Njewa *et al. Water Emerg. Contam. Nanoplastics* **2025**, *4*, 3
DOI: 10.20517/wecn.2024.71

Water Emerging Contaminants & Nanoplastics

Review

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The impact of dumping sites on air, soil and water pollution in selected Southern African countries: challenges and recommendations

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How to cite this article: Njewa, J. B.; Mweta, G.; Sumani, J.; Biswick, T. T. The impact of dumping sites on air, soil and water pollution in selected Southern African countries: challenges and recommendations. *Water Emerg. Contam. Nanoplastics* **2025**, *4*, 3. https://dx.doi.org/10.20517/wecn.2024.71

Received: 7 Nov 2024 **First Decision:** 9 Dec 2024 **Revised:** 31 Dec 2024 **Accepted:** 14 Jan 2025 **Published:** 23 Jan 2025

Academic Editor: Lin Wang **Copy Editor:** Pei-Yun Wang **Production Editor:** Pei-Yun Wang

Abstract

Rapid population growth, industrialization, and urbanization have contributed to the generation of large volumes of waste, causing disposal challenges. This present study examined the impact of dumping sites on air, soil, and water pollution in five Southern African countries. The five selected Southern African countries have unique situations concerning landfill pollution caused by a mix of environmental, social and health issues. These countries encounter significant water, air and soil pollution due to inadequate waste management techniques. The study adopted a literature survey approach, reviewing published papers and reports on chemical pollutants. A total of 151 downloaded papers, obtained through systematic keyword searches across multiple databases, were analyzed. The chemical pollutants investigated include heavy metals, polybrominated diphenyl ethers (PBDEs), per- and polyfluoroalkyl substances (PFAS), polycyclic aromatic hydrocarbon (PAH) substances in water resources, and polychlorinated biphenyls (PCBs). The reported levels of heavy metals (lead), PBDE, PFAS, PAHs, and PCBs ranged from 23,000 to 14,600,000 µg/kg, 127-3,702 pg·L^{-1}, 310-1,089 ng·L^{-1}, 45-95 mg/kg, and 0.2-5.3 mg/kg, respectively. The results indicate that landfills, as well as open dumping sites, are major threats to surface and underground water resources. The study suggests that policies to regulate and monitor landfills should be implemented to mitigate the environmental impact of landfills.

Keywords: Landfills, PBDE, PFAS, PAHs, PCBs, heavy metals, water resources

INTRODUCTION

Municipal solid waste (MSW) generation has rapidly increased recently due to high population growth, economic progression and urbanization[1]. Today, MSW disposal is an issue of global concern not only in developing nations, but also in developed ones, mainly due to rapid urbanization. Such being the case, the management of solid waste has become a public health and environmental concern in most urban areas[2]. This has resulted in a severe challenge, especially in most developing countries whose ability to handle such waste is inadequate[3]. In a recent World Bank report, the authors highlighted the need for mandatory extension of solid waste management (SWM), considering the rapid and uncontrolled increase in waste generation. The report further projected a double increase in waste generation by the year 2025[4]. However, effective waste management is a critical aspect of building sustainable cities. This is because waste management is a key component of the environmental management process, directly influencing a city's socio-economic and political development, as well as its overall attractiveness[5].

The world's solid waste generation ranges from seven to ten billion tonnes every year. The largest percentage of the generated waste is from the municipalities. MSW is said to be approximately two billion tonnes yearly[6]. Furthermore, reports indicate that by the year 2025, waste generation in the municipalities is expected to be around 2.2 billion tonnes per year[7]. During the period from 2012 to 2016, the MSW generation in Africa alone had increased by a whopping 55%. Although the quantity of MSW generated in Africa is recorded to be on a tremendous increase, the average MSW generation per capita per day is still far lower than that of other continents[8].

Waste production in Sub-Saharan Africa (SSA) is projected to be 62 million tonnes per year. It is further documented that African towns produce waste at a ratio of 0.3 to 1.4 kg per capita per day, as compared to the average 1.22 kg per capita of waste produced by each developed country daily[9]. MSW remains a major setback to most SSA countries. Despite the knowledge of the ecological and environmental impact associated with improper handling of MSW, very little effort is being made to effectively respond to the challenges[10]. SSA countries have experienced large volumes of solid waste production over the past years, due to the increase in rural-urban migration, progress in production processes and standards of living[11]. It is further documented that SSA is the fastest-urbanizing region in the world, with the fastest-growing poverty trend[4,12]. Mismanagement and improper handling of large quantities of solid waste are associated with health and environmental risks[13].

Environmentalists have suggested that knowledge of the quantity and composition of MSW is necessary for proper planning of waste management systems[14]. However, in most developing countries, MSW management does not get the serious attention it requires due to several factors, namely lack of awareness, use of inexpensive or adaptable technology, finances, and proper governance[15]. The common traditional way of disposing of MSW worldwide is by landfilling, as it is considered the most inexpensive option to eliminate MSW[16]. MSW landfills can naturally absorb and reduce a range of contaminants[17].

Landfilling and thermal treatment are the most significant components of the safe final waste treatment technologies adopted in developed countries. However, most developing nations can hardly adopt these technologies due to financial constraints. Hence, they resort to open dumping and open burning[15]. Land-

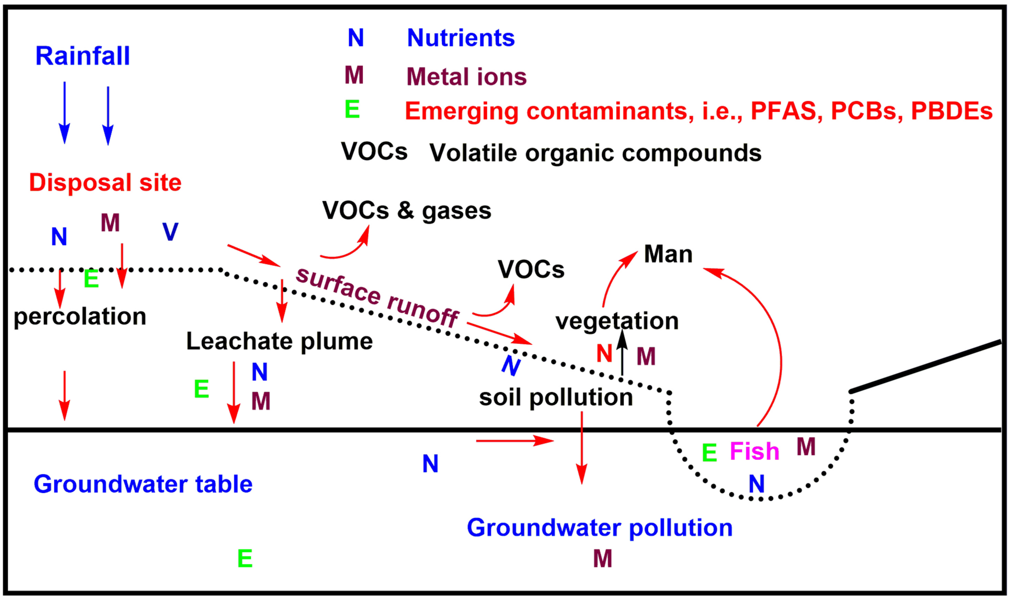

Figure 1. Schematic representation of landfill leachate water resource pollution.

based waste disposal poses several environmental problems, including gas emissions, pollution of water and land, noise and rodents, dust and odor [Figure 1][18]. Thus, landfills are categorized as possible harmful places owing to the assortment of chemical substances that are discarded into them. Municipal landfills are considered to be the source of several hazardous chemical substances that pose risks to the environment, wildlife and human health[19].

Environmental degradation induced by insufficient good waste disposal sites is characterized by contamination of surface and ground water through leaching, as well as soil contamination. Air pollution may also happen when waste is burned or left to decompose, as the case may be. Landfills dispose of trash directly on the soil surface, and the byproducts of waste decomposition are at risk of leaching by rain, which causes them to accumulate beneath the landfill and eventually migrate into the shallow groundwater table, surface water, and soil profile, ultimately polluting water resources[20]. Municipal landfills and open dumps are recognized as the sources of various compounds with environmental, wildlife, and human health concerns.

Despite the existence of MSW management protocols and strategies, agreements of conventions and multilateral environmental treaties, an efficient SWM system in Southern African countries is still deficient because of the gap between established policies and their implementation[6]. Therefore, this paper has presented and discussed the effects of landfills or dumping sites on air, water and soil in selected Southern African countries. The countries were chosen for the study as there are landfill issues and reports pertaining to soil, air, and water pollution threatening public health and the ecosystem. This research paper has analyzed how dumping sites contribute to water, soil and air pollution, with different chemical pollutants such as polybrominated diphenyl ethers (PBDEs), per- and polyfluoroalkyl substances (PFAS), polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and heavy metals (including mercury, lead and arsenic), and the implications of these pollutants on human health and the environment at large as summarized in [Table 1]. Additionally, the paper has evaluated the effectiveness of existing policies in regulating and monitoring these sites, as well as the potential for necessary policy adjustments to increase capacity and mitigate the environmental impacts associated with landfills. Finally, the paper has

Table 1. Human health and environmental effects associated with chemical pollutants

Pollutant	Source/industry	Health effects	Environmental impact	Ref.
Heavy metals (lead, mercury, cadmium)	Industrial Activities (e.g. mining, smelting) Transportation (e.g. gasoline)	Lead (developmental delays, anemia and damage to nervous system)	Accumulate in soils and sediments, contaminate water ways and can bioaccumulate in the food chain, harming wildlife populations	[21-24]
	Consumer products (e.g., batteries)	Mercury (damage to kidneys, brain, and developing fetus)		[25]
		Cadmium (kidney damage and cancer)		
PCBs	Industrial applications (e.g. non-stick coatings) Consumer products (e.g. fluorescent lights) Contaminated waste sites	Neurological and development effects, immunological effects and increased risk of cancer	Persistent in the environment, can bioaccumulate in the food chain, and can harm wildlife populations	[26-28]
PFAS	Industrial applications (e.g. non-stick coatings) Consumer products (e.g. strain resistant fabrics) Firefighting foams	Increased cholesterol levels, decreased fertility, developmental effects, increased risk of cancer	Persistent in the environment, can accumulate in organisms and detected in water supplies	[29-31]
PAHs	Incomplete combustion of fossil fuels (e.g. coal, oil. *etc.*) Wildlife and cigarette smoke	Increased risk of cancer, developmental defects, reproductive problems	Accumulate in sediments and soils, can harm aquatic organisms and can be toxic to plants	[32-34]
PBDEs	Flame retardants in consumer products (e.g. electronics, furniture) Building materials	Neurological and developmental effects, thyroid hormone disruption, increased risk cancer	Persistent in the environment, can accumulate in organisms, can harm wildfire wildlife, populations	[35-37]

PCBs: Polychlorinated biphenyls; PFAS: per- and polyfluoroalkyl substances; PAHs: polycyclic aromatic hydrocarbons; PBDEs: polybrominated diphenyl ethers.

provided recommendations that require implementation to improve waste management practices currently existing in Southern African countries.

The occurrence of these reported chemical substances in landfill leachate poses serious threats to human health and the environment. Their existence is associated with short- and long-term health threats to both human health and the environment. Leachate is recognized as hazardous due to its greater concentration levels of organic materials, inorganic substances (heavy metals), and xenobiotic organic compounds, which can resist decomposition and persevere in the environment for long periods[38].

