PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol x(x): xx–xx
https://doi.org/10.14719/pst.4767

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REVIEW ARTICLE

Effect of landfill leachates on urban soil: A review

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OPEN ACCESS

ARTICLE HISTORY

Received: 22 August 2024
Accepted: 15 September 2024

Available online
Version 1.0 : 09 October 2024

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
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CITE THIS ARTICLE

Jagasri S, Kannan J, Jayashree R, Sheeba S, Prabakaran K, Jayabalakrishnan RM, Murugaragavan R, Poornachandra C, Madhusree S. Effect of Landfill Leachates on Urban Soil: A Review. Plant Science Today (Early Access). https://doi.org/10.14719/pst.4767

Abstract

The increasing generation of Municipal Solid Waste (MSW) is a significant global concern, with landfills receiving around 1.4 billion tonnes of MSW yearly. Inadequate landfill management contributes to environmental degradation, with landfill leachate being a substantial outcome of MSW decomposition. Leachate contains inorganic nutrients, volatile and dissolved organic molecules and heavy metals and its properties vary depending on waste composition, moisture content and seasonal elements. Heavy metals found in leachate include Pb, Cu, Cr, Ni, Mn, Hg, Fe, Zn and Cd and Emerging Organic Contaminants (EOCs) such as Persistent Organic Pollutants (POPs), Endocrine Disrupting Chemicals (EDC), pharmaceuticals and Personal Care Products (PCPs) are also prevalent. Microplastics (MPs) have been found in raw leachate samples at concentrations ranging from 49.0 ± 24.3 to 507.6 ± 37.3 items/L. Landfill leachate production ranks among the most aggressive pollutants to the environment, particularly to soil and poses a danger of contaminating both surface and groundwater. This review examines the potential impacts of landfill leachate on soil quality and the broader implications of this phenomenon, summarizing recent scientific studies and presenting the direct and indirect effects of leachate on soil based on the literature. Bibliometric analysis of publications in the Scopus database reveals a growing scholarly interest in this topic, with the number of publications in the Science Citation Index (SCI) database increasing dramatically to over 464 articles between 2009 and 2024.

Keywords

Emerging Organic Contaminants (EOCs); environmental degradation; heavy metal; Municipal Solid Waste (MSW); soil contamination

Introduction

Worldwide, the increasing generation of Municipal Solid Waste (MSW) is becoming a significant concern. On average, about 1.04 kilograms of waste is produced globally per person daily. Waste generation rates differ significantly across countries, ranging from 0.5 to 2.3 kilograms per person daily. By 2050, 3.40 billion tonnes of MSW will be generated globally, with 19 % and 40 % growth rates in industrialized and developing countries, respectively (1). The statistics on global MSW generation are shown in Table 1 (2). Top 10 Indian City's waste generation are shown in Table 2 (3). Most

Table 1. Statistics of global MSW generation

Region	Total MSW (million tonnes)	MSW per capita (kg/ person/day)
North America	320	2.3
Central America and the Caribbean	80	0.9
South America	140	0.95
Northern Europe	60	1.3
Western Europe	110	1.4
Southern Europe	80	1.2
Eastern Europe	120	1.0
West Asia and North Africa	150	0.8
Sub-Saharan Africa	220	0.55
Central and South Asia	280	0.5
East and South-East Asia	580	0.75
Oceania	15	0.5
Australia and New Zealand	20	1.4

Source: UNEP, 2024

MSW comes from everyday activities, including residential, commercial and institutional sources. The increasing volume of solid waste highlights the need for safe landfills. Many cities find landfills to be an unsuitable technique for safe disposing of MSW. Landfills receive around 1.4 billion tonnes of MSW annually, accounting for 70 % of total MSW. Landfills in India need 1240 acres of land annually, with just 21% of MSW being adequately managed and disposed of. However, the remaining MSW is disposed of in unsanitary landfills without sufficient treatment (4), which degrades the environment. According to (5) and (6), inadequate landfill management can lead to environmental degradation. The health impacts studied included mortality, adverse birth and neonatal outcomes, cancer, respiratory problems, gastroenteritis, vector-borne illnesses, mental health issues and cardiovascular diseases. However, occupational risks were not considered in the assessment (7).

