environmental situation because the combination of high organic pollution (62.6) with significant inorganic contamination (13.6) and elevated heavy metal concentrations (43.8) produced the highest total LPI value of 37.2 during dry season conditions.

Study results show organic pollution dominates the overall contamination potential with maximum values reaching 80.0 during the intermediate season of 2024. Research into landfill biodegradation processes supports this result while emphasizing the necessity for improved organic waste management approaches. The heavy metal pollution surge during dry season 2024 creates the most pressing environmental danger which demands immediate action because these levels threaten groundwater quality and ecosystem health based on Ahamad et al. [4].

The seasonal analysis demonstrates irregular patterns throughout the three-year monitoring period which indicates that traditional seasonal management methods may fail to handle complex interactions between climatic conditions and waste composition and leachate generation processes. The low pollution potential during wet season 2023 (total LPI = 10.0) stands out against rising pollution values in later periods which shows that effective leachate management needs continuous attention together with adaptable strategies. The variability in contamination potential has led to the creation of updated LPI approaches which can accurately track changes over time. The study provides definite proof that static assessments fail to properly characterize leachate pollution potential because all measured components show significant variations.

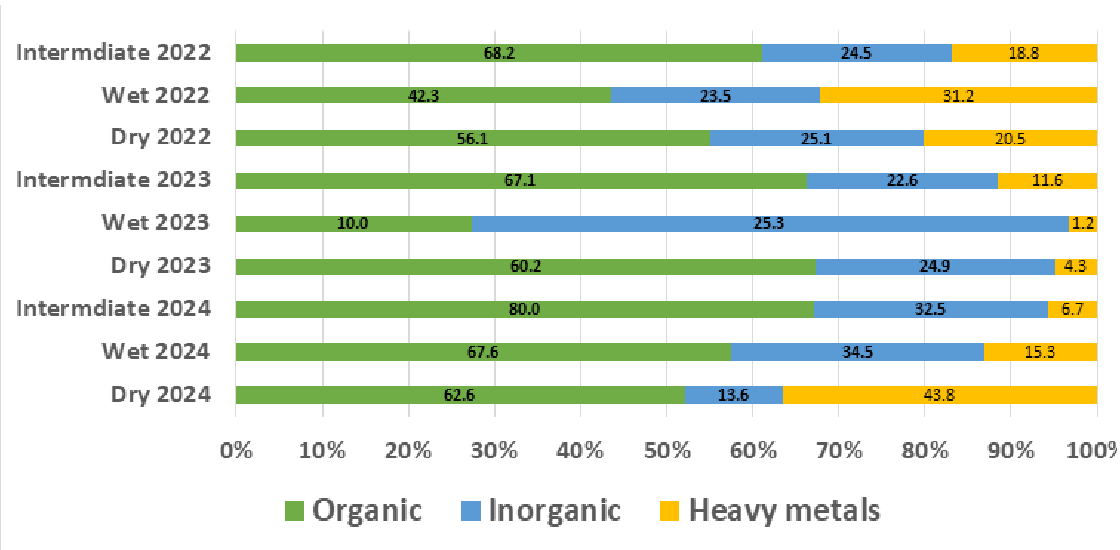

Figure 1. Seasonal Variation of Leachate Pollution Index (%) for years 2023 & 2024

TABLE I. LEACHATE POLLUTION INDEX FOR YEARS 2022,2023 & 2024

LPI	*Dry 2024*	*Wet 2024*	*Intermediate 2024*	*Dry 2023*	*Wet 2023*	*Intermediate 2023*	*Dry 2022*	*Wet 2022*	*Intermediate 2022*
Organic	62.6	67.6	80.0	60.2	10.0	67.1	56.1	42.3	68.2
Inorganic	13.6	34.5	32.5	24.9	25.3	22.6	25.1	23.5	24.5
Heavy metals	43.8	15.3	6.7	4.3	1.2	11.6	20.5	31.2	18.8
Total LPI	37.2	29.0	25.6	19.0	10.0	23.2	27.2	30.5	27.9

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