Studies have indicated that short-term effects associated with landfill leachate can result in acute health effects, such as skin irritation, respiratory difficulties, and gastrointestinal disorders[39]. Other researchers have reported that the presence of macro pollutants in landfill leachate poses short- and long-term hazardous effects [Figure 2]. The occurrence of several severe health impacts, such as neurological disease, cancers, and teratogenic effects, are associated with the breathing in of benzene, toluene, ethylbenzene and xylenes (BTEX) particles[40]. Still more, PAHs are recognized to be carcinogenic in nature and also pose risks to the ecosystem for living organisms[41-43]. Perfluorinated chemical substances (PFCs) are reported to cause oxidative toxicity in aqueous organisms[44]. Another study has stated that exposure to leachate can cause stress responses in mammalian cells, which signifies the cytotoxic effects[45]. Another separate study indicated that the occurrence of antibiotic-resistant bacteria (ARB) and antibiotic resistance genes (ARGs) in landfill leachate has raised serious worries regarding the possibility of these pathogens entering the human food chain, causing high sickness linked with resistant infections[46,47]. Furthermore, on ecological effects, studies have indicated that landfill leachate can result in the death of aquatic organisms and disrupt local ecosystems.

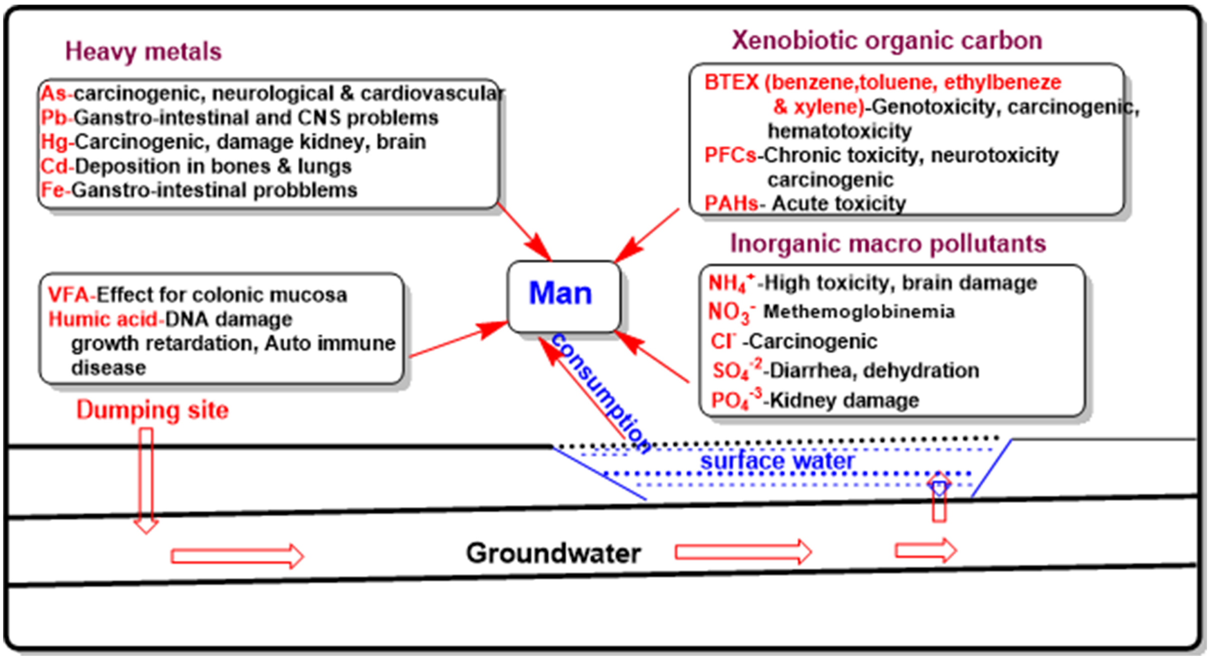

Figure 2. Short- and long-term hazardous effects of landfill leachate components.

The release of leachate into the surrounding ecosystem can result in long-term soil deterioration, loss of biodiversity, and disturbance of natural water cycles[48]. Furthermore, prolonged exposure to various chemical substances leads to bioaccumulation in the food chain, and these substances are consumed together with food items, resulting in long-term health effects[49,50]. Studies have further indicated that PFCs are extremely resistant in the environment and can continue to exist for long periods of contact[44,51,52]. Leachate containing high levels of inorganic pollutants, such as ammoniacal nitrogen and heavy metals, can pollute groundwater and adjacent surface water, leading to long-term environmental and ecological damage[53-55]. Long-term exposure to leachate contamination is more dangerous, as it is associated with the prevalence of serious health issues, such as cancer, developmental disorders, and reproductive problems. These conditions are linked to chronic exposure to hazardous substances found in leachate, such as heavy metals and organic contaminants[53,56]. Additionally, leachate is also documented to induce phytotoxicity, affecting plant growth and soil health, which are significant for ecological balance[57].

METHODOLOGY

Five selected Southern African countries were considered in this study. The countries have unique situations concerning landfill pollution caused by a combination of environmental, social, and health issues. These countries encounter significant water, air, and soil pollution due to inadequate waste management techniques. The present study adopted a literature-based approach, conducting a thorough search for relevant published papers for the selected Southern African countries. Key words such as “landfill leachate, air quality, water pollution, soil contamination, PFASs, PCBs, PAHs and MSW” were used in searches across different databases such as Google Scholar, PubMed, Sciencedirect.com, Web of Science, and Scopus. The selection criteria focused on peer-reviewed articles published in reliable journals in recent decades to ensure the relevance and correctness of the outcomes. A total of 246 articles were retrieved from the databases and were screened based on relevance and research quality standards on landfill leachate pollution to soil, air, and water resource pollution. Thereafter, the screening process narrowed down to 151 papers, which were finally studied in depth and analyzed thoroughly to extract the required information and data presented in this paper.

Study locations

The study focused on five selected Southern African countries, all of which are part of the SSA countries. These countries are South Africa, Zimbabwe, Botswana, Zambia, and Malawi. Studies conducted in South Africa and Zimbabwe have reported the detection of chemical pollutants in soil and water resources near landfills, surpassing allowable limits. Zambia and Malawi share similar issues with landfill pollution. Studies done in Zambia reported leachate from municipal landfills contaminating local water supplies. In Malawi, dependence on open dump waste and burning of waste contributes to air quality issues, leading to respiratory issues for nearby residents. Botswana does not experience severe impact from landfill leachate pollution, but challenges remain to ensure that all landfills are engineered to prevent leachate groundwater pollution.

RESULTS AND DISCUSSION

Chemical pollutants from dumping sites and/or landfills on water pollution

The impact of dumping sites and/ or landfills on water pollution is a crucial issue. Chemical pollutants from household waste, industrial chemicals, agricultural runoff, and hazardous wastes can leak or be washed away into local streams, lakes, and coastal areas[58-62]. These chemical pollutants have the potential to significantly impact water quality, leading to potential health complications for both humans and aquatic life. Polluted water from dumping sites has the potential to contaminate drinking water in some areas, leading to a risk of public health crisis[63]. The results obtained in this study, thus, for heavy metals, PBDEs, PFAS, PAHs, and PCBs, are summarized in Table 2.

Heavy metals

Previous studies carried out in Southern African countries on heavy metal pollution reported contamination of water aquifers, which is mostly attributed to inappropriate land-based activities including agriculture, industries, and waste disposal[64]. In South Africa, for example, studies conducted in Bloemfontein to find out the impact of landfills on soil quality, surface and ground water quality indicated that most of the physiochemical and microbiological parameters exceeded permissible limits of the South African National Standards and the World Health Organization (WHO).

These results suggest possible contamination from leachate originating from the landfills. In a study conducted by Nevondo *et al.*, mercury determination in leachate and sediment samples taken from four selected landfill sites in Gauteng Province showed that Thohoyandou and Soshanguve registered higher levels of mercury for groundwater samples[81]. At Hatherly and Onderstepoort, they detected higher mercury levels in leachate and borehole water, respectively. The results obtained indicate the possibility of groundwater contamination by mercury emanating from landfill leachate. The levels of mercury were examined in leachate, sediment, and groundwater samples from monitored boreholes within the study area.

In a related study conducted on physico-chemical analysis in surface water around a closed sanitary landfill in Gaborone, Botswana, it was revealed that most of the tested parameters exceeded the permissible limits of the Botswana Bureau of Standards and the WHO[82].

Furthermore, another study that focused on physico-chemical parameter assessment of ground water quality of selected boreholes around two MSW sites in Bloemfontein City in South Africa, has shown that the water was dominated by Ca, Mg, SO_4, and HCO_3 ions. Other major cations tested in the water samples exceeded permissible limits of the South African National Standards and the WHO for drinking water.

Table 2. Results for different chemical pollutants detected in sediments, leachate and water resources

Chemical pollutants		Sediments	Leachate	Water	Country/location		Ref.
Heavy metals	Mercury	0.03-0.48 μg/g	0.12-2.07 μg/L	0.09-2.12 μg/L	South Africa	Thohoyandou	[64]
		0.04-0.62 μg/g	0.10-1.20 μg/L	0.1-1.66 μg/L		Shoshanguve	[65]
		0.06-0.78 μg/g	0.42-1.31 μg/L			Hatherly	
		0.03-0.50 μg/g	0.12-2.41 μg/L	0.05-2.44 μg/L		Onderstepoort	
	Manganese			598-742 μg/L		Eastern cape	
	Iron			589-3,221 μg/L			
	Copper	2.26 mg/kg				Bloemfontein	[2]
	Zinc	0.96 mg/kg					
	Manganese	10.3 mg/kg					
	Iron	18.2 mg/kg					
	Chromium	1,225 mg/kg				Johannesburg	[66]
	Lead	46 mg/kg					
	Cadmium	67 mg/kg					
Antibiotics	Sulfamethoxazole			BDL-0.133 μg·L^{-1}		Soweto	[67]
	Flumequin			0.222-0.686 μg·L^{-1}			
	Trimethoprim			BDL-0.0618 μg·L^{-1}			
PBDEs		0.8-8.4 ng·g^{-1}	127-3,702 ng·L^{-1}			Gauteng	[68]
			0.04-0.48 μg·L^{-1}				
			5.652-240, 0.28-20.51 μg·L^{-1}			Cape town	[69]
PFAS				10.7-772, 2.53-21.1 ng·g^{-1}		Western cape	[70]
				310-1,089 ng·L^{-1}			[71]
				54.2 and < 14.6 ng·L^{-1}			
PAH				Napth 0.0339-0.0382 mg/L		Klip	[72]
				Ace 00815-0.0828 mg/L		Vaal	
				Phe 0.0214-0.0263 mg/L		Vaal	
				Anth 0.0073-0.0092 mg/L		Vaal	
				Anth 0.3582-0.4072 mg/L		Klip	
		2.4-6.3 mg/kg		45-95 mg/kg		Johannesburg	[73]
		2.8-42.0 μg/kg		170.07-12.7 μg/L		Kwazulu Natal	
		19 μg/kg		2.0-10.4 μg/L			
		2.8-3.9 μg/kg		2.5-3.5 μg/L			[74]
				0-482 ng·L^{-1} (summer)		KWT	[75]

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PCBs					0-2,383 ng·L^{-1} (autumn)			
		0.17–0.80 mg/kg			0.2-5.3 mg/kg		Johannesburg	[73]
	Copper		HMI	0.92	0.013-0.246 mg/L	Zambia	Chunga Lusaka	[76]
	Lead			1,124.19	0.005-2.591 mg/L			
	Chromium			47.2	0.007-2.699 mg/L			
	Cadmium			994.17	0.004-1.149 mg/L			
	Zinc			1.48	0.008-2.032 mg/L			
	Chromium	71 mg/kg	0.38 mg/L		0.113 mg/L	Zimbabwe	Bulawayo	[77]
	Lead	89 mg/kg	1.08 mg/L		0.183 mg/L			
	Copper	111 mg/kg	0.37 mg/L		0.003 mg/L			
	Lead		0.196 mg/L				Mutare	[78]
	Chromium		0.015 mg/L					
	Zinc		0.033 mg/L					
	Lead	23,000-14,600,000 µg/kg					Ponoma, Harare	[79]
		30,000-1,800,000 µg/kg					Norton, Harare	
	Lead				0.0-0.71 mg/L	Malawi	Zomba	[80]
	Chromium				0.0-0.39 mg/L			
	Zinc				0.0-0.10 mg/L			

BDL: Below detection limit; PBDEs: polybrominated diphenyl ethers; PFAS: per- and polyfluoroalkyl substances; PAH: polycyclic aromatic hydrocarbon; PCBs: polychlorinated biphenyls; KWT: King William's Town; HMI: heavy metal index.

