

LEACHATE CHARACTERIZATION AND POLLUTION POTENTIALS FROM UNCONTROLLED LANDFILLS IN THE CENTRAL REGION OF GHANA

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Abstract

Uncontrolled landfilling remains the main method for municipal solid waste disposal in Ghana, despite its potential to generate highly contaminated leachate that can degrade soil and water resources. This study characterized leachate from three major uncontrolled landfills in Breman Asikuma, Agona Swedru, and Cape Coast in Ghana's Central Region, and assessed their pollution potential using the Leachate Pollution Index (LPI). Composite leachate samples were collected monthly over 6 months and analysed for physicochemical, microbiological, and heavy metal parameters according to Standard Methods. Pearson correlation and principal component analyses (PCA) were used to identify relationships among contaminants and infer their possible sources. Most parameters measured such as electrical conductivity, total dissolved solids, biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), ammonium nitrogen (NH₄-N), chloride, total coliform bacteria, and various heavy metals exceeded Ghana Environmental Protection Agency and WHO guidelines for wastewater discharge. The BOD₅/COD ratios (0.14–0.35) and alkaline pH levels indicated that the landfills were mostly in the methanogenic stage of stabilisation. Overall LPI values ranged from 10.00 to 16.00, which are significantly above the safe threshold for inland water discharge, indicating high pollution potential. Organic components, especially COD, BOD₅, and total coliform bacteria, along with inorganic pollutants like chloride, NH₄-N, and total dissolved solids, contributed most to the overall LPI. Although heavy metals contributed less to the index, they remain environmentally significant due to their persistence and toxicity. Multivariate analyses showed strong associations among contaminants, suggesting common human-related sources stemming from municipal, household, and industrial waste. These findings demonstrate that uncontrolled landfills in the Central Region are major sources of environmental pollution and highlight the urgent need for comprehensive leachate management that combines biological treatment with advanced membrane-based physicochemical technologies to protect groundwater resources and public health.

Keywords

Leachate, uncontrolled landfills, Leachate Pollution Index, Central Region, Ghana

Introduction

The generation of municipal waste (MSW) is rising rapidly due to fast urbanisation, population increase, economic development, and changing consumer patterns (Sharma and Jain, 2020). The global annual waste generation exceeds 2 billion tons, with forecasts indicating a rise to 3.4 billion tons by 2050, particularly in developing nations (Maalouf and Mavropoulos, 2022). By 2025, Africa is projected to generate around 243 million tons of waste yearly (Jones et al., 2023). Ghana produces around 1.1 million tons of waste yearly, with annual generation rates rising by approximately 10% (Awafo et al., 2023). Most of the waste generated constitutes municipal solid waste (Kanhai et al., 2021; Miezah et al., 2015) and the surge in waste generation outpaces the capacity of existing waste management systems, many of which are inadequate to handle the increased volume. In the wake of this challenge, sustainable waste management approaches, like recycling, composting, and advanced landfill technologies, are options expected/envisaged to play key roles in protecting the environment (Nanda and Berruti, 2021).

Among the options, however, uncontrolled landfilling remains the predominant method of waste disposal in Ghana. These facilities are unregulated disposal sites where waste is dis-

posed of indiscriminately without any proper environmental safeguards (Mishra et al., 2019). They are popular because they are more economical, easily accessible and capable of receiving large volumes of waste (Gani et al., 2021; Grugnaletti et al., 2016; Shah et al., 2021). These facilities further produce offensive odour, pollute the air and contribute to greenhouse gas emissions, contaminate soil and groundwater through leachate infiltration. They also attract disease-carrying pests, and pose serious public health and environmental risks (Hussein et al., 2019).

The central region, like other regions in Ghana, is vulnerable to the impacts of uncontrolled landfills because engineered landfills are absent. Many communities in the region depend significantly on shallow groundwater systems, including hand-dug wells and boreholes, for drinking water. Many of these groundwater sources are located within the environs of uncontrolled landfills, exposing them to potential pollution from leachate intrusion. Since most uncontrolled landfills were not planned, they tend to spring up anywhere in communities, negatively impacting the quality of life through direct exposure to odours, smoke from burning waste, disease vectors, and offensive leachate runoff. Furthermore, rapid urbanisation and population growth in the region has increased waste volumes

that outwit the capacity of existing management infrastructure (Awafo et al., 2023). The high volume of waste generation is partly responsible for the sporadic growth of the uncontrolled landfills and the associated environmental pollution.

Leachate is an aqueous liquid discharged from landfills as solid waste decomposes, resulting from physical, chemical, and biological processes within the landfill (Parvin and Tareq, 2021; Youcai, 2018). It contains pollutants including organic, inorganic and heavy metals. Its discharge and management present challenges for the metropolitan, municipal and district assemblies due to the varied contaminant compositions of the leachates. Contaminants in leachate are influenced by the types of waste, the age of the landfill, and climatic conditions (Kamaruddin et al., 2017). Typical recent leachate treatment approaches involve characterizing contaminants to identify the most effective treatment method. The characterization also enables the determination of the Leachate Pollution Index (LPI), a measure of the overall pollution potential of leachate (Maiti et al., 2016).

The objectives of this paper are therefore: 1. to characterise leachate from three major uncontrolled landfills and assesses leachate pollution potential using leachate pollution indices, 2. to identify the major pollutants contributing to contamination and their probable sources, and 3. to recommend suitable treatment options for effective management of landfill leachate, in order to minimise environmental and public health impacts.

Materials and Methods

Study Sites

The study was conducted at three major uncontrolled landfills in the Central Region of Ghana: Cape Coast, Agona Swedru, and Brehman Asikuma. The Cape Coast uncontrolled landfill covers about 98 km² of land and lies between 5°10'45.75' N and 1°15'07.86' W. The Agona Swedru site in the Agona East Municipality is between 5°38'26.41' N and 0°42'11.87' W. The site spans 81 km². The Brehman Asikuma uncontrolled landfill covers 3.9 km² of land size and lies between 5°39'17.70' N and 0°57'22.66' W. All the landfills lack facilities for leachate collection, storage, treatment, and stabilisation.