The significant outcome of MSW decomposition is the generation of landfill leachate, which is the aqueous effluent produced from solid waste due to its physical, chemical and biological transformation within landfills (8). Municipal solid waste (MSW) composition varies widely across different regions but generally consists of a combination of biodegradable and non-biodegradable materials derived from organic and inorganic sources. MSW is typically collected from residential areas, offices, institutions and commercial establishments, comprising items such as organic waste (e.g., food scraps and yard trimmings), paper, plastics, metals, glass and a variety of other materials, including electronic waste, inert substances, pharmaceuticals and debris from construction, demolition and renovations. The approach to managing MSW differs by locality but generally follows three key stages: (i) waste generation at the source, (ii) collection and transportation and (iii) disposal, processing and treatment (9).

Table 2. Top 10 Indian Cities and Their Waste Generation Patterns

MSW generation in tons per day (TPD) in India, CPCB					
Cities	1971	1999	2004	2010	2015
Mumbai	2039	5355	5320	6500	11000
Delhi	766	4000	5922	6800	8700
Chennai	508	3124	3036	4500	5000
Hyderabad	593	1556	2187	4200	4000
Kolkata	1574	3692	2653	3670	4000
Bangalore	529	2000	1669	3700	3700
Ahmedabad	381	1683	1302	2300	2500
Surat	74	900	1000	1200	1680
Pune	205	700	1175	1300	1600
Jaipur	178	580	904	810	1000

Source: Dutta, 2020

MSWs contain organic biodegradable components and compacted waste layers, creating an anaerobic environment in landfills (10). Most landfills receive and dispose of municipal, commercial and mixed industrial garbage. One tonne of landfilled waste produces approximately 0.2 m^3 of landfill leachate during decomposition (11). Leachates from various landfills have similar constituents (12) and contain inorganic nutrients, volatile and dissolved organic molecules and heavy metals, which occur when water flows through a landfill and absorbs dissolved elements from degraded garbage (13). A well-designed landfill can reduce leachate leaking into the soil. To improve landfills, surface runoff should be altered and proper vegetation and leachate should be collected and pumped to a treatment facility (14).

Landfill leachate is characterized using standard criteria such as COD, TOC, BOD, suspended particles, pH, ammonia and heavy metal concentrations. The BOD 5/ COD and COD/TOC ratios indicate the biodegradability and oxidation of organic carbon. Several variables influence landfill leachate quality, including waste type, operational conditions, climate, hydrogeology and landfill age (15). Landfill leachate properties vary depending on waste composition, moisture content and seasonal elements such as temperature and precipitation (16). Microplastics (MPs) concentration in raw leachate samples ranged from 49.0 ± 24.3 to 507.6 ± 37.3 items/L. A potential correlation was found between the concentration of MPs in raw leachate samples from landfill sites and the annual leachate (17). Heavy metals found in leachate include Pb, Cu, Cr, Ni, Mn, Hg, Fe, Zn and Cd (18), with different concentrations for each landfill. Heavy metals remain in polluted sites for an extended period and, unlike other pollutants, cannot be degraded chemically or biologically (19). Recent years have seen a lot of attention paid to Emerging Organic Contaminants (EOCs), like Persistent Organic Pollutants (POPs), Endocrine Disrupting Chemicals (EDC), pharmaceuticals, Personal Care Products (PCPs), antibiotic resistance genes and disinfection by-products, due to their prevalence in landfill leachate and their potential for harm to the environment and people

(20). (17) found MP concentrations in raw leachate samples ranging from 49.0 ± 24.3 to 507.6 ± 37.3 items/L. Over the past two decades, 172 pharmaceutical and PCPs have been found in landfill leachate worldwide, including antibiotics, anti-inflammatories, stimulants and beta-blockers (21). Due to its properties and content, landfill leachate production ranks among the most aggressive pollutants in the environment today, mostly in soil and poses a danger of contaminating both surface and groundwater (22).

This review aims to examine the potential impacts of landfill leachate on soil quality and the broader implications of this phenomenon. The main aims of this review were to (i) summarise the most recent scientific studies on landfill leachate and (ii) present the direct and indirect impacts of leachate on soil based on the literature. Studies in the literature have examined the impact of landfill leachates on soil physical, chemical and biological properties. Modern remedial techniques to treat soil degradation from landfill leachate are also presented here.