Most of the boreholes had higher values of the total dissolved solids and electrical conductivity than those described by South African National Standards and WHO[65]. Similar research carried out in the Roundhill landfill vicinity reported dominance in pollution by Mn^{2+}, Fe^{2+} and NH_4^+, which exceeded South African permissible limits for groundwater[83]. The results suggest human activities specifically responsible for landfill leachate as the main cause of the pollution.

Furthermore, similar studies were conducted to determine the linkage between groundwater contamination and contaminants at the Roundhill landfill site in South Africa. The water samples collected from boreholes indicated the occurrence of heavy metal contamination, including lead, mercury, and arsenic, exceeding permissible limits defined by South African National Standards. The researchers linked the presence of these metals to leachates originating from the landfill, which resulted from the disposal of toxic and hazardous chemical waste materials[84]. Another study carried out in Bulawayo, Zimbabwe, assessed heavy metal pollution in groundwater samples from unlined landfills. The investigators reported high levels of heavy metal pollution of lead and cadmium, exceeding the WHO's standards for drinking water. The results of the study suggested health risks to the communities that depended on the water for domestic purposes[77]. The findings from the studies conducted on physicochemical parameters on water samples collected from closed Gaborone Sanitary landfill in Botswana indicated high levels that exceeded the permissible limits for drinking water standards BOS 32: 2000, WHO (2004) and USEPA (1991). The results indicated that the landfill had negatively impacted the water resources surrounding the community, posing a serious health threat[82]. Another study carried out in Malawi[80] evaluated the physical and chemical parameters of water samples collected from the Likangala River. The study revealed considerable river water pollution with chemical pollutants associated with indiscriminate solid waste disposal along the river.

PBDEs

A separate study assessed PBDEs in landfill sediments and leachate samples from Gauteng Providence, South Africa. The PBDEs were detected in two distinct matrices involved in the study. BDE-209 was notably found in the sediments and was frequently detected[68]. The results showed a strong statistical correlation, suggesting a potential effect of trace metals on PBDE levels in leachates. In the same province, another study detected brominated flame retardants in leachate samples collected from eight sites. Although the PBDEs and six bromine substituents were below the detection limit, the mean values were still measurable. The investigation revealed a weak correlation between dissolved organic carbon and PBDEs[69]. A comparable study conducted on landfill leachate at three sites in Cape Town, South Africa, also reported varying mean levels of total PBDEs, including BDE 209, at the Bellville, Coastal Park, and Vissershok landfill sites[69]. The results suggest the possible groundwater and surface water sources PBDEs pollution originating from landfill leachate.

PFAS substances in water resources

Chemicals known as PFAS are frequently found in consumer and industrial goods due to their ability to withstand strain and water. They have the potential to negatively impact both human and animal health, and they are known to persist in the environment[85]. There is an increasing concern for PFAS contamination in water resources globally, and landfill sites are recognized as one of the PFAS pollution sources due to the disposal of PFAS-containing waste. Southern Africa is facing various environmental challenges, such as the management of solid waste with limited research on PFAS pollution[70].

Studies done by[71] investigated the existence and distribution of PFAS in aquatic resources in Western Cape, South Africa. The levels of PFOS detected in the River Diep were higher than those of PFOA. However, the study suggested the need for continuous monitoring of PFAS in the region due to the potential long-term environmental risks associated with PFAS contamination. A similar study by[86] investigated the presence of PFOA and PFOS in surface and pore water in South Africa. The study reported measurable levels of PFAS in the surface water, with higher concentrations of PFOA detected in the aMatikulu and uMvoti sources, respectively. The highest concentration of PFOS in these two sources was recorded at 54.2 $ng \cdot L^{-1}$. These studies highlighted that the pollution was linked to improper disposal of PFAS-containing compounds, as well as the role of landfill sites in causing water pollution in South Africa. These findings, therefore, suggest the need for more research to assess the extent of PFAS pollution in water resources in the Southern African region and to innovate effective approaches for monitoring and managing PFAS contamination.

PAH substances in water resources

PAHs are a class of organic compounds produced by the incomplete combustion of fossil fuels. PAHs are generally distributed in the environment and are considered to be persistent organic pollutants (POPs). This is due to their resistance to degradation. Landfills are one of the major sources of PAH pollution in water resources in many parts of the world. Studies conducted in South African countries on water quality have reported water pollution by PAHs triggered by human activities.

The study conducted by[72] on surface water resources in the Vaal Triangle, South Africa, reported detectable concentrations of PAHs. Ten PAHs were analyzed from collected water samples. Of these, only seven were detected, with variations in their concentrations. Specifically, detectable concentrations were measured for Naph in the Klip River, Ace in Vaal and Klip Rivers and Vaal Barrage, phe in the Vaal and Klip Rivers and Vaal Barrage, Anth in the Vaal and Klip Rivers and Vaal Barrage, Fluo in the Vaal and Klip Rivers and Vaal Barrage, and lnPy only at the Barrage locations. Furthermore, water and sediment samples from the Klip River in Johannesburg were analyzed for PAHs. The study reported higher concentrations of PAHs in water than in sediment samples[73]. The investigators suggested that anthropogenic activities were the major leading cause of pollution and that the sites were at potential ecological risk.

Another study by[74] also reported levels of PAHs in surface water, wastewater and sediment samples collected from the Msunduzi River in KwaZulu Natal province, South Africa. The study involved a total of 100 samples, thus, both water and sediments for PAHs quantitative analysis. The water samples were collected along the Msunduzi River while waste water samples were sampled from four separate WWTPs. Finally, the sediment samples were taken along Msunduzi River and Cedara Farm. The PAHs (naphthalene, acenaphthene, 16 acenaphthylene, fluorine, anthracene, phenanthrene, and pyrene) were detectable in water samples such as wastewater, river water, and dam water. Similarly, PAHs were also found in samples from both the river and dam. The results indicated significant contamination of water resources at the dumpsite.

PCBs

PCBs are toxic chemicals that had been in use in various industrial and commercial applications before their banning in many countries due to their harmful effects on human health and the environment. PCBs are POPs that do not easily break down in the environment, and they can bioaccumulate in the food chain, posing a significant risk to human health. There have been some studies on PCBs pollution in some Southern African countries, but the extent of the problem and its associated impact on human health and the environment is not well documented.

In a study by[75], a total of 19 samples were sourced from King William's Town (KWT), Izele (IZ), Zwelitsha (ZW), Maden (MD), Mdantsane (MSN), and Buffalo River Estuary (BRE) in Eastern Cape Province, South Africa, for PCB testing. The results varied across seasons, with the lowest levels observed in summer and the highest in autumn. Specifically, the highest levels in summer were found at KWT, while BRE registered the highest levels in autumn. The summer results were below the permissible limits of the WHO for human consumption. However, the autumn results exceeded WHO limits, except for one site, MD. Furthermore, the study showed that the hazard quotients slightly exceeded the maximum threshold of 1, as set by the United States Environmental Protection Agency (USEPA).

Olasupo *et al.* assessed the presence of PCBs in the water and sediments of the Klip River wetland in Johannesburg, South Africa[73]. The wetland serves as a source of water for domestic use and the purification of chemical pollutants. The concentrations of PCBs ranged from 0.2 to 5.3 mg/kg in water and from 0.17 to 0.80 mg/kg in sediments. The results indicated that the downstream areas were highly polluted with PCB residues due to human activities, especially from Soweto and Lenasia residents. The researcher concluded that these sites could be classified as highly polluted, with potential toxicological risk. Overall, the findings highlight that PCB contamination in water resources is a significant issue in South Africa, underscoring the need for efforts to mitigate this pollution. Recommended measures include improved waste management practices, the remediation of contaminated sites, and continuous monitoring of PCB levels in water resources.

Negative effects of dumping sites and/or landfills on air pollution

The impact of landfills on air pollution is a significant concern. The uncontrolled dumping of wastes in landfills and other sites has been shown to release both toxic and non-toxic air pollutants. These pollutants pose potential significant health risks to human populations and can negatively affect local ecosystems.

Recent studies in Zimbabwe have highlighted the issue of medical waste management. A study by[87] reported that infectious diseases, respiratory diseases, gastrointestinal problems and injuries were mainly caused by poor medical waste handling. Similarly, research in Gweru City attributed high levels of air pollution to the illegal disposal of MSW[88]. Another study conducted in Makokoba, Bulawayo City, found a high prevalence of diarrhea among inhabitants residing within a 90-meter radius of dumping sites[89].

Similar studies conducted in South Africa have shown that 78% of residents living near landfills complained of serious air quality contamination, primarily due to unpleasant odors emanating from the landfill site. Furthermore, cases of flue, eye irritation, and general body weakness were more frequently recorded among those living close to the landfill compared to those residing at a greater distance[90]. Additionally, a study by[91] examined the levels of methane, carbon dioxide, and volatile compounds (VOCs) in the air around the Roolkraal landfill in Gauteng Province, South Africa. The results revealed that the concentrations of these gases were much higher than WHO's standards, suggesting the presence of potential air pollution around the landfill. Another related investigation conducted at the Chunga dumpsite in Lusaka, Zambia, reported that smoke and several gases produced from the burning and decomposition of waste negatively impacted air quality in nearby communities. These areas were also plagued by flies, mosquitos, and other vermin. Residents frequently experienced illnesses such as coughing, respiratory issues, headaches, and diarrhea[92].

Impact of landfills on soil contamination

Soil contamination often occurs when pollutants such as heavy metals or hazardous chemicals from landfills and dumpsites seep into the soil. This contamination can have long-lasting environmental effects, as it is challenging to contain and remove. Soil contamination resulting from landfills and dumpsites has been linked to various health issues in both humans and animals, including birth defects, infertility, and cancer. Additionally, this type of contamination leads to soil infertility, which ultimately results in decreased agricultural productivity in nearby areas. However, it should be noted that SWM practices differ from state to state and city to city[60,93,94].

The study that assessed four heavy metals in soil and water samples from the surrounding Gamodubu landfill in Botswana showed higher concentrations in the soil, which were comparable with those in the water samples, except for lead. However, the study's results did not suggest that the landfill was the possible source of pollution, as the detected metal concentrations were very low and below Botswana's permissible standards[95]. Studies conducted at two Zimbabwean waste dumping sites examined lead exposure among children and scavengers (adults) through contaminated air, water, soil, and food. The detected levels ranged from 23,000 to 14,600,000 μg/kg and 30,000 to 1,800,000 μg/kg for the two separate sites[79]. The calculated inadvertent daily exposure amounts were higher than the daily ingestion rate of 20-500 mg of soil/dust provided by the WHO. The results indicated a potential health risk to the scavengers. Additionally, a related study on soil samples from a landfill in Cape Town, South Africa, found high levels of heavy metals. However, the concentration of these metals decreased with distance from the landfill, except for Cd, which still remained elevated[96].