Sampling of Leachate

Sampling was done monthly for six months (July–December, 2022 and January, 2023). All sampling equipment was sterilised to prevent contamination of samples and pre-treated sampling bottles were rinsed with leachate samples before sampling (Hussein et al., 2021). At each landfill site, leachate samples were collected from major points where leachate drained out. These were mixed homogeneously to yield a composite sample representing leachate of a particular site. Four composite leachate samples were collected from each study site on each field visit. One composite sample was collected into a 500 ml high-density polyethylene (HDPE) and acidified with 2 ml concentrated HNO₃ to a pH of less than

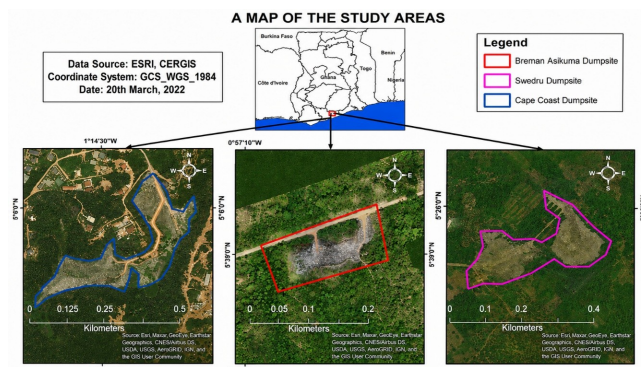


Figure 1. Map of study sites

2 for heavy metal determination. This was to reduce microbial activity, limit heavy metal escape through precipitation, adsorption, and complex formation and prevent chemical and biological changes that could alter the natural homogeneity of samples (Hussein et al., 2021). Another 500 ml non-acidified sample was taken for *ex-situ* physico-chemical analyses. A third sample of 250 ml was collected for BOD analysis, and a fourth sample of 250 ml was taken into pre-sterilised glass bottle for total and faecal coliform enumeration. A pre-calibrated multi-meter quality checker, HORIBA U-50 series, was used for *in-situ* determination of temperature, pH, EC, TDS, DO and salinity. The pH meter was calibrated with standard pH buffers 4.01, 7.0, and 9.21. The conductivity meter was calibrated using standard solutions: 0.01 M KCl (413 $\mu\text{S cm}^{-1}$) and 0.1 M KCl (12880 $\mu\text{S cm}^{-1}$). A geographical positioning system (GPS) model (Garmin etrex 20) was used to record the geographical coordinates of each sampling point. Samples were stored on ice and transported to the laboratory for analysis (Vaverková, 2019).

Laboratory Analysis

Leachate samples were stored at 4 °C in a fridge for preservation. The physico-chemical and biological parameters were analysed using standard methods (APHA, AWWA, WPCF, 20th edition). Total dissolved solids (TDS) were determined using the gravimetric method, while sodium and potassium were measured using the flame photometric method. Chloride (Cl⁻) was analysed using the argentometric method, and bicarbonate (HCO₃⁻) was determined using titrimetric methods. Cyanide (CN⁻) was measured with a nano-colorimeter (500D), and phosphate (PO₄³⁻-P) was analysed using the stannous chloride method. Ammonia-nitrogen (NH₃-N) was determined using an Expandable Ion Analyzer (EA940), and Total Kjeldahl Nitrogen (TKN) was measured using the Kjeldahl method. Biochemical oxygen demand over five days (BOD₅) was analysed using the Azide modification of the Winkler method, while chemical oxygen demand (COD) was determined through the open reflux digestion method. Phenolic compounds were measured using a UV-Vis spectrophotometer. Total and faecal coliform enumeration was incubated on Violet Red Bile Agar at 37°C for 24 hours. The concentrations of heavy metals, including arsenic, cadmium, copper, iron,

mercury, manganese, nickel, lead, and zinc, were determined using a Perkin Elmer Pinnacle 900T atomic absorption spectrometer (AAS). All sample preparations and analyses were conducted at the Ecological Laboratory of the University of Ghana, Legon.

Data treatment and statistical analysis

The data was entered and preserved in MS Excel 20.0 loaded into IBM SPSS version 27 for statistical analysis. The Kolmogorov-Smirnov (K-S) test assessed normality of results at $p < 0.05$. Descriptive statistics (mean, range, standard deviation) were calculated at a 95% confidence interval. One-way ANOVA identified statistically significant differences in mean pollutant concentrations. The Pearson correlation coefficient was used to determine relationships between parameters and their possible sources while Principal Component Analysis was used to reduce data dimensionality.

Estimation of LPI

The Leachate Pollution Index (LPI) was calculated following Kumar and Alappat (2003), providing a single value (5–100) that indicates the overall contamination potential of a landfill. Higher LPI values reflect greater pollution (Kumar and Alappat, 2003). The estimation of the LPI entails the selection of pollutant variables and their corresponding weights, formulating sub-index curves for each variable, and aggregating the chosen variables to ascertain the final LPI (Mai et al., 2019). The sub-LPI was estimated by the use of equation 1:

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

where LPI is the weighted additive leachate pollution index, n is the total number of leachate pollutant parameters used in estimating LPI, w_i is the weight of the i th pollutant, and p_i is the sub-index score of the i th leachate pollutant parameter. The sub-index (P) values for each parameter were derived from sub-index curves based on pollutant concentrations, following Kumar and Alappat (2005a,b). The overall LPI was estimated using equation 2:

$$LPI = 0.232LPI_{or} + 0.257LPI_{in} + 0.511LPI_{hm} \quad (2)$$

Quality Assurance and Quality Control

Glassware and bottles were soaked in 10% nitric acid, washed with 10% hydrochloric acid, rinsed with distilled water, and dried (Boadi et al., 2013). Reagent blanks corrected spectrophotometric readings, and results were validated with certified reference material (SRM-1570). Recovery tests showed efficiencies between $80.5\% \pm 0.8$ and $88.7\% \pm 2.3$. All analyses were carried out in triplicate, with mean concentrations calculated.

Results and Discussions

Leachate characterisation and age

The physico-chemical, and biological properties of leachate are presented in Table 1. Generally, the levels of most parameters exceeded the WHO and Ghana EPA threshold for

treated leachate. The pH of landfill leachate increases with landfill age, ranging from 5.0–6.5 in young landfills to 7.8–8.64 in older ones, due to the reduction of volatile fatty acids by methanogenic bacteria. The present study's pH range of 7.4–8.9 indicates a mature landfill stage and aligns with values reported at the Sarbah and Oblogo dumpsites in Accra, Ghana, as well as findings by Ashraf et al. (2013), Atta et al. (2015), Emenike et al. (2012), Nazrieza et al. (2015), and Thaiyalnayaki and Jayanthi (2016). The elevated pH levels may alter nearby drinking water quality and promote trihalomethane formation, posing health risks.

The concentration of minerals and salts in leachate is generally due to TDS. The TDS values were high across the landfills (Table 1). This could be attributed to decomposition of organic waste in the landfills (Gyabaah et al., 2023) as well as the observed elevated EC values. The dissolved substances could pose environmental risks to vegetation, aquatic life, and soil. The high TDS values may hinder biological treatment of leachate (Kumar and Alappat, 2005c) and coupled with turbidity, reduce water clarity and photosynthesis, impacting aquatic ecosystems (Naveen et al., 2017). The EC values ranged from 2050 to 11162 $\mu\text{S cm}^{-1}$, 11572 to 24398 $\mu\text{S cm}^{-1}$, and 3560 to 16876 $\mu\text{S cm}^{-1}$ for BALL, CCLL, and SWLL respectively. The EC of the leachate primarily results from the presence of ions such as calcium, magnesium, sodium, and potassium (Wdowczyk and Szymańska-Pulikowska, 2021a).