Scientific focus on leachate impact on soil

The Scopus database was selected to methodically monitor the effects of landfill leachate on soil among reputable publications because of its consistency in citation records. Only peer-reviewed English-language literature was the subject of this literature search. Bibliometric data were gathered by deciding on the best sources of information, establishing search parameters and creating the dataset. Following data cleaning and anomaly identification, bibliometric analysis was performed (Fig. 1). About 653 publications with titles, abstracts, and keywords like "landfill leachate impact on soil"-such as "landfill AND leachate AND impact AND on AND soil"-were analyzed when they were retrieved on July 3, 2024. After that, 168 publications were found using Boolean search terms like "landfill AND leachate AND impact AND on AND soil." The growing number of papers about the effects of landfill leachate on soil during the previous 16 years (from 2009 to 2024) indicates a growing scholarly interest in this topic (Kurniawan et al., 2021d). Consequently, the total number of publications in the Science Citation Index (SCI) database (2009-2024) concerning the effect of landfill leachate on soil increased dramatically to over 464 articles (Fig. 2) (23).

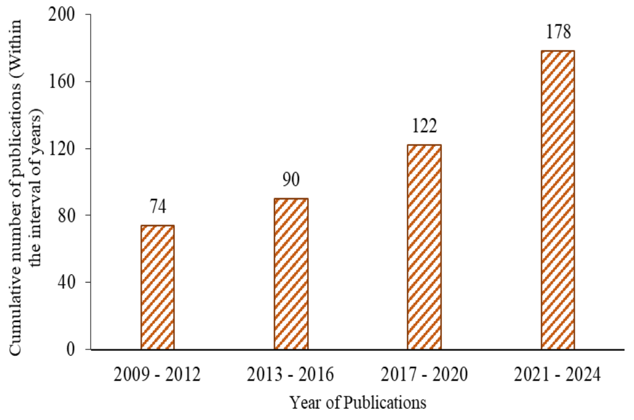

Fig. 2. Trends of landfill leachate-related publications in the body of knowledge (2009-2024)

Bibliometric analysis on current hotspot

A bibliometric analysis was carried out using data gathered from Scopus and VOS viewer to visualize the network, as shown in Fig 3.

Searching the Scopus database with the keywords "landfill AND leachate AND impact AND on AND soil," about 168 documents were found. All key terms were used as the unit of analysis in a co-occurrence analysis. It was decided that ten keyword occurrences would be minimal. 108 keywords out of 3284 matched the criterion. The 108 keywords exhibit significant connectedness.

Impact

Soil structure

Xu et al. (24) found that increasing landfill leachate concentrations decreased soil strength, leading to plastic deformation. The dislocation between soil particles and plastic lateral deformation occurred due to leachate pollution and axial load, ultimately destroying the soil structure (25). Giri and Reddy (26) showed that leachate significantly influences pore water pressure and forms numerous pores in the soil. Meanwhile, water adsorption by soil particles increased (27).

At higher landfill leachate concentrations, the maximum pore radius saturated with leachate expanded from 1.03 to 1.18 μm, while the radius of other pores grew from 11.01 to 135.73 μm. Pore sizes in leachate-contaminated soil were primarily between 0.02-1 μm and 3 -12 μm (28). Increased leachate concentrations led to

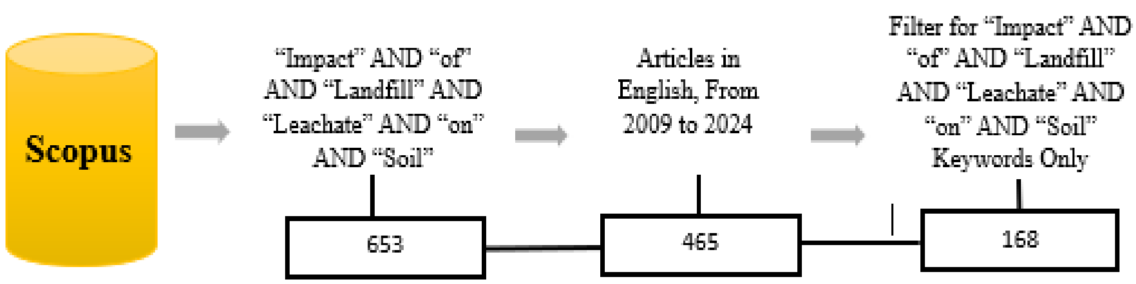

Fig. 1. Method of Bibliometric Analysis