Several published studies have reported that the regional characteristics of water pollution caused by leachate worldwide, including in South African countries, have become a serious human health and environmental concern, especially in areas where landfills are insufficiently managed. The characteristics of leachate differ depending on several factors such as the age of the landfill, the type of waste deposited, and local climatic conditions such as temperature and rainfall. In South Africa, researchers stated that leachate emanating from landfills contains high levels of organic matter, ammonia nitrogen, heavy metals, and other noxious substances[83,97,98]. For instance, studies have indicated that leachate can penetrate underlying soil layers and contaminate underground and surface water resources, which are important drinking water supplies for numerous South African households, such as in provinces Mpumalanga and Northwest[69]. Several studies have reported that the presence of chemical pollutants, such as heavy metals lead, cadmium, and mercury, can cause serious harm to human health, including neurological disorders and developmental issues in children[68,99]. Furthermore, the toxic effects of leachate are also reported to negatively impact aquatic life and disrupt local ecosystems[100,101].

In recent years, pollutant levels in landfill leachate have revealed significant trends influenced by factors such as landfill management practices, waste composition, and environmental conditions[102]. Several studies have shown increased concentrations of heavy metals and organic pollutants in leachate from aging landfills that were not designed to handle electronic waste or other hazardous wastes[69]. These elevated levels are linked to operational constraints in landfills, including insufficient lining and illegal dumping, which exacerbate leachate generation and pollutant load[66,83]. Studies analyzing leachate from South African landfills have detected high concentrations of heavy metals that exceed the tolerance limits for effluent discharge guidelines, posing risks to both surface and groundwater quality[97]. Furthermore, the detection of flame retardants and other hazardous compounds in leachate raises concerns about the impact of recent waste streams on leachate quality[67].

Another factor contributing to the rising concentrations of pollutants in leachate is seasonal variation in precipitation, which significantly affects leachate generation. Heavy rainfall can increase leachate production, diluting some pollutants while simultaneously introducing new contaminants from surface runoff[103,104]. These findings highlight the need for effective leachate management strategies that consider seasonal changes and the specific characteristics of the waste being landfilled.

The relationship between soil, air, and water pollution

The relationships among water, air, and soil pollution are crucial to understanding the broader implications of environmental deterioration. These forms of pollution not only directly affect the environment but also trigger cascading effects on one another, creating a complex web of ecological and health issues.

Water resource pollution is generally aggravated by air pollution, especially through the deposition of airborne contaminants. Studies report that sulfur dioxide and nitrogen oxides produced from industrial activities result in the formation of acid rain, consequently contaminating water bodies and soil[105,106]. The acidification can damage aquatic life and disturb the chemical stability of the ecosystem, resulting in an additional decline in water quality. Moreover, chemical pollutants such as heavy metals and PAHs can be transported via atmospheric routes and deposited into water resources. This further complicates water quality management challenges[107,108]. Further, the Lancet Commission on Pollution and Health has reported that toxic pollutants in air and water contribute greatly to global health crises, with millions of deaths associated with pollution-related illnesses[109].

Soil pollution is linked to air and water pollution. Chemical contaminants originating from landfill leachate can leach into the soil profile, altering its structure and affecting its capacity to support plant growth[110,111]. Studies have indicated that the leachate emanating from MSW landfills can lead to high levels of chlorides, sulfates, nitrates, and heavy metals in the nearby soil, greatly affecting its value for agricultural production[100]. The existence of heavy metals in soil does not only decrease agricultural productivity but also result in bioaccumulation in the food chain, affecting human health[112]. A study carried out in Bloemfontein on a landfill found that leachate compromised soil and water quality, raising concerns about the safety of the food grown in contaminated areas. The presence of heavy metals in crops irrigated with contaminated water was further exacerbated by the migration of leachate from landfills. This highlights the urgent need for improved leachate management in South Africa[26]. Furthermore, the use of fertilizers and pesticides in agriculture promotes both soil and water pollution since runoff from farms transports these chemicals into proximate water bodies, causing eutrophication and further deterioration of aquatic ecosystems[113]. The link between soil health and air quality is also significant; for instance, soil deterioration can increase the amount of dust and particulate matter in the air, inducing breathing difficulties for nearby residents[114,115].

Air pollution, in turn, can affect both water and soil quality. Methane and hydrogen sulfide gases are produced in landfills due to the decomposition of organic waste; these gases have strong offensive odors and endanger the health of those nearby[116,117]. Chemical pollutants such as particulate matter and volatile organic compounds can settle on soil and water surfaces, causing contamination[106,118]. The interaction of these chemical pollutants coupled with environmental factors can trigger complex chemical reactions that further degrade water and soil quality. For instance, the existence of certain atmospheric pollutants can also promote the leaching of hazardous substances from soil into groundwater, posing risks to drinking water supplies[119,120]. Furthermore, studies indicate that air pollution has serious negative health impacts, and exposure to airborne pollutants is significantly correlated with a number of illnesses, including circulatory and respiratory disorders[114].

Technical aspects of waste leachate treatment

The handling of landfill leachate is a significant environmental issue due to its complicated composition, which can comprise organic and inorganic contaminants; the existence of heavy metals and nutrients poses serious risks to soil and water quality if not handled properly. Several viable treatment technologies have been created and employed to resolve these challenges, each with its own success and setbacks. The existing knowledge and recommendations on the technical aspects of waste leachate treatment are discussed below.

The primary strategy for decreasing leachate production involves waste segregation at the source. This approach reduces the quantities of leachate produced and improves the quality of waste deposited in landfills, thereby decreasing the operational costs related to leachate treatment. It is reported that effective waste segregation can lead to significant cost savings in leachate treatment processes and enhance the sustainability of landfill operations by minimizing the need for new landfill sites. Furthermore, reducing leachate volumes through segregation can relieve the burden on subsequent treatment processes, making them more efficient and cost-effective[121].

Research recommends implementing biological treatment technologies due to their success in removing organic pollutants and nutrients from leachate. One study found that young landfill leachate, which contains a higher proportion of biodegradable organic matter, can be effectively managed with biological treatments such as anaerobic digestion and activated sludge processes[122]. However, as leachate ages, managing it becomes more demanding due to the accumulation of recalcitrant compounds and a lower biochemical oxygen demand to chemical oxygen demand (BOD/COD) ratio[98]. In such cases, integrated treatment methods that combine biological processes with advanced oxidation or membrane technologies are necessary to improve overall treatment performance.

Advanced oxidation processes (AOPs) and membrane technologies such as reverse osmosis and nanofiltration are recognized as efficient and reliable options for treating mature leachate. AOPs can efficiently decompose complex organic contaminants, while membrane processes can separate contaminants from treated water. Published studies have indicated that membrane processes can achieve high removal efficiencies; however, they are associated with the production of concentrated retentate, which requires additional management. Nonetheless, the recirculation of produced retentate back to the landfill has been reported as a viable and cost-effective method for handling this waste stream[102].

Electrocoagulation and the use of constructed wetlands are reported to be effective in the treatment of leachate. Electrocoagulation technology involves passing an electric current through leachate, which enhances the coagulation and flocculation of pollutants. Studies have shown that electrocoagulation is effective in eliminating the heavy metals and organic pollutants from leachate[123,124]. Nevertheless, the performance of electrocoagulation is dependent on the presence of organic load in the leachate, requiring the pretreatment steps in some cases[123]. On the other hand, the use of constructed wetlands symbolizes a natural treatment option that can be both cost-effective and ecologically friendly. Another study recommended subsurface constructed wetlands as a reliable solution for leachate treatment, suggesting their ability to reduce organic and inorganic pollutants while providing extra ecological benefits[125]. This method is particularly appealing for sustainable waste management, as it leverages the filtration capacities of wetland plants and microorganisms.

Other studies have proposed the integration of several treatment options to overcome adverse effects associated with landfill leachate. Excellent results have been reported. For instance, the combination of biological treatment with membrane filtration was reported to promote treatment efficiency while reducing the setback connected with each protocol[54]. Similarly, a hybrid method was developed that united electrocoagulation with biofiltration, which demonstrated remarkable outcomes by reducing levels of turbidity and organic load in leachate. The integrated treatment systems can be developed based on the specific characteristics of the leachate being treated to improve performance and resource use[54].

Landfill leachate can also be treated by incorporating emerging technologies such as microbial fuel cells (MFCs). MFCs have gained the attention of researchers toward landfill leachate treatment. The MFCs protocol not only promotes the removal of toxic organic pollutants but also produces electricity, offering a double advantage for waste handling and management. This treatment method supports the increasing emphasis on sustainability and resource recovery in waste management practices[126].

CHALLENGES ASSOCIATED WITH MSW MANAGEMENT IN SOUTHERN AFRICAN COUNTRIES

Control and decision making

The controls and decisions made by the central government are one of the challenges faced by the municipalities when dealing with SWM. In most selected Southern African countries, operations and decisions are controlled by a centralized system of government rather than a decentralized system. For example, in Malawi, power has been decentralized to the municipal level; however, municipalities are regarded as the implementers of the decisions made at the ministerial level. This weakens the operations of local governments in waste management[127].

High urbanization growth rate

Another key challenge is attributed to the expansion in size of the cities and towns due to the ever-increasing urban population. The African continent faced an alarming human population growth from 294 million in 1960 to 1.0 billion in 2010, and it is anticipated to increase to 2.2 billion by the year 2050. The urban population growth rate is expected to reach 47% in 2050 from 20% in 1960[128]. This rapid urban growth contributes to the development of urban slums and unplanned settlements in most developing African cities and towns. Usually, informal settlements have little or no access to sanitation and waste management systems[129]. Though waste generation per individual in such slums could be lower, the overall quantity of waste increases due to population growth and urbanization. This results in further challenges in waste management systems which are already crippled and incapacitated to provide sufficient services[128].

Furthermore, existing dumping sites are now surrounded by housing estates and communities as a result of the fast rise in urbanization. Initially, disposal sites were situated outside of the municipal limits at a safe distance. However, because of the current rate of urbanization, waste disposal sites are located near residential areas[130]. People who live close to these landfills run the danger of getting sick from the dust, odor, and other pollutants they release. For example, research conducted on 328 children living near the Dandora dumpsite in South Africa found that half of them had elevated blood lead levels. Anaemia, skin infections, asthma, and other respiratory infectious disorders also disproportionately impacted them. High levels of pollutants at the landfill, which receives plastics, rubber, wood, metals, chemicals, and medical waste, were linked to these negative health impacts[131].

Insufficient funding

Lack of financial resources is another key challenge encountered by the municipalities. SWM is a cost-intensive service as it involves waste collection, transportation, and disposal at designated dumping sites. For instance, in developing countries, the biggest portion of the municipalities' budget is spent on SWM, with a large portion spent on solid waste collection[9]. The district and city councils receive their revenue from central government grants, which are usually subject to cuts and/or unreliable disbursements. In addition, most local governments are weak and underfunded, thus incapable of rendering enough and effective SWM[128]. Consequently, they resort to environmentally unfriendly waste disposal methods.

Selection of inappropriate MSW disposal methods

The majority of Southern African municipalities opt to dispose of solid waste in landfills using open dumps. Waste is typically dumped in open spaces with low elevations. There are no engineering safeguards against leachate or gas in open landfills[88]. Thus, leachates, which can contaminate surface and ground water, are frequently produced by the biological and chemical processes that take place in open landfills[132]. Additionally, methane produced by the breakdown of organic materials has the potential to cause gas explosions and fire in open dumps. In unplanned communities, the issue is significantly worse since there is either no solid waste collection or it is done haphazardly. This results in major environmental risks such as air pollution from burning, direct contact, and rodents[129].

Weak law enforcement

SWM problems are exacerbated by the failure to enforce existing SWM laws by responsible institutions. Municipal, political, and bureaucratic officials and community leaders refuse to enforce municipality waste management by-laws for their own political reasons. As a result, solid waste is indiscriminately disposed of, resulting in massive pollution of very delicate areas such as rivers and swamps[12,133].