Nutrients ($\text{NH}_4\text{-N}$, $\text{NO}_3\text{-N}$, $\text{NO}_2\text{-N}$, and PO_4^{3-}) were high across all landfills and may contribute to increased EC levels. The EC may influence groundwater flow across soil strata, facilitating the leaching of contaminants into the groundwater system and potentially increasing ion concentrations in drinking water (Mishra et al., 2019). This can cause laxative effects, high blood pressure, cardiovascular problems, methemoglobinemia (blue baby syndrome) in infants, and increase cancer risks in adults.

The Cl^- concentrations ranged from 2894 to 5548 mg/L, 3016 to 5648 mg/L, and 1877 to 4574 mg/L in BALL, CCLL, and SWLL, respectively. Chloride (Cl^-) is an inorganic macronutrient with minimal sorption, complexation, and precipitation processes (Kumar et al., 2023) and a conservative pollutant (Bag et al., 2016). It exhibits significant mobility under various conditions due to its inert, non-biodegradable nature (Ofomola et al., 2017). The elevated Cl^- concentrations in leachate could be attributed to the disposal of industrial waste at the landfills. Studies conducted by Saha et al. (2021) and Naveed et al. (2020) indicate that Cl^- contaminated leachate entering water sources can lead to the death of aquatic species. The Cl^- levels observed in this study are consistent with those reported by Wdowczyk and Szymańska-Pulikowska (2021b), who also reported similarly high concentrations (2132.3 mg/L) at the Legnica landfill in Poland.

Biological oxygen demand, BOD_5 , measures the amount of oxygen needed by microorganisms to breakdown organic pollutants in wastewater (Amenu, 2014). The BALL, CCLL, and SWLL recorded BOD_5 values ranging from $230.94 \pm$

Table 1. Leachate characteristics from uncontrolled landfills in the central region of Ghana (N=18)

Parameter	BALL		CCLL		SWLL		WHO	EPA
	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range		
pH	7.60 $\pm$ 0.68	7.43–9.52	7.50 $\pm$ 0.98	7.38–8.90	7.50 $\pm$ 1.21	7.73–8.88	6–9	6–9
EC	8455.78 $\pm$ 3263.69	2050–11162	19409.96 $\pm$ 649.37	11572–24398	11898.26 $\pm$ 717.14	3560–16876	1200	1500
BOD ₅	230.94 $\pm$ 11.26	181–412.86	4573.94 $\pm$ 801.74	372–14980	305.48 $\pm$ 10.83	256.45–484	<5	50
COD	1550.03 $\pm$ 79.26	538–2544.52	3447.87 $\pm$ 60.46	3014–4190	982.06 $\pm$ 45.28	489–1330	<5	250
TDS	4982.01 $\pm$ 322.99	126–6745	6763.07 $\pm$ 886.95	360–14552	5426.95 $\pm$ 558.56	338–1330	250	1000
TCB	411.81 $\pm$ 44.90	8–800	79.96 $\pm$ 21.96	2–380	4406.33 $\pm$ 116.96	3245–5567	–	–
Ca	147.51 $\pm$ 27.72	108.45–173.67	168.66 $\pm$ 42.89	74.23–198	164.83 $\pm$ 35.43	90.48–197.69	–	–
Cu	0.03 $\pm$ 0.01	0.01–0.51	0.12 $\pm$ 0.01	0.03–0.27	0.20 $\pm$ 0.07	0.01–0.39	–	–
Mg	141.01 $\pm$ 44.79	97.75–205.90	102.32 $\pm$ 16.50	85.94–135.80	108.08 $\pm$ 26.63	89.74–165.78	2	5
Na	1887.06 $\pm$ 463.74	241.67–9443	3938.94 $\pm$ 348.97	1862–7497	2937.51 $\pm$ 221.52	1036–6250	0.5	–
Zn	0.12 $\pm$ 0.09	0.02–0.29	0.12 $\pm$ 0.07	0.01–0.35	0.41 $\pm$ 0.11	0.03–0.37	–	–
K	1545.38 $\pm$ 191.01	158.40–3060	1426.42 $\pm$ 165.89	276.55–3367	1127.22 $\pm$ 88.34	274.45–2276	3	5
PO ₄	11.73 $\pm$ 6.98	3.78–19.56	23.65 $\pm$ 6.28	4.33–59	9.17 $\pm$ 3.46	1.26–16.82	–	–
SO ₄	132.67 $\pm$ 33.96	6–689	19.19 $\pm$ 8.63	4.23–28.98	19.80 $\pm$ 3.00	5–70	500	50
NH ₄ -N	72.26 $\pm$ 18.12	1.32–134	234.52 $\pm$ 172.73	21.40–574	73.86 $\pm$ 15.20	0.02–146.80	–	1.5
NO ₃ -N	63.23 $\pm$ 31.91	7.20–98	40.07 $\pm$ 17.56	20–58.64	45.30 $\pm$ 7.17	33–56.45	50	10
NO ₂ -N	20.55 $\pm$ 3.35	1.58–58.82	3.01 $\pm$ 0.16	1.84–5.50	9.26 $\pm$ 2.77	0.02–54.85	0.20	–
TKN	212.20 $\pm$ 13.19	47.42–289	1251.80 $\pm$ 109.49	90–2019	241.56 $\pm$ 26.92	22.23–507	–	–
Ph. Cpds	6.42 $\pm$ 0.83	0.11–13.56	7.88 $\pm$ 0.73	0.13–13.73	0.78 $\pm$ 0.23	0.05–1.99	–	–
Cl ⁻	3728.01 $\pm$ 145.76	2894–5548	4584.25 $\pm$ 109.27	3016–5648	2780.79 $\pm$ 105.99	1877–4574	250	250
As	0.27 $\pm$ 0.01	0.26–0.28	0.06 $\pm$ 0.03	0.01–0.13	0.04 $\pm$ 0.00	0–0.07	–	–
Cd	0.19 $\pm$ 0.01	0.08–0.44	0.17 $\pm$ 0.01	0.08–0.31	0.65 $\pm$ 0.20	0.38–0.84	0.03	<0.1
Cr	0.07 $\pm$ 0.04	0.02–0.14	0.24 $\pm$ 0.12	0.18–0.56	0.07 $\pm$ 0.03	0.04–0.14	0.01	0.10
CN ⁻	0.09 $\pm$ 0.02	0.03–0.19	0.41 $\pm$ 0.12	0.02–0.65	0.08 $\pm$ 0.02	0.01–0.15	–	–
Hg	0.01 $\pm$ 0.00	0.01–0.03	0.06 $\pm$ 0.03	0.01–0.12	0.02 $\pm$ 0.01	0.01–0.04	–	0.01
Pb	0.13 $\pm$ 0.05	0.08–0.22	0.36 $\pm$ 0.20	0.02–0.93	0.26 $\pm$ 0.05	0.07–1.01	0.01	5
Ni	0.49 $\pm$ 0.19	0.10–0.69	0.26 $\pm$ 0.16	0.10–0.47	0.24 $\pm$ 0.06	0.13–0.32	0.02	–
Fe	4.06 $\pm$ 2.11	0.43–6.56	59.21 $\pm$ 11.76	47.78–71.20	4.19 $\pm$ 1.38	0.57–6.87	0.30	10

Note: All parameters in mg/L except pH and TCB (MPN/100 ml); N = Number of samples analysed; BALL = Breman Asikuma landfill leachate; CCLL = Cape Coast landfill leachate; SWLL = Agona Swedru landfill leachate; EPA = Ghana Environmental Protection Agency; S.D. = Standard Deviation; TCB = Total Coliform Bacteria. Dashes (–) indicate no standard available.

11.26 mg/L to 4573.94 $\pm$ 801.74 mg/L. These values are intermediate and may be likely due to the organic waste content. Elevated BOD levels of leachates lower oxygen in receiving waters, causing hypoxic or anoxic conditions that harm aquatic life and promote algal blooms. The findings are consistent with Salami and Susu (2019), who reported BOD₅ values of 912 and 1396 mg/L at Soluos 3 landfill in Lagos, Nigeria. Meanwhile, COD levels are relatively high across the sites, ranging from 538–2544.52 mg/L, 3014–4190 mg/L, and 489–1330 mg/L for BALL, CCLL and SWLL respectively. COD measures the oxygen required to oxidise organic matter into inorganic end-products (Bhalla et al., 2012) and indicates the presence of hazardous and oxidisable substances in leachate (Enitan et al., 2018). As landfills age, leachate becomes less biodegradable, resulting in lower COD levels (Mohammad-Pajoooh et al., 2017; Teng et al., 2021).

COD values above 400 mg/L could pose environmental risks (Zakaria and Aziz, 2018). The high COD in leachate, just like BOD, may deplete oxygen in receiving waters, affecting aquatic organisms and disrupting ecosystem balance. The observed COD values suggest that the landfills are transitioning from the medium to the old phase (Baiju et al., 2018; Regaldo et al., 2020; Zailani and Zin, 2018). Similar COD levels have been reported at the Sarbah dumpsite in Weija, Ghana (Sackey and Meizah, 2015) and uncontrolled landfills

in Nigeria (Salami and Susu, 2019). The BOD₅/COD ratio of leachate is influenced by the age of the landfills, and decreases over time as biodegradable materials decompose (Shadi et al., 2020). Elevated ratios (≥ 0.5) indicate young landfills (< 5 years), (0.1–0.5), medium age landfill (5–10 years) and < 0.1 old landfills (>10 years) (Kamaruddin et al., 2015; Naveen et al., 2017).

The definite ages of the uncontrolled landfills were not known by the facility managers. Therefore, in order to estimate the ages, BOD₅/COD ratios were employed. The BOD₅/COD ratios of 0.35, 0.17, and 0.14 recorded for SWLL, BALL, and CCLL, respectively, suggest differences in the stabilisation stages of the uncontrolled landfills. The ratio of 0.35 for SWLL indicates an intermediate or transitional landfill, approximately 5–10 years old, with a moderate proportion of biodegradable organic matter. In contrast, the lower ratios of 0.17 and 0.14 recorded for BALL and CCLL indicate that the landfills are in the methanogenic stage, and are likely to be more than 10 years old and contain predominantly refractory organic compounds. The ratio observed in the present study could be ascribed to reduced anaerobic decomposition activity, which reduces the biodegradable fraction of organic pollutants (El-Gohary and Kamel, 2016).

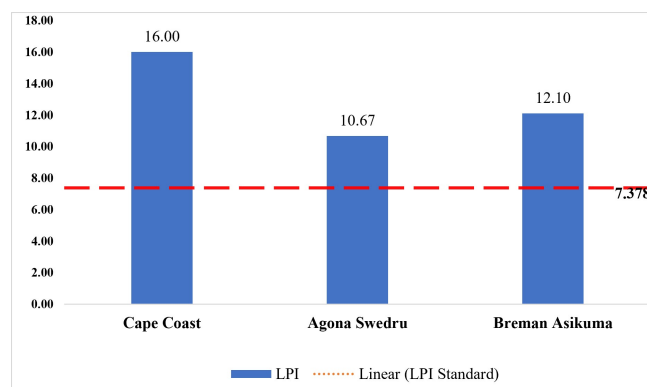
Phenolic compounds were low across all landfills (Table 1) which may signal rapid aerobic decomposition during the aci-

Table 2. Sub-indices and overall Leachate Pollution Index (LPI)

Index	Parameter	BALL				ASLL			CCLL		
		Conc.	Wi	Pi	WiPi	Conc.	Pi	WiPi	Conc.	Pi	WiPi
Organic	COD	1550.03	0.267	40	10.68	982.06	30	8.01	3447.87	50	13.35
	BOD ₅	230.94	0.263	8	2.104	305.48	10	2.63	4573.94	50	13.15
	Ph. cpds	6.42	0.246	10	2.46	0.78	5	1.23	7.88	10	2.46
	TCB	411.81	0.224	55	12.32	147.70	50	11.2	102.93	45	10.08
LPI_{or}		27.56				23.07			39.04		
Inorganic	pH	7.63	0.214	5	1.07	7.54	5	1.07	7.55	5	1.07
	TKN	212.20	0.206	8	1.648	241.56	5	1.03	1251.80	8	1.648
	NH ₄ -N	72.26	0.198	10	1.98	73.86	10	1.98	234.52	20	3.96
	TDS	4982.01	0.195	10	1.95	5426.95	15	2.925	6763.07	15	2.925
	Cl ⁻	3728.01	0.187	30	5.61	2780.79	20	3.74	4584.25	40	7.48
LPI_{in}		12.258				10.745			17.083		
Heavy metal	Cr	0.07	0.125	5	0.625	0.07	5	0.625	0.24	5	0.625
	Pb	0.13	0.123	5	0.615	0.26	5	0.615	0.36	5	0.615
	Hg	0.02	0.121	5	0.605	0.02	5	0.605	0.06	5	0.605
	As	0.27	0.119	5	0.595	0.04	5	0.595	0.06	5	0.595
	CN	0.09	0.114	5	0.57	0.08	5	0.57	0.41	5	0.57
	Zn	0.12	0.110	5	0.55	0.14	5	0.55	0.12	5	0.55
	Ni	0.49	0.102	5	0.51	0.24	5	0.51	0.26	5	0.51
	Cu	0.03	0.098	5	0.49	0.19	5	0.49	0.12	5	0.49
	Fe	4.06	0.088	5	0.44	4.14	5	0.44	59.21	5	0.44
LPI_{hm}		5.00				5.00			5.00		
Overall LPI		12.10				10.67			16.00		

Note: LPI_{or} = Leachate Pollution Sub-index of organics; LPI_{in} = Leachate Pollution Sub-index of inorganics; LPI_{hm} = Leachate Pollution Sub-index of heavy metals; BALL = Breman Asikuma landfill leachate; ASLL = Agona Swedru landfill leachate; CCLL = Cape Coast landfill leachate; Conc. = Concentration; Wi = Weight; Pi = Sub-index value; WiPi = Weighted sub-index value.