Unstable governance and inefficient implementation of policies

Corrupt leadership is also another major setback faced by municipalities in SWM. Some city officials take advantage of solid waste to siphon public funds for their own benefit[129]. Corruption in SWM is manifested in several ways, including the illegal sale of sorted garbage, illegal sale of public land, misrepresentation of documents, inflating procurement costs, direct embezzlement of public procurement funds, false accounting, encroachment and grabbing dumping site land, and inadequate supervision of workers (such as drivers and their turn boys, and sorters). This is coupled with inadequate monitoring of factory and private hospital owners[130,134]. Consequently, this leads to the loss of revenue for the municipality as money generated ends up in the pockets of the corrupt leaders, who, in turn, encourage the indiscriminate disposal of hazardous industrial and hospital waste.

Lack of community participation in SWM

Most community members, especially those from very low-income urban areas in developing nations, believe that the government has the responsibility to manage and dispose of waste[135]. This misperception has led to improper waste disposal, with the expectation that the government will provide cleaning services to remove large piles of solid waste. This issue is commonly observed in most urban markets in developing nations, where heaps of waste are left to decompose on the ground, resulting in the emission of terrible odors that contribute to air pollution[133].

RECOMMENDATIONS

- An integrated approach to SWM is required to enable local or national authorities to reduce the overall amount of waste generated and to recover valuable materials for recycling and for the generation of energy. SWM should incorporate integrated waste management programs like recycling, composting, and incineration with energy recovery[136].

- Municipal councils should streamline and encourage practices that improve settlement patterns, reduce slums, improve the livelihoods of low-income earners and promote behavioral changes to discourage indiscriminate dumping of garbage[128].

- Landfill gas (LFG) recovery could be a solution and an opportunity for energy recovery and a potential source of energy in areas with low access to energy[11].

- Ensuring that all factories and hospitals have suitable and appropriate SWM plans and facilities before being approved to operate in the municipality. Factories without proper waste management facilities should have their operating licenses revoked until they establish appropriate facilities for dealing with waste. Again, the municipalities should conduct regular and unannounced inspections of these sites to ensure that the individuals or organizations operating the facilities are really utilizing them. Unannounced visits should be used to identify any violations of the rules, and those found in breach must be fined according to the laws[135].

- Promote community participation in waste management. Community participation involves an active process in which beneficiaries initiate development projects to promote their social welfare. It involves the engagement of various stakeholders, including community members, government institutions, local businesses, community-based organizations (CBOs), and non-governmental organizations (NGOs), who work together in decision-making processes that influence the outcomes of developmental agendas within municipal jurisdictions[127,135]. Involving communities in SWM can help achieve healthier, more sanitized environments, foster a sense of patriotism, and promote responsibility in sustainable environmental management, as households - who are primary handlers of solid waste - are actively included in the process.

STRATEGIES FOR DEALING WITH SWM

Prevention approach

• Supporting education and awareness programs: Local governments must regularly run campaigns in schools and communities. As a result, people will be more inclined to cooperate and take part in appropriate waste management procedures[12]. In addition, people must occasionally be informed of the significance of environmental consciousness and the health hazards connected to inadequate waste management techniques[137].

• People living close to municipal areas should understand the value of paying for waste management services and segregate their waste to encourage recycling practices.

• Furthermore, raising public awareness and encouraging community participation are important for effective landfill management. Involving local communities in decision-making processes concerning landfill operations can foster transparency and responsibility. Studies have shown that communities near landfill sites are generally the most affected by pollution, and their input can be invaluable in shaping policies that address their concerns[138,139]. Therefore, it is recommended that policymakers should facilitate community forums and educational programs to inform residents about the potential impacts of landfills and the importance of regulatory compliance.

• Implementation of strict leachate management systems is one of the major strategies for effectively managing landfills. Leachate is the liquid that drains or leaches from landfills and consists of a complex mixture of organic and inorganic pollutants, including heavy metals and harmful pathogens[138,140,141]. Studies have shown that leachate can significantly degrade groundwater quality, rendering it unsafe for consumption and domestic purposes[65,139]. Consequently, it is recommended that policies mandate the installation of modern leachate collection and treatment systems at landfill sites to prevent the migration of contaminants into the surrounding environment[142].

• Besides these approaches, the design and operation of landfills must adhere to best management practices to reduce the environmental effects. This includes ensuring that landfills are built with appropriate liners and covers to safeguard leachate penetration and gas emissions[63,142]. Regulatory frameworks should support the adoption of state-of-the-art technologies in landfill design and operation, ensuring that environmental safeguards are in place.

• Another fundamental policy for addressing the environmental impacts of landfills involves the integration of scientific research. It is advisable for policymakers to team up with researchers to stay informed about the latest findings on landfill effects and treatment approaches. This partnership can lead to the development of evidence-based policies that efficiently resolve the problems caused by landfills[143,144]. For example, research on leachate contamination dynamics can inform the design of more effective leachate management systems and groundwater protection strategies.

Control approaches

• Transform the open dump to managed landfills. Open dumping remains the most cost-effective method for solid waste disposal; however, it is essential to improve this system. Disposal sites ought to be fenced, covered with soil, and equipped with a compacted base. The compacted base prevents the spread of disease-causing vectors and the infiltration of leachate into the ground. The fence serves to keep animals out of the landfills[88].

• Furthermore, leachate management can be achieved by establishing buffer zones around landfill sites. These zones serve as protective shields, reducing the catastrophic impact of leachate on nearby water resources. Research has shown that the lack of geological barriers can result in higher concentrations of pollutants in groundwater[143,145]. By implementing policies that ensure the creation of sufficient buffer zones, policymakers can help safeguard water quality and reduce the risk of contamination from landfill operations.

• Air quality is another significant issue associated with landfill operations. Landfills are known sources of greenhouse gases and VOCs, which are major contributors to air pollution and climate change[140,142]. Implementing protocols that capture and treat LFG emissions can significantly lower these emissions. For instance, the installation of gas collection systems can convert methane, a potent greenhouse gas, into a renewable energy source, offering the dual benefits of decreasing emissions and generating renewable energy[146,147]. It is recommended that policymakers should consider incentivizing the adoption of such technologies through grants or tax credits to promote compliance among landfill operators.

Mitigation approach

• Encourage recycling and resource recovery initiatives. These efforts, often led by the unorganized sector and typically carried out under hazardous conditions, have gained acceptance in developing nations. In certain instances, local officials even hinder these recovery efforts. Local governments and businesses that will ultimately utilize the recovered materials should foster positive attitudes toward informal waste recovery. Additionally, businesses should offer higher compensation to scavengers for the waste they collect[129].

• Similarly, promote alternative waste management practices, such as recycling and composting, to reduce the volume of waste sent to landfills[148]. By implementing policies that encourage waste reduction and resource recovery, governments can lessen the pressure on landfill capacity and minimize their environmental footprint. In this context, extended producer responsibility (EPR) policies are particularly important, as they hold companies responsible for the entire lifecycle of their products, fostering sustainable waste management practices[148].

• Moreover, regular motoring and assessment of groundwater quality near landfill sites are essential components of effective policy implementation. The use of indices such as the Landfill Water Pollution Index (LWPI) provides a quantitative measure of groundwater contamination levels[145,149]. Continuous monitoring enables the timely detection of pollution trends, facilitating prompt interventions to mitigate environmental effects. Policies should require landfill operators and managers to conduct continuous groundwater assessments and report the outcomes to regulatory authorities[150,151].

CONCLUSION

This paper has examined the environmental impact of dumping sites on air and water pollution. It highlights how waste from illegal dumping sites significantly contributes to air, soil, and water pollution, with far-reaching consequences for both the environment and human health. While existing policies aimed at regulating and monitoring waste management in dumping sites serve as valuable tools, they are inefficient in effectively mitigating the environmental damage caused by improper waste disposal practices. The findings underscore the need for further policy enhancements to address these issues comprehensively and protect the environment from the harmful effects of dumping sites and/or landfills. Ultimately, this paper demonstrates that the effective management of dumping sites and/or landfills is essential to sustainable environmental health and well-being.

DECLARATIONS

Authors' contributions

Methodology, validation, writing - original draft, investigation, formal analysis: Njewa, J. B.
Conceptualization, data curation: Mweta, G.
Supervision: Sumani, J., Biswick, T. T.
Writing - review and editing: Sumani, J., Biswick, T. T.

Availability of data and materials

Not applicable.

Financial support and sponsorship

None.

Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

REFERENCES

1. Ma, W.; Wenga, T.; Frandsen, F. J.; Yan, B.; Chen, G. The fate of chlorine during MSW incineration: vaporization, transformation, deposition, corrosion and remedies. *Prog. Energ. Combust.* **2020**, *76*, 100789. DOI
2. Ololade, O. O.; Mavimbela, S.; Oke, S. A.; Makhadi, R. Impact of leachate from Northern Landfill site in Bloemfontein on water and soil quality: implications for water and food security. *Sustainability* **2019**, *11*, 4238. DOI
3. Nyika, J. M.; Onyari, E. K.; Mishra, S.; Dinka, M. O. Waste management in South Africa. In: Pariatamby A, Shahul Hamid F, Bhatti MS, editors. Sustainable Waste Management Challenges in Developing Countries. IGI Global; 2020. pp. 327-51. DOI
4. Schenck, C. J.; Blaauw, P. F.; Swart, E. C.; Viljoen, J. M. M.; Mudavanhu, N. The management of South Africa's landfills and waste pickers on them: Impacting lives and livelihoods. *Dev. South. Afr.* **2019**, *36*, 80-98. DOI
5. Mohee, R.; Simelane, T. Future directions of municipal solid waste management in Africa. Africa Institute of South Africa; 2015. DOI
6. Mmereki, D. Current status of waste management in Botswana: a mini-review. *Waste. Manag. Res.* **2018**, *36*, 555-76. DOI PubMed
7. Njoku, P. O.; Edokpayi, J. N.; Odiyo, J. O. Modeling landfill gas potential and potential energy recovery from Thohoyandou landfill site, South Africa. *J. Air. Waste. Manag. Assoc.* **2020**, *70*, 820-33. DOI PubMed
8. Shi, Y.; Wang, Y.; Yue, Y.; Zhao, J.; Maraseni, T.; Qian, G. Unbalanced status and multidimensional influences of municipal solid waste management in Africa. *Chemosphere* **2021**, *281*, 130884. DOI
9. Idowu, I. A.; Atherton, W.; Hashim, K.; et al. An analyses of the status of landfill classification systems in developing countries: Sub Saharan Africa landfill experiences. *Waste. Manag.* **2019**, *87*, 761-71. DOI
10. George, M. J.; Sichilongo, K. F.; Ramabulana, T.; Madala, N. E.; Dubery, I. A. Comparison of Soxhlet and reflux techniques for extraction and characterisation of potential endocrine-disrupting compounds from solid waste dumpsite soil. *Environ. Monit. Assess.* **2019**, *191*, 149. DOI PubMed
11. Dlamini, S.; Simatele, M. D.; Serge, K. N. Municipal solid waste management in South Africa: from waste to energy recovery through waste-to-energy technologies in Johannesburg. *Loc. Environ.* **2019**, *24*, 249-57. DOI
12. Ezeah, C.; Roberts, C. L. Analysis of barriers and success factors affecting the adoption of sustainable management of municipal solid waste in Nigeria. *J. Environ. Manage.* **2012**, *103*, 9-14. DOI PubMed
13. Korai, M. S.; Mahar, R. B.; Uqaili, M. A. The feasibility of municipal solid waste for energy generation and its existing management practices in Pakistan. *Renew. Sustain. Energy. Rev.* **2017**, *72*, 338-53. DOI
14. Bolaane, B.; Ali, M. Sampling household waste at source: lessons learnt in Gaborone. *Waste. Manag. Res.* **2004**, *22*, 142-8. DOI