dogenic phase (Abunama et al., 2021; Aziz et al., 2010). These toxic and endocrine-disrupting compounds from domestic and personal care products disposed into landfills could infiltrate nearby soil and water systems, posing serious health and ecological risks (Matike and Ngole-Jeme, 2024; Vaverková et al., 2020). They may harm the health of agricultural soil, inhibit plant growth (Vaverková et al., 2020), disturb microbial communities in impacted habitats and reduce biodiversity (Zhang et al., 2019). Total Kjeldahl Nitrogen (TKN) levels ranged from 47.42–289 mg/L in BALL, 90–2019 mg/L in CCLL, and 22.23–507 mg/L in SWLL, indicating ongoing active waste disposal. TKN typically declines during landfill stabilization (Scott et al., 2019). Ammonia nitrogen (NH₄-N) concentrations were also high; 32–134 mg/L, 21.40–574 mg/L, and 28.4–146.80 mg/L respectively, reflecting persistent anaerobic activity and potential risks of eutrophication, oxygen depletion, and inhibition of biological treatment processes (Liu et al., 2019; Marek et al., 2021; Zhang et al., 2021). Furthermore, NH₄-N can contribute to offensive odours, attract flies, and when volatilized above 0.50 mg/L, become a harmful air pollutant posing health risks to nearby residents (Prakash and Khanam, 2021).

**Figure 2.** Overall LPI compared to standard LPI value

Heavy metals

The mean concentrations of heavy metals were observed to be higher compared to the regulatory limits established by the WHO and the Environmental Protection Agency of Ghana (Table 1). The BALL, CCLL and SWLL exhibited mean concentrations of Pb (0.13, 0.36, 0.26 mg/L), Hg (0.06, 0.02 mg/L), Cd (0.19, 0.17, 0.65 mg/L), and Cr (0.07, 0.24, 0.07 mg/L), respectively. The elevated levels of heavy metals in leachate are of concern when they enter into water sources for

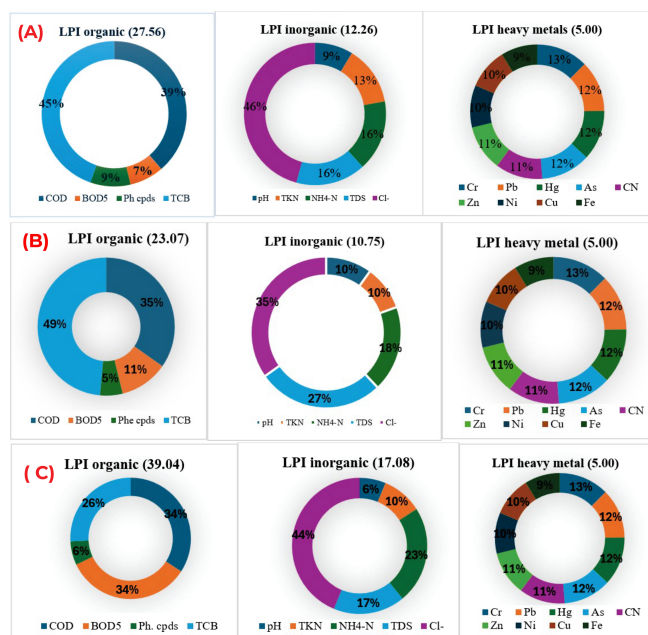


Figure 3. (A) Percentage distribution of LPI organic, LPI inorganic and LPI heavy metals for Breman Asikuma uncontrolled landfill; (B) Percentage distribution of LPI organic, LPI inorganic, and LPI heavy metals for Agona Swedru uncontrolled landfill and (C) Percentage distribution of LPI organic, LPI inorganic, and LPI heavy metals for Cape Coast uncontrolled landfill

drinking purpose. Essential elements like zinc (Zn), copper (Cu), and iron (Fe) in their right proportion play vital roles in biological processes and function as coenzymes for maintaining health. Iron (Fe), is a key component of haemoglobin and myoglobin while also playing a role in vitamin B12. However, when these metals accumulate beyond permissible limits, they can become harmful as they may interact with proteins and DNA, impairing their functions and potentially leading to gastrointestinal issues (Kim et al., 2019). In contrast, heavy metals like Cr, Pb, As, and Cd pose significant threats even at minute levels. They are non-biodegradable and can accumulate in living systems, leading to serious health consequences (Kim et al., 2019; Wijekoon et al., 2022). Mercury (Hg) is both neurotoxic and carcinogenic, capable of damaging the kidney and brain. Chromium exposure may cause allergic reactions, neurological impairments, and cardiovascular issues. Lead (Pb) disrupts cellular function by generating reactive oxygen species and reduces the body's antioxidant defenses. Furthermore, exposure to As, Cd, and Hg during pregnancy has been linked to impaired brain function and neurodevelopmental disorders among infants (Kim et al., 2019). The concentration of heavy metals in this study was higher than those reported in leachates from Jordan by Abu-Daabes et al. (2013). The increased levels of heavy metals including Pb, Hg, Cd, and Cr indicate extended waste accumulation and leaching processes typical of older landfills. The accumulation of these metals over time substantiates the assertion that the sites are in an advanced phase of landfill development, which could present environmental and public health hazards.

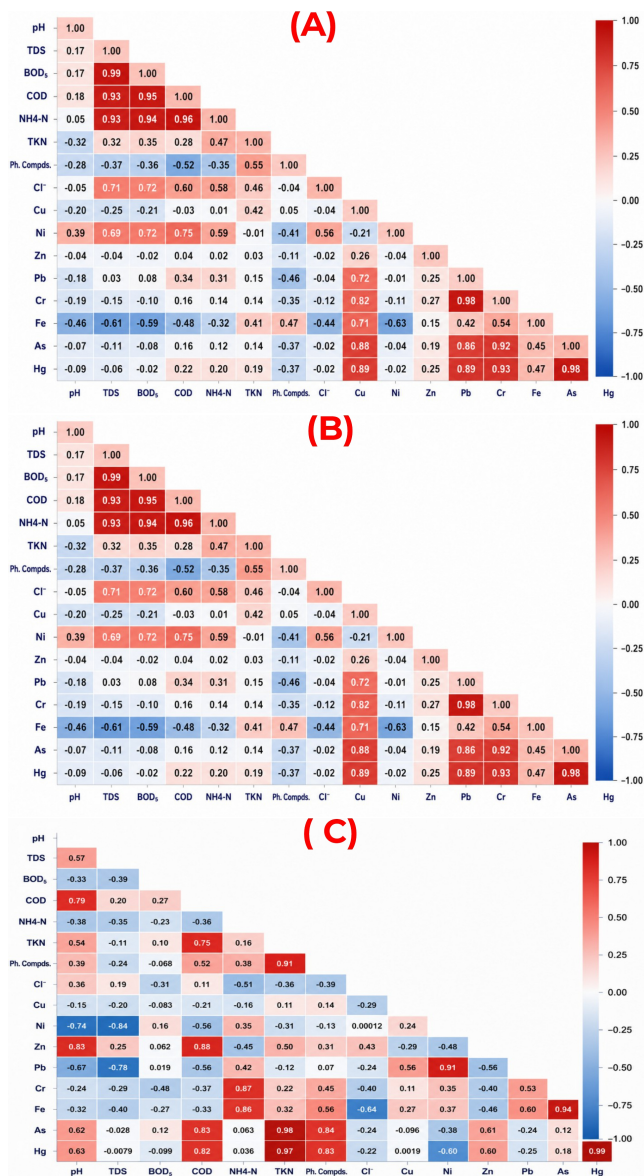


Figure 4. (A) Correlation analysis of physico-chemical parameters of Breman Asikuma leachate samples, (B) Correlation analysis of physico-chemical parameters of Agona Swedru leachate samples, (C) Correlation analysis of physico-chemical parameters of Cape Coast leachate samples

Leachate Pollution Indices (LPI)

The Leachate Pollution Index (LPI) was used to assess the pollution potential and propose an appropriate treatment method of leachate from three uncontrolled landfills located in Breman Asikuma, Agona Swedru, and Cape Coast in the Central Region of Ghana. The overall LPI values of 12.10, 10.67, and 16.00 obtained in the present study exceeded the recommended disposal threshold of 7.378 proposed by Kumar and Alappat (2003). This threshold represents the maximum pollution index considered acceptable for treated leachate to be discharged into surface water bodies. The elevated LPI values from this study therefore indicate that the leachates from all three landfill sites are highly polluted and require treatment before discharge, to minimise any associated ecological impacts.

Table 3. PCA of Breman Asikuma Leachate (KMO=0.857; Bartlett's test=2877.999)

Parameter	Component			Communalities
	1	2	3	
pH	-0.976*	-0.170	0.072	0.986
BOD ₅	-0.297	-0.527**	0.794*	0.997
COD	-0.254	0.234	0.934*	0.991
Ph. Cpds	0.793*	0.606**	0.017	0.996
NH ₄ -N	0.889*	0.413	-0.179	0.993
TKN	0.305	0.947*	0.018	0.989
TDS	0.452	0.667**	-0.589**	0.997
Cl ⁻	-0.781*	-0.179	0.590**	0.990
Pb	-0.373	-0.867*	0.303	0.982
Cr	-0.101	-0.967*	0.187	0.981
Hg	0.551**	0.774*	-0.088	0.910
CN	0.633**	0.730*	0.038	0.936
Cu	0.751*	0.494	-0.378	0.950
Ni	0.491	0.640**	-0.580**	0.986
Zn	0.143	-0.114	0.982*	0.998
Fe	0.974*	0.199	0.020	0.988
As	0.140	0.945*	0.010	0.912
Total Coliforms	0.810*	0.200	-0.309	0.791
Eigenvalue	10.107	6.262	1.262	
% of variance	61.22	19.67	2.906	
% cumulative	61.22	80.89	83.80	

Note: *Strong (factor score > 0.75); **Moderate (0.5 ≤ score ≤ 0.75); Weak (score < 0.5).

Despite being in the same region, variations in LPI were observed, likely due to differences in waste composition, landfill age, and management practices. The high LPI values confirm the presence of significant pollutants, which require leachate collection and treatment before release into the environment. Sub-index values for organics (LPI_{or}), and inorganics (LPI_{in}) exceeded acceptable levels. BALL recorded values of 27.564 and 12.258, SWLL had 23.07 and 10.745; while CCLL showed the highest at 39.04 and 17.083. COD was the dominant organic pollutant in BALL and SWLL, while it was BOD₅ at CCLL. Chloride was the most significant inorganic pollutant, followed by NH₄-N and TDS. Cr was the most prevalent heavy metal in leachate across landfills. High Pollution Index (Pi) values for COD, BOD₅, TCB, NH₄-N, and Cl⁻ confirm both organic and inorganic contamination, which could pose risks to water quality and ecosystem balance (Kumar and Alappat, 2005c; Mishra et al., 2018, 2019).

Pollution Index (LPI) values above 10 may also impact plant growth (Arunbabu et al., 2017). Elevated LPI values may result from high infiltration of rainwater, which increases pollutant dissolution (Zhou et al., 2024), and higher temperatures, which enhance microbial activity in the landfills (Lu et al., 2024). Key pollutants identified in leachate from this study (BOD₅, COD, TKN, NH₄-N, Cl⁻, and TDS) align with those identified by Koranteng and Adams (2024) from Nsumia landfill in the Greater Accra Region of Ghana, and also with

Mishra et al. (2019) and Arunbabu et al. (2017) in India, Mahler et al. (2020) in Brazil, and Parvin and Tareq (2021) in Bangladesh. These are all developing countries and the findings may point to similar consumption pattern as well as waste management approach. The high LPIs established in this study revealed the urgent need for improved leachate management to prevent degradation of water and soil quality to protect public health.

Sources of Leachate Pollutants

Figure 4 A, B, C present Pearson correlation matrices showing the strength, direction, and statistical significance of relationships among the leachate physicochemical parameters from the landfill sites. Breman Asikuma Landfill Leachate (BALL) revealed strong positive correlations ($r \geq 0.8$) between pH and Cl⁻; TDS and Cu, Ni, Hg; BOD₅ and Pb; COD and Zn; NH₄-N and phenolic compounds, Fe, TCB; TKN and As, Hg; phenolic compounds and Cu, Fe, Hg; Cu and Ni, Fe, Hg; Ni; Hg and Pb and Cr (Figure 4a). In SWLL, a high positive correlation ($r \geq 0.8$) was observed between the following variables: pH and Cr; COD and NH₄-N, Hg; TKN and phenolic compounds, Cu, As, Hg; phenolic compounds and Cu, Fe, As, Hg; Cu and Fe, As; Ni and Zn; Zn and Pb; Fe and As, Hg; As and Hg (Figure 4b). In CCLL, a high positive correlation ($r \geq 0.8$) was observed between the following parameters: pH and NH₄-N, Cu; COD and NH₄-N; TKN and phenolic

Table 4. PCA of Agona Swedru Leachate (KMO=0.833; Bartlett's test=2853.005)