PubMed

15. Hettiarachchi, H.; Meegoda, J. N.; Ryu, S. Organic waste buyback as a viable method to enhance sustainable municipal solid waste management in developing countries. *Int. J. Environ. Res. Public. Health.* **2018**, *15*, 2483. DOI PubMed PMC
16. Snyman, J.; Vorster, K. Sustainability of composting as an alternative waste management option for developing countries: a case study of the City of Tshwane. *Waste. Manag. Res.* **2011**, *29*, 1222-31. DOI
17. Rosqvist, N. H.; Dollar, L. H.; Fourie, A. B. Preferential flow in municipal solid waste and implications for long-term leachate quality: valuation of laboratory-scale experiments. *Waste. Manag. Res.* **2005**, *23*, 367-80. DOI PubMed
18. Amsterdam, H.; Thopil, G. A. Enablers towards establishing and growing South Africa's waste to electricity industry. *Waste. Manag.* **2017**, *68*, 774-85. DOI PubMed
19. Eggen, T.; Moeder, M.; Arukwe, A. Municipal landfill leachates: a significant source for new and emerging pollutants. *Sci. Total. Environ.* **2010**, *408*, 5147-57. DOI PubMed
20. Mavimbela, S. S. W.; Ololade, O. O.; van, T. J. J.; Aghoghovwia, M. P. Characterizing landfill leachate migration potential of a semi-arid duplex soil. *Heliyon* **2019**, *5*, e02603. DOI PubMed PMC
21. Wani, A. L.; Ara, A.; Usmani, J. A. Lead toxicity: a review. *Interdiscip. Toxicol.* **2015**, *8*, 55-64. DOI PubMed PMC
22. Massányi, P.; Massányi, M.; Madeddu, R.; Stawarz, R.; Lukáč, N. Effects of cadmium, lead, and mercury on the structure and function of reproductive organs. *Toxics* **2020**, *8*, 94. DOI PubMed PMC
23. Kumar, R.; Pradhan, A.; Khan, F. A.; et al. Comparative analysis of stress induced gene expression in Caenorhabditis elegans following exposure to environmental and lab reconstituted complex metal mixture. *PLoS. One.* **2015**, *10*, e0132896. DOI PubMed PMC
24. Pain, D. J.; Dickie, I.; Green, R. E.; Kanstrup, N.; Cromie, R. Wildlife, human and environmental costs of using lead ammunition: an economic review and analysis. *Ambio* **2019**, *48*, 969-88. DOI PubMed PMC
25. Hossain, S.; Latifa, G. A.; Prianqa; Al, N. A. Review of cadmium pollution in Bangladesh. *J. Health. Pollut.* **2019**, *9*, 190913. DOI PubMed PMC
26. Narayanan, P. K.; Carter, W. O.; Ganey, P. E.; Roth, R. A.; Voytik-Harbin, S. L.; Robinson, J. P. Impairment of human neutrophil oxidative burst by polychlorinated biphenyls: inhibition of superoxide dismutase activity. *J. Leukoc. Biol.* **1998**, *63*, 216-24. DOI PubMed
27. Peper, M.; Klett, M.; Morgenstern, R. Neuropsychological effects of chronic low-dose exposure to polychlorinated biphenyls (PCBs): a cross-sectional study. *Environ. Health.* **2005**, *4*, 22. DOI PubMed PMC
28. Oakley, G. G.; Devanaboyina, U.; Robertson, L. W.; Gupta, R. C. Oxidative DNA damage induced by activation of polychlorinated biphenyls (PCBs): implications for PCB-induced oxidative stress in breast cancer. *Chem. Res. Toxicol.* **1996**, *9*, 1285-92. DOI PubMed
29. Foguth, R.; Sepúlveda, M. S.; Cannon, J. Per- and polyfluoroalkyl substances (PFAS) neurotoxicity in sentinel and non-traditional laboratory model systems: potential utility in predicting adverse outcomes in human health. *Toxics* **2020**, *8*, 42. DOI PubMed PMC
30. Guelfo, J. L.; Korzeniowski, S.; Mills, M. A.; et al. Environmental sources, chemistry, fate, and transport of per- and polyfluoroalkyl substances: state of the science, key knowledge gaps, and recommendations presented at the August 2019 SETAC Focus Topic Meeting. *Environ. Toxicol. Chem.* **2021**, *40*, 3234-60. DOI PubMed PMC
31. McCord, J.; Strynar, M. Identification of per- and polyfluoroalkyl substances in the cape fear river by high resolution mass spectrometry and nontargeted screening. *Environ. Sci. Technol.* **2019**, *53*, 4717-27. DOI PubMed PMC
32. Koelschbach, J. S.; Mouttaki, H.; Merl-Pham, J.; Arnold, M. E.; Meckenstock, R. U. Identification of naphthalene carboxylase subunits of the sulfate-reducing culture N47. *Biodegradation* **2019**, *30*, 147-60. DOI PubMed
33. Pfeifer, G. P.; Denissenko, M. F.; Olivier, M.; Tretyakova, N.; Hecht, S. S.; Hainaut, P. Tobacco smoke carcinogens, DNA damage and p53 mutations in smoking-associated cancers. *Oncogene* **2002**, *21*, 7435-51. DOI PubMed
34. Yao, Z.; Li, J.; Wu, B.; Hao, X.; Yin, Y.; Jiang, X. Characteristics of PAHs from deep-frying and frying cooking fumes. *Environ. Sci. Pollut. Res. Int.* **2015**, *22*, 16110-20. DOI
35. Horrocks, A. R. The potential for bio-sustainable organobromine-containing flame retardant formulations for textile applications - a review. *Polymers* **2020**, *12*, 2160. DOI PubMed PMC
36. Law, R. J.; Covaci, A.; Harrad, S.; et al. Levels and trends of PBDEs and HBCDs in the global environment: status at the end of 2012. *Environ. Int.* **2014**, *65*, 147-58. DOI
37. Taheran, M.; Komtchou, S.; Lonappan, L.; et al. Environmental issues of polybrominated diphenyl ethers. *Crit. Rev. Env. Sci. Tec.* **2017**, *47*, 1107-42. DOI
38. Purba, L. D. A.; Ibiyeye, H. T.; Yuzir, A.; et al. Various applications of aerobic granular sludge: a review. *Environ. Technol. Innov.* **2020**, *20*, 101045. DOI
39. Mahler, C. F.; de, A. J. R.; Bassin, J. P. Index to evaluate closed landfills based on leachate parameters. *Detritus* **2020**, *10*, 200-11. DOI
40. Moolla, R.; Curtis, C. J.; Knight, J. Occupational exposure of diesel station workers to BTEX compounds at a bus depot. *Int. J. Environ. Res. Public. Health.* **2015**, *12*, 4101-15. DOI PubMed PMC
41. Dudnikova, T.; Sushkova, S.; Minkina, T.; et al. Main factors in polycyclic aromatic hydrocarbons accumulations in the long-term technogenic contaminated soil. *EJSS.* **2023**, *12*, 282-9. DOI
42. Fu, J.; Sheng, S.; Wen, T.; et al. Polycyclic aromatic hydrocarbons in surface sediments of the Jialu River. *Ecotoxicology* **2011**, *20*,

940-50. DOI

43. An, D.; Guo, C.; Chen, Y. Analysis of polycyclic aromatic hydrocarbon (PAH) mixtures using diffusion-ordered NMR spectroscopy and adsorption by powdered activated carbon and biochar. *Materials* **2018**, *11*, 460. DOI PubMed PMC
44. Liu, C.; Chang, V. W. C.; Gin, K. Y. H. Oxidative toxicity of perfluorinated chemicals in green mussel and bioaccumulation factor dependent quantitative structure-activity relationship. *Environ. Toxicol. Chem.* **2014**, *33*, 2323-32. DOI
45. Töre, G. Y.; Ata, R.; Çelik, S. Ö.; Kırhan, S. Ş. Colour removal from biologically treated textile dyeing wastewater with natural and novel pre-hydrolysed coagulants. *J. Turk. Chem. Soc. Sec. A.* **2017**, *5*, 23-36. DOI
46. Anand, U.; Reddy, B.; Singh, V. K.; et al. Potential environmental and human health risks caused by antibiotic-resistant bacteria (ARB), antibiotic resistance genes (ARGs) and emerging contaminants (ECs) from municipal solid waste (MSW) landfill. *Antibiotics* **2021**, *10*, 374. DOI PubMed PMC
47. Bai, L.; Tan, Z.; Gong, H.; et al. Study on antibiotics, antibiotic resistance genes, bacterial community characteristics and their correlation in the landfill leachates. *J. Appl. Microbiol.* **2022**, *132*, 445-58. DOI
48. Clarke, B. O.; Anumol, T.; Barlaz, M.; Snyder, S. A. Investigating landfill leachate as a source of trace organic pollutants. *Chemosphere* **2015**, *127*, 269-75. DOI PubMed
49. Sleight, T. W.; Khanna, V.; Gilbertson, L. M.; Ng, C. A. Network analysis for prioritizing biodegradation metabolites of polycyclic aromatic hydrocarbons. *Environ. Sci. Technol.* **2020**, *54*, 10735-44. DOI PubMed
50. Desalme, D.; Binet, P.; Chiapusio, G. Challenges in tracing the fate and effects of atmospheric polycyclic aromatic hydrocarbon deposition in vascular plants. *Environ. Sci. Technol.* **2013**, *47*, 3967-81. DOI PubMed
51. Savoca, D.; Pace, A. Bioaccumulation, biodistribution, toxicology and biomonitoring of organofluorine compounds in aquatic organisms. *Int. J. Mol. Sci.* **2021**, *22*, 6276. DOI PubMed PMC
52. Awad, E.; Zhang, X.; Bhavsar, S. P.; et al. Long-term environmental fate of perfluorinated compounds after accidental release at Toronto airport. *Environ. Sci. Technol.* **2011**, *45*, 8081-9. DOI
53. Hussieny, M. A.; Morsy, M. S.; Ahmed, M.; Elagroudy, S.; Abdelrazik, M. H. Municipal solid waste and leachate characterization in the Cairo metropolitan area. *Resources* **2022**, *11*, 102. DOI
54. Dia, O.; Drogui, P.; Buelna, G.; Dubé, R. Hybrid process, electrocoagulation-biofiltration for landfill leachate treatment. *Waste. Manag.* **2018**, *75*, 391-9. DOI PubMed
55. Scott, M.; Millar, G. J.; Altaee, A. Process design of a treatment system to reduce conductivity and ammoniacal nitrogen content of landfill leachate. *J. Water. Proc. Eng.* **2019**, *31*, 100806. DOI
56. Jaishankar, M.; Tseten, T.; Anbalagan, N.; Mathew, B. B.; Beeregowda, K. N. Toxicity, mechanism and health effects of some heavy metals. *Interdiscip. Toxicol.* **2014**, *7*, 60-72. DOI PubMed PMC
57. Bae, Y. S.; Yazaydin, A. O.; Snurr, R. Q. Evaluation of the BET method for determining surface areas of MOFs and zeolites that contain ultra-micropores. *Langmuir* **2010**, *26*, 5475-83. DOI PubMed
58. Kjeldsen, P.; Barlaz, M. A.; Rooker, A. P.; Baun, A.; Ledin, A.; Christensen, T. H. Present and long-term composition of MSW landfill leachate: a review. *Crit. Rev. Environ. Sci. Technol.* **2002**, *32*, 297-336. DOI
59. Dervišević, I.; Đokić, J.; Elezović, N.; Milentijević, G.; Ćosović, V.; Dervišević, A. The impact of leachate on the quality of surface and groundwater and proposal of measures for pollution remediation. *JEP.* **2016**, *07*, 745-59. DOI
60. Wang, H.; Ding, K. Effect of self-made TiO_2 nanoparticle size on the performance of the PVDF composite membrane in MBR for landfill leachate treatment. *Membranes* **2022**, *12*, 216. DOI PubMed PMC
61. Hu, X.; Han, Y.; Wang, Y.; Zhang, X.; Du, L. Experiment on monitoring leakage of landfill leachate by parallel potentiometric monitoring method. *Sci. Rep.* **2022**, *12*, 20496. DOI PubMed PMC
62. El-Salam MM, I Abu-Zuid G. Impact of landfill leachate on the groundwater quality: a case study in Egypt. *J. Adv. Res.* **2015**, *6*, 579-86. DOI PubMed PMC
63. Grybauskienė, V.; Vycienė, G.; Grubas, A. Leachate dynamics from municipal jerubaiciai landfill: management and clarification. *Air. Water. Components. Environ.* **2017**, *9*, 304-10. https://www.researchgate.net/publication/319648409_Leachate_Dynamics_from_Municipal_Jerubaiciai_Landfill_Management_and_Clarification/fulltext/59b7da4ea6fdcc7415c01687/Leachate. (accessed 2025-01-20)
64. Nel, J.; Xu, Y.; Batelaan, O.; Brendonck, L. Benefit and implementation of groundwater protection zoning in South Africa. *Water. Resour. Manage.* **2009**, *23*, 2895-911. DOI
65. Makhadi, R.; Oke, S. A.; Ololade, O. O. The influence of non-engineered municipal landfills on groundwater chemistry and quality in Bloemfontein, South Africa. *Molecules* **2020**, *25*, 5599. DOI PubMed PMC
66. Nyika, J.; Onyari, E.; Dinka, M.; Shivani, B. Assessment of trace metal contamination of soil in a landfill vicinity: a southern Africa case study. *Curr. Chem. Lett.* **2020**, *9*, 171-82. DOI
67. Ncube, S.; Nuapia, Y. B.; Chimuka, L.; Madikizela, L. M.; Etale, A. Trace detection and quantitation of antibiotics in a South African stream receiving wastewater effluents and municipal dumpsite leachates. *Front. Environ. Sci.* **2021**, *9*, 733065. DOI
68. Olukunle, O. I.; Sibiya, I. V.; Okonkwo, O. J.; Odusanya, A. O. Influence of physicochemical and chemical parameters on polybrominated diphenyl ethers in selected landfill leachates, sediments and river sediments from Gauteng, South Africa. *Environ. Sci. Pollut. Res. Int.* **2015**, *22*, 2145-54. DOI PubMed
69. Daso, A. P.; Rohwer, E. R.; Koot, D. J.; Okonkwo, J. O. Preliminary screening of polybrominated diphenyl ethers (PBDEs), hexabromocyclododecane (HBCDD) and tetrabromobisphenol A (TBBPA) flame retardants in landfill leachate. *Environ. Monit.*