Parameter	Component			Communalities
	1	2	3	
pH	-0.940*	-0.176	0.129	0.932
BOD ₅	-0.683**	0.701**	0.137	0.977
COD	0.499	0.814*	0.267	0.983
Phenol	0.940*	0.260	-0.062	0.955
NH ₄ -N	0.324	0.885*	0.307	0.983
TKN	0.845*	0.392	-0.060	0.871
TDS	0.278	0.626**	-0.208	0.512
Cl ⁻	-0.221	-0.390	-0.891*	0.995
Pb	-0.343	-0.774*	0.500**	0.967
Cr	-0.777*	-0.590**	-0.184	0.986
Hg	0.806*	0.556**	-0.012	0.959
CN	0.891*	0.444	-0.058	0.993
Cu	0.956*	0.274	-0.060	0.992
Ni	-0.107	0.061	0.985*	0.985
Zn	-0.345	-0.403	0.832*	0.975
Fe	0.834*	0.298	-0.382	0.929
As	0.901*	0.403	-0.059	0.977
TCB	0.532**	-0.055	0.018	0.287
Eigenvalue	10.822	3.294	2.143	
% of variance	60.75	20.75	8.83	
% cumulative	60.75	81.50	90.33	

Note: *Strong (factor score > 0.75); **Moderate (0.5 ≤ score ≤ 0.75); Weak (score < 0.5).

compounds, Hg; phenolic compounds and As, Hg; Cu and Ni; Zn and Pb (Figure 4c). The strong positive correlations among leachate parameters indicate a similar origin. A strong positive correlation between pH and Cl⁻ implies that pH influences Cl⁻ levels, thereby affecting ion solubility (Barnie et al., 2018). TDS correlating with Cu, Ni, and Hg highlights contributions from industrial waste (Ozbay et al., 2021). Strong correlations between COD and Zn; TKN, As, and Hg suggest anthropogenic origins (Sarkar et al., 2024; Wdowczyk and Szymańska-Pulikowska, 2021a), while correlations between phenolics and Cu, Fe, and Hg indicate both natural and anthropogenic sources of pollution (Chaudhary, 2022).

While the correlation coefficient assesses relationships between two variables, its usefulness is limited when multiple parameters are involved (Schober et al., 2018). Principal Component Analysis (PCA) addresses this by analysing inter-correlations among multiple variables, reduces dimensionality of data and identifies key factors influencing leachate composition. This is validated by KMO > 0.75 and Varimax rotation with Eigenvalues > 1 (Ergene et al., 2022). For each landfill, the main two principal components of leachate contaminants are presented (Figure 5 a, b, c). Across the three landfill sites, PCA revealed distinct yet interrelated pollution patterns that reflect both site-specific and common leachate characteristics. The first two principal components explained over 75% of the total variance at the landfills. This indicates that few key con-

taminants dominate leachate chemistry. The PCA loadings for each landfill, their respective KMO and Bartlett's test values are presented in Tables 3 to 5.

The PCA of BALL reveals that the first two principal components PC-1 (61.22%) and PC-2 (19.67%) explain 80.89% of the total variance (Figure 5a). PC-1 is strongly loaded with Fe, NH₄-N, CN⁻, Pb, TDS, and TKN, which cluster on the positive axis, indicating that these variables contribute most to the variation along this component and likely represent the major sources of inorganic and nutrient contamination in the leachate. Conversely, variables such as pH, Cl⁻, BOD₅, and TCB are negatively loaded on PC-1, suggesting that these parameters are inversely related to the metal-nutrient group. PC-2 captures TCB and Zn with positive loadings, while COD and As show negative associations. This suggests that PC-2 differentiates leachate samples based on variability in organic contaminants and heavy metals.

Likewise, the PCA of SWLL shows that PC-1 and PC-2 account for 81.5% of the total variance, with PC-1 and PC-2 contributing 60.75% and 20.75%, respectively (Figure 5b). PC-1 is loaded with Hg, Cd, Fe, TDS, NH₄-N, and COD on the positive side, and pH, Pb, and Cl⁻ on the negative side, indicating that this axis differentiates between metal-nutrient enrichment and other physicochemical parameters. PC-2, dominated by Ni, Zn, BOD₅, and TCB on the positive side and Cl⁻ on the negative side, represents variations associated

Table 5. PCA of Cape Coast Leachate Parameters (KMO=0.797; Bartlett's test=2427.194)

Parameter	Component				Communalities
	1	2	3	4	
pH	-0.731**	0.661**	-0.082	-0.049	0.981
BOD ₅	0.327	0.349	0.737**	0.337	0.885
COD	-0.032	0.989*	-0.084	-0.028	0.986
Ph. cpds	0.956*	-0.229	0.154	0.003	0.990
NH ₄ -N	-0.261	0.939*	0.122	-0.051	0.968
TKN	0.924*	-0.333	-0.094	0.086	0.981
TDS	0.496	-0.217	-0.740**	-0.270	0.913
Cl ⁻	0.727**	0.632**	0.212	-0.047	0.975
Pb	-0.841*	-0.513**	0.133	-0.050	0.990
Cr	-0.245	0.329	-0.798*	0.185	0.838
Hg	0.942*	-0.186	0.082	0.105	0.941
CN	0.981*	0.049	0.041	-0.048	0.969
Cu	-0.963*	0.235	-0.064	-0.041	0.988
Ni	-0.897*	0.342	-0.265	0.001	0.992
Zn	-0.918*	-0.355	0.126	-0.064	0.989
Fe	0.116	-0.094	0.085	0.899*	0.837
As	0.948*	-0.053	0.116	0.129	0.931
TCB	-0.611**	-0.077	0.360	-0.229	0.562
Eigenvalue	9.90	3.65	2.14	1.03	
% of variance	57.81	20.11	9.22	5.72	
% cumulative	57.81	77.92	87.14	92.86	

Note: *Strong (factor score > 0.75); **Moderate (0.5 ≤ score ≤ 0.75); Weak (score < 0.5).

with organic load and microbial activity.

Similarly, the PCA biplot of CCLL indicates that PC-1 (57.81%) and PC-2 (20.11%) together account for 77.92% of the total variance (Figure 5c). COD, NH₄-N, and Cr in the first quadrant are associated with organic and nutrient pollution. Cl⁻, BOD₅, and Fe in the second quadrant indicate organic and iron solubilisation, while CN⁻, As, Pb, and TKN in the third indicate inorganic and toxic metal contamination. The fourth quadrant, with pH, Cd, Ni, Cu, Zn, and TCB, suggests heavy metal mobilization and microbial activity under slightly alkaline conditions. The high loadings of COD and BOD₅ in PC-1 for BALL and CCLL indicate strong coupling between biodegradation processes and metal complexation. The PCA of leachate from the three landfills indicates that the organics are associated together, and so are the heavy metals. The factors in each of the two groups can therefore be inferred to originate from the same sources. Common sources of the organics undoubtedly could come from anthropogenic (municipal and household) sources (Adelopo et al., 2018; Daniel et al., 2021; Lindamulla et al., 2022), while heavy metals could originate from industrial and hazardous waste sources (Essien et al., 2022; Sanga et al., 2023). The clustering of contaminants in the biplots indicates that these contaminants likely originate from a common source.