Assess. **2017**, *189*, 418. DOI PubMed
70. Dauchy, X.; Boiteux, V.; Bach, C.; Rosin, C.; Munoz, J. F. Per- and polyfluoroalkyl substances in firefighting foam concentrates and water samples collected near sites impacted by the use of these foams. *Chemosphere* **2017**, *183*, 53-61. DOI PubMed
71. Mudumbi, J. B.; Ntwampe, S. K.; Muganza, F. M.; Okonkwo, J. O. Perfluorooctanoate and perfluorooctane sulfonate in South African river water. *Water. Sci. Technol.* **2014**, *69*, 185-94. DOI PubMed
72. Moja, S. J.; Mtunzi, F.; Madlanga, X. Determination of polycyclic aromatic hydrocarbons (PAHs) in river water samples from the Vaal Triangle area in South Africa. *J. Environ. Sci. Health. A. Tox. Hazard. Subst. Environ. Eng.* **2013**, *48*, 847-54. DOI PubMed
73. Olasupo, A.; Buah-Kwoe, A. Assessment of persistent organic pollutant accumulation in sediments of the Klip River Wetland, Johannesburg. 2018. https://wiredspace.wits.ac.za/items/3c2d76c1-1931-4b4e-88d1-6e17d1c53796. (accessed 2025-01-20).
74. Ngubo, A.; Mahlambi, P. N.; Ojwach, S. O. Occurrence of polycyclic aromatic hydrocarbons in water and sediment samples from KwaZulu Natal Province, South Africa. *Water. Environ. J.* **2021**, *35*, 84-96. DOI
75. Yahaya, A.; Adeniji, O.; Okoh, O.; Songca, S.; Okoh, A. Distribution of polychlorinated biphenyl along the course of the Buffalo River, Eastern Cape Province, South Africa, and possible health risks. *Water. SA.* **2018**, *44*. DOI
76. Nyirenda, J.; Mwansa, P. M. Impact of leachate on quality of ground water around Chunga Landfill, Lusaka, Zambia and possible health risks. *Heliyon* **2022**, *8*, e12321. DOI PubMed PMC
77. Teta, C.; Hikwa, T. Heavy metal contamination of ground water from an unlined landfill in Bulawayo, Zimbabwe. *J. Health. Pollut.* **2017**, *7*, 18-27. DOI PubMed PMC
78. Oyinkanola, L. O. A.; Aremu, O. A.; Fajemiroye, J. A.; Makinde, S. O. On the physical significance and di-electric response of Castor oil processed in Nigeria as transformer insulating fluid. *Int. J. Res. Innov. Appl. Sci.* **2024**, *VIII*, 60-6. https://rsisinternational.org/journals/ijrias/. (accessed 2025-01-20)
79. Tongesayi, T.; Kugara, J.; Tongesayi, S. Waste dumpsites and public health: a case for lead exposure in Zimbabwe and potential global implications. *Environ. Geochem. Health.* **2018**, *40*, 375-81. DOI
80. Chidya, R.; Sajidu, S.; Mwatseteza, J.; Masamba, W. Evaluation and assessment of water quality in Likangala River and its catchment area. *Phys. Chem. Earth. Parts. A/B/C.* **2011**, *36*, 865-71. DOI
81. Nevondo, V.; Malehase, T.; Daso, A.; Okonkwo, O. Leachate seepage from landfill: a source of groundwater mercury contamination in South Africa. *Water. SA.* **2019**, *45*. DOI
82. Gwisai, R. D.; Areola, O. O.; Segosebe, E. M. Physico-chemical analysis in surface waters around the closed Gaborone sanitary landfill in Botswana. *Environ. Ecol. Res.* **2019**, *7*, 220-38. DOI
83. Nyika, J.; Onyari, E. Hydrogeochemical analysis and spatial distribution of groundwater quality in roundhill landfill vicinity of South Africa. *Air. Soil. Water. Res.* **2019**, *12*, 1178622119872771. DOI
84. Mepaiyeda, S.; Madi, K.; Gwavava, O.; Baiyegunhi, C. Geological and geophysical assessment of groundwater contamination at the Roundhill landfill site, Berlin, Eastern Cape, South Africa. *Heliyon* **2020**, *6*, e04249. DOI PubMed PMC
85. Sorensen, J. P.; Lapworth, D. J.; Nkhuwa, D. C.; et al. Emerging contaminants in urban groundwater sources in Africa. *Water. Res.* **2015**, *72*, 51-63. DOI
86. Fauconier, G.; Groffen, T.; Wepener, V.; Bervoets, L. Perfluorinated compounds in the aquatic food chains of two subtropical estuaries. *Sci. Total. Environ.* **2020**, *719*, 135047. DOI PubMed
87. Takunda, S.; Steven, J. Medical solid waste management status in Zimbabwe. *J. Mater. Cycles. Waste. Manag.* **2023**, *25*, 717-32. DOI PubMed PMC
88. Mangizvo, V. R. Illegal dumping of solid waste in the alleys in the central business district of gweru, zimbabwe. *J. Sustain. Dev. Africa.* **2010**, *12*, 110-23. https://jsd-africa.com/Jsda/V12No2_Spring2010_B/PDF/Illegal%20Dumping%20of%20Sold%20Wastes.pdf. (accessed 2025-01-20)
89. Khumalo, N.; Maviza, A.; Nunu, W. N. Spatial dynamics of illegal dumpsites and prevalence of diarrhoeal diseases in Makokoba Township in Bulawayo, Zimbabwe. *Sci. Afr.* **2021**, *13*, e00939. DOI
90. Njoku, P. O.; Edokpayi, J. N.; Odiyo, J. O. Health and environmental risks of residents living close to a landfill: a case study of Thohoyandou landfill, Limpopo Province, South Africa. *Int. J. Environ. Res. Public. Health.* **2019**, *16*, 2125. DOI PubMed PMC
91. Luvhimbi, N.; Tshitangano, T. G.; Mabunda, J. T.; Olaniyi, F. C.; Edokpayi, J. N. Water quality assessment and evaluation of human health risk of drinking water from source to point of use at Thulamela municipality, Limpopo Province. *Sci. Rep.* **2022**, *12*, 6059. DOI PubMed PMC
92. Chibwe, W.; Mbewe, A.; Hazemba, A. N. The health effects of Chunga Dumpsite on sorrounding communities in Lusaka, Zambia. medRxiv 2021. Available online: https://doi.org/10.1101/2021.12.21.21268110 (accessed 20 Jan 2025).
93. Hussein, O.; Ibrahim, J. Leachates recirculation impact on the stabilization of the solid wastes - a review. *J. Ecol. Eng.* **2023**, *24*, 172-83. DOI
94. Vrijheid, M. Health effects of residence near hazardous waste landfill sites: a review of epidemiologic literature. *Environ. Health. Perspect.* **2000**, *108 Suppl 1*, 101-12. DOI PubMed PMC
95. Popego, T.; Dikinya, O.; Gaobotse, G. Characterization of soils in the Gamodubu landfill area in the Kweneng District, Botswana. *African J Soil Sci* 2019;7:501-6. https://ubrisa.ub.bw/bitstream/handle/10311/1894/Popego2_AJSS_2019.pdf?sequence=1&isAllowed=y. (accessed 2025-01-20).
96. Osibote, A. O.; Rabiu, A. M. Assessment of heavy metals contamination at Cape Town landfill sites. *IJESD.* **2016**, *7*, 831-4. DOI
97. Edokpayi, J. N.; Durowoju, O. S.; John, O. Assessment of heavy metals in landfill leachate: a case study of Thohoyandou landfill,

Limpopo Province, South Africa. 2018. https://www.intechopen.com/chapters/59339. (accessed 2025-01-20).

98. Firiyal Imtinan S, Purwanto P, Yulianto B, Warsito B, Sudarno, Triadi Putranto T. The biological treatment method for landfill leachate. *E3S. Web. Conf.* **2020**, *202*, 06006. DOI
99. Tałałaj, I. A.; Biedka, P.; Bartkowska, I. Treatment of landfill leachates with biological pretreatments and reverse osmosis. *Environ. Chem. Lett.* **2019**, *17*, 1177-93. DOI
100. Žaltauskaitė, J.; Vaitonyte, I. Toxicological assessment of closed municipal solid-waste landfill impact to the environment. *EREM.* **2018**, *72*. DOI
101. Del, P. A. M. L.; Cortés, H.; Caballero-Florán, I. H.; et al. Therapeutic applications of terpenes on inflammatory diseases. *Front. Pharmacol.* **2021**, *12*, 704197. DOI PubMed PMC
102. Kamal, A.; Makhatova, A.; Yergali, B.; et al. Biological treatment, advanced oxidation and membrane separation for landfill leachate treatment: a review. *Sustainability* **2022**, *14*, 14427. DOI
103. Yu, F.; Yu, Z.; Huang, X.; et al. Effective membrane distillation of landfill leachate concentrate using a superhydrophobic SiO_2/PVDF membrane for resource recovery. *ACS. EST. Water.* **2024**, *4*, 1711-9. DOI
104. Le, S. T.; Le, K. C.; Doan, L. T.; Doan, A. T. Effect of some effective parameters on COD Removal from Nam Son Landfill Leachate by electrocoagulation. *JST.* **2017**, *55*, 540. DOI
105. Azzazy, M. F. Plant bioindicators of pollution in Sadat City, Western Nile Delta, Egypt. *PLoS. One.* **2020**, *15*, e0226315. DOI PubMed PMC
106. Zuhara, S.; Isaifan, R. The impact of criteria air pollutants on soil and water: a review. *JESPR.* **2018**, *4*, 278-84. DOI
107. Zhu, Y.; Li, Y.; Wang, Y.; Li, L. The impact of water and soil scarcity and pollution on industrial agglomeration: evidence from China. *Sustainability* **2021**, *13*, 5428. DOI
108. Singh, V. K.; Anand, M.; Rawtani, D.; et al. Blood levels of polycyclic aromatic hydrocarbons in women with benign and malignant breast lesions: a case-control study. *Asian. J. Med. Sci.* **2011**, *1*, 80-6. DOI
109. Basu, N.; Lanphear, B. P. The challenge of pollution and health in Canada. *Can. J. Public. Health.* **2019**, *110*, 159-64. DOI PubMed PMC
110. Beena, K. N.; Jaya, D. S. Evaluation of soil contamination in the surroundings of Kerala Minerals and Metals Limited (KMML) industrial area in Kollam District, Kerala, South India. *J. Soil. Sci. Environ. Manage.* **2016**, *7*, 92-9. DOI
111. Braduliene, J.; Sveikauskaite, I. Soil surface pollution with heavy metals caused by coal-fired boilers. In *10th International Conference, "Environmental Engineering"* 2017. DOI
112. Setiawan, A. A.; Budianta, D.; Suheryanto, S.; Priadi, D. P. Review: pollution due to coal mining activity and its impact on environment. *SJE.* **2018**, *3*, 1-5. DOI
113. Sarikaya, E.; Demirer, G. N. Biogas production from broiler manure, wastewater treatment plant sludge, and greenhouse waste by anaerobic co-digestion. *J. Renew. Sustain. Energy.* **2013**, *5*, 043126. DOI
114. Ravichandran, S.; Singh, R.; Sri, R. M. M. Air pollution: a major threats to sustainable development. *Int. J. Clin. Biochem. Res.* **2021**, *8*, 176-8. DOI
115. Sarker, R.; Yeasmin, M.; Rahman, M.; Islam, M. People's perception and awareness on air pollution in rural and urban areas of Mymensingh Sadar upazila. *Prog. Agric.* **2018**, *29*, 22-32. DOI
116. Haboubi, K.; Himri, A. E.; Hanafi, I. Sources and propagation mechanism of odor nuisance in the landfill of Al Hoceima, Morocco. *BJSTR.* **2023**, *51*. DOI
117. Heaney, C. D.; Wing, S.; Campbell, R. L.; et al. Relation between malodor, ambient hydrogen sulfide, and health in a community bordering a landfill. *Environ. Res.* **2011**, *111*, 847-52. DOI PubMed PMC
118. Ugrina, M.; Jurić, A. Current trends and future perspectives in the remediation of polluted water, soil and air - a review. *Processes* **2023**, *11*, 3270. DOI
119. Gworek, B.; Dmuchowski, W.; Koda, E.; et al. Impact of the municipal solid waste Łubna landfill on environmental pollution by heavy metals. *Water* **2016**, *8*, 470. DOI
120. Aryampa, S.; Maheshwari, B.; Sabiiti, E. N.; Namuddu, S.; Bukenya, B.; Bateganya, N. L. Understanding the impact of waste disposal sites on soil quality for agricultural production: a case study of the Kiteezi landfill, Uganda. *Environ. Qual. Manag.* **2023**, *32*, 325-34. DOI
121. Rangga, J. U.; Syed, I. S. N.; Rasdi, I.; Karuppiah, K. Estimation of leachate volume and treatment cost avoidance through waste segregation programme in Malaysia. *Pertanika. J. Sci. Technol.* **2023**, *32*, 339-64. DOI
122. Ahmad, I.; Abdullah, N.; Chelliapan, S.; et al. Chapter 7 Effectiveness of anaerobic technologies in the treatment of landfill leachate. https://books.google.com/books?hl=zh-CN&lr=&id=gaotEAAAQBAJ&oi=fnd&pg=PA93&dq=Effectiveness+of+anaerobic+technologies+in+the+treatment+of+landfill+leachate.&ots=7swHsQ2v1j&sig=CbSYTBV33fUSu8xF-lrlKHV5KoQ#v=onepage&q=Effectiveness%20of%20anaerobic%20technologies%20in%20the%20treatment%20of%20landfill%20leachate.&f=false. (accessed 2025-01-20).
123. Hamid, M. A. A.; Aziz, H. A.; Yusoff, M. S.; Rezan, S. A. Clinoptilolite augmented electrocoagulation process for the reduction of high-strength ammonia and color from stabilized landfill leachate. *Water. Environ. Res.* **2021**, *93*, 596-607. DOI PubMed
124. Ishaq, A.; Said, M. I. M.; Azman, S. B.; Dandajeh, A. A.; Lemar, G. S.; Jagun, Z. T. Utilization of microbial fuel cells as a dual approach for landfill leachate treatment and power production: a review. *Environ. Sci. Pollut. Res. Int.* **2024**, *31*, 41683-733. DOI PubMed PMC

125. Ratnawati, R.; Permata, S. D.; Mukhtar, N. A. Leachate treatment using sub-surface flow constructed wetland by hippochaetes lymenalis. *JPSL*. **2024**, *14*, 298. DOI
126. Li, S.; Chen, G. Effects of evolving quality of landfill leachate on microbial fuel cell performance. *Waste. Manag. Res.* **2018**, *36*, 59-67. DOI
127. Chirwa, J. A.; McDonnell, D.; Petersen, B.; Schipper, J. Assessment of community participatory interventions in solid waste management in Chitete Township-Kasungu Municipality-Malawi. 2020. https://www.proquest.com/openview/85907e88575acf472546b5d2abbe53b3/1?pq-origsite=gscholar&cbl=18750&diss=y. (accessed 2025-01-20).
128. Scarlat, N.; Motola, V.; Dallemand, J.; Monforti-Ferrario, F.; Mofor, L. Evaluation of energy potential of municipal solid waste from African urban areas. *Renew. Sustain. Energy. Rev.* **2015**, *50*, 1269-86. DOI
129. Kasinja, C.; Tilley, E. Formalization of informal waste pickers' cooperatives in Blantyre, Malawi: a feasibility assessment. *Sustainability* **2018**, *10*, 1149. DOI
130. Gumisiriza, P.; Kugonza, S. Corruption and solid waste management in Mbarara Municipality, Uganda. *J. Environ. Public. Health.* **2020**, *2020*, 4754780. DOI PubMed PMC
131. Malenya, K. M. Determinants of effective solid waste management in Kakamega County. 2015. DOI
132. Medina, M. Solid wastes, poverty, and the environment in developing country cities: challenges and opportunities. urbanization and development. Oxford University Press; 2010. pp. 268-84. DOI
133. Henry, R. K.; Yongsheng, Z.; Jun, D. Municipal solid waste management challenges in developing countries - Kenyan case study. *Waste. Manag.* **2006**, *26*, 92-100. DOI PubMed
134. Zhang, D. Q.; Tan, S. K.; Gersberg, R. M. Municipal solid waste management in China: Status, problems and challenges. *J. Environ. Manage.* **2010**, *91*, 1623-33. DOI
135. Ndala, G.; Ndala, N. N. Assessing the role of community members in waste disposal in Lilongwe - Capital City of Malawi. 2022. DOI
136. Orhorhoro, E.; Oghoghorie, O. Review on solid waste generation and management in Sub-Saharan Africa: a case study of Nigeria. *J. Appl. Sci. Environ. Manag.* **2019**, *23*, 1729. DOI
137. Kubanza N. The role of community participation in solid waste management in Sub-Saharan Africa: a study of Orlando East, Johannesburg, South Africa. *S. Afr. Geogr. J.* **2021**, *103*, 223-36. DOI
138. Nagarajan, R.; Thirumalaisamy, S.; Lakshumanan, E. Impact of leachate on groundwater pollution due to non-engineered municipal solid waste landfill sites of erode city, Tamil Nadu, India. *Iranian. J. Environ. Health. Sci. Eng.* **2012**, *9*, 35. DOI PubMed PMC
139. Ozbay, G.; Jones, M.; Gadde, M.; Isah, S.; Attarwala, T. Design and operation of effective landfills with minimal effects on the environment and human health. *J. Environ. Public. Health.* **2021**, *2021*, 6921607. DOI PubMed PMC
140. Hossain, M. L.; Das, S.; Hossain, M. K. Impact of landfill leachate on surface and ground water quality. *J. Environ. Sci. Technol.* **2014**, *7*, 337-46. DOI
141. Khanal, L. N.; Adhikari, N. P.; Paudel, G.; Adhikari, S. Physicochemical assessment of leachate from Pokhara landfill site and its impact on the quality of Seti River water, Nepal. *Arch. Agric. Environ. Sci.* **2021**, *6*, 194-201. DOI
142. Wysocka, M. E.; Zabielska-Adamska, K. Impact of protective barriers on groundwater quality. In *"Environmental Engineering" 10th International Conference* 2017. pp. 27-8. https://www.researchgate.net/profile/Katarzyna-Zabielska-Adamska/publication/319389571_Impact_of_Protective_Barriers_on_Groundwater_Quality/links/59cd29f50f7e9b454f9f8f9f/Impact-of-Protective-Barriers-on-Groundwater-Quality.pdf. (accessed 2025-01-20)
143. Talalaj, I. A.; Biedka, P. Use of the landfill water pollution index (LWPI) for groundwater quality assessment near the landfill sites. *Environ. Sci. Pollut. Res. Int.* **2016**, *23*, 24601-13. DOI PubMed PMC
144. Rykała, W.; Dąbrowska, D. Risk assessment for groundwater in the region of municipal landfill systems in Tychy-Urbanowice (Southern Poland). *Environ. Socio. econ. Stud.* **2020**, *8*, 9-17. DOI
145. Knopek, T.; Dabrowska, D. The use of the contamination index and the LWPI index to assess the quality of groundwater in the area of a municipal waste landfill. *Toxics* **2021**, *9*, 66. DOI PubMed PMC
146. Vedantam, A.; Suresh, N. C.; Ajmal, K.; Shelly, M. Impact of China's National Sword Policy on the U.S. landfill and plastics recycling industry. *Sustainability* **2022**, *14*, 2456. DOI
147. Fahriani, F.; Hambali, R.; Yofianti, D. Improvement of quality environment at TPA Parit 6 Pangkalpinang using the Sanitary Landfill Method. *IOP. Conf. Ser. Earth. Environ. Sci.* **2022**, *1108*, 012048. DOI
148. Walsh, A.; Woods, C. G. Presence of perfluoroalkyl substances in landfill adjacent surface waters in North Carolina. *Int. J. Environ. Res. Public. Health.* **2023**, *20*, 6524. DOI PubMed PMC
149. Naveen, B. P.; Sumalatha, J.; Malik, R. K. A study on contamination of ground and surface water bodies by leachate leakage from a landfill in Bangalore, India. *Geo. Eng.* **2018**, *9*, 95. DOI
150. Laner, D.; Cencic, O.; Svensson, N.; Krook, J. Quantitative analysis of critical factors for the climate impact of landfill mining. *Environ. Sci. Technol.* **2016**, *50*, 6882-91. DOI PubMed
151. Danthurebandara, M.; Van, P. S.; Vanderreydt, I.; Van, A. K. Assessment of environmental and economic feasibility of Enhanced Landfill Mining. *Waste. Manag.* **2015**, *45*, 434-47. DOI PubMed