Potential Leachate Treatment Approach

The effective treatment of leachate from uncontrolled landfills should be guided by the dominant pollutants identified in the leachate. However, the treatment methods must be efficient, cost-effective, environmentally friendly, and accessible to developing countries like Ghana. The primary pollutants influencing the overall LPI in this study are organics (BOD₅ and COD) and inorganics (TDS, TKN, and Cl⁻). Any leachate treatment approach must address both pollutants. A multistage treatment technique is required to effectively treat leachate with elevated TDS, TKN, and Cl⁻ levels. Membrane treatment technologies, including microfiltration, ultrafiltration, nanofiltration, and reverse osmosis, have been reported to achieve removal efficiencies above 95% for both organic pollutants and key inorganic contaminants, especially chloride (Cl⁻) and total nitrogen (Elfilali et al., 2022; Jamrah et al., 2024; Talalaj et al., 2019; Teng et al., 2021; Wang and Qiao, 2024), which are major contributors to the high total dissolved solids (TDS) in landfill leachates. The high levels of TDS and chloride (Cl⁻) indicate the need for membrane-based technologies such as reverse osmosis or nanofiltration, which are effective at removing dissolved salts. High ammonium-nitrogen (NH₄-N) levels can be managed through biological nitrification-denitrification or ammonia stripping, while high organic loads (BOD₅ and COD) are best treated with biological processes such as anaerobic digestion or membrane bioreactors. Acti-

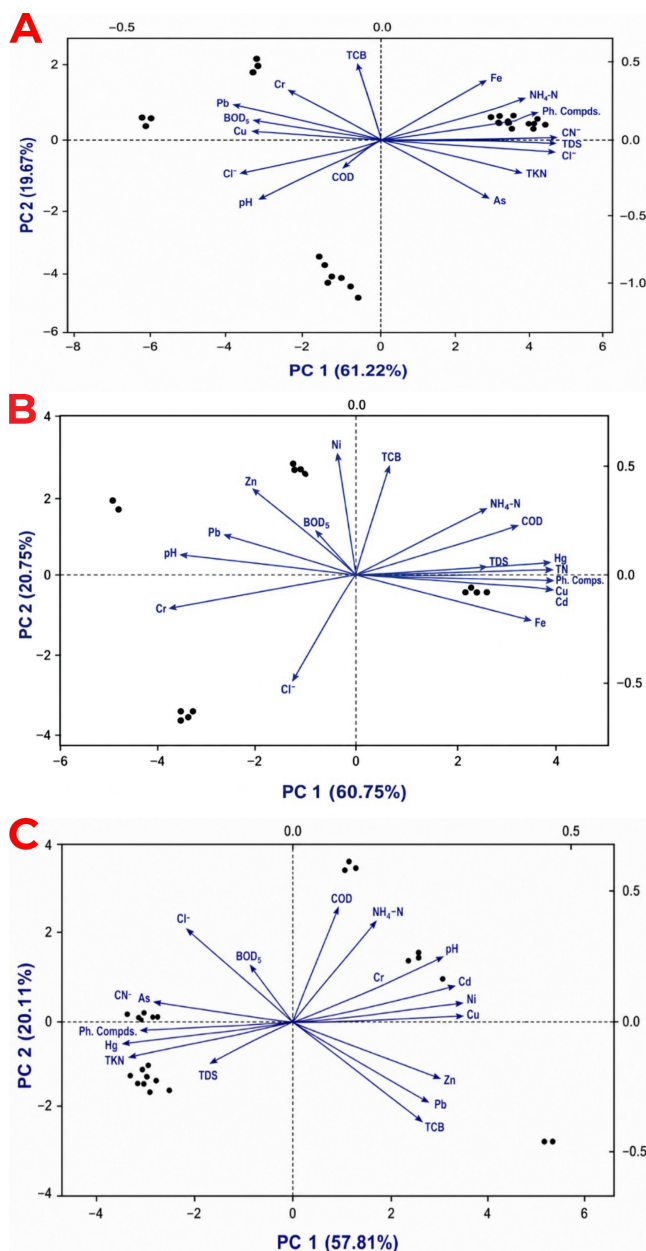


Figure 5. (A) 2D plot of Bremam Asikuma leachate contaminants, (B) 2D plot of Agona Swedru leachate contaminants, (C) 2D plot of Cape Coast leachate contaminants

vated carbon adsorption or constructed wetlands are alternative options to improve leachate quality before discharge. This paper proposes a hybrid treatment system comprising biological treatment followed by a subsurface-flow constructed wetland amended with activated carbon or engineered biochar. This may substantially improve the removal of biodegradable organic matter, refractory organics, nutrients, and selected heavy metals. However, because the elevated total dissolved solids in the present study are primarily associated with highly soluble ions such as chloride and alkali metals, an advanced desalination process such as nanofiltration or reverse osmosis would still be required to achieve effective

TDS reduction and compliance with discharge standards. This integrated approach offers a technically robust and potentially cost-effective strategy for landfill leachate management in developing countries.

Limitations of the study

First, the study was limited to leachate characterisation and did not include concurrent groundwater sampling. Hence the extent of contaminant migration from the landfills into adjacent aquifers could not be directly established. Second, the data collection period was limited to 6 months, which may not fully capture long-term seasonal variability in leachate composition.

Conclusions

This study provides a comprehensive assessment of the physicochemical, microbiological, and heavy metal characteristics of leachate generated from three major uncontrolled landfills in the Central Region of Ghana and demonstrates their substantial pollution potential. The consistently elevated levels of electrical conductivity, total dissolved solids, COD, BOD₅, ammonium nitrogen, chloride, total coliform bacteria, and several heavy metals, all exceeding regulatory limits, indicate that untreated leachate poses a significant threat to surrounding soil, surface water, and groundwater systems. The alkaline pH, together with low BOD₅/COD ratios, confirmed that the investigated landfills have reached medium-to-old or methanogenic stages of stabilization, where reduced biodegradability necessitates advanced treatment technologies. Computed LPI values (10.67–16.00) exceeded the recommended safe discharge threshold, confirming that all three landfill sites present considerable environmental pollution risks. Organic pollutants (COD, BOD₅, and total coliform bacteria) and inorganic constituents (chloride, ammonium nitrogen, and total dissolved solids) were the principal contributors to pollution potential, while heavy metals remain a long-term ecological and public health concern because of their persistence, bioaccumulation potential, and toxicity. Correlation analysis and PCA further demonstrated that most contaminants originated from common anthropogenic sources associated with municipal, household, and industrial waste disposal. These findings underscore the urgent need to replace uncontrolled waste-disposal practices with engineered landfill systems that incorporate leachate collection and treatment facilities. For existing uncontrolled landfills, integrated treatment systems combining biological processes such as membrane bioreactors with advanced physicochemical technologies, including nanofiltration or reverse osmosis, are recommended to improve contaminant removal. Strengthened regulatory enforcement, routine environmental monitoring, and long-term groundwater surveillance are also essential to minimize environmental degradation and protect communities that depend on groundwater resources in Ghana's Central Region.

Acknowledgement

The authors acknowledge the technical assistance of the technicians of the Ecological Laboratory of the University of Ghana, Legon.

Conflict of Interest

The authors declare no conflict of interest.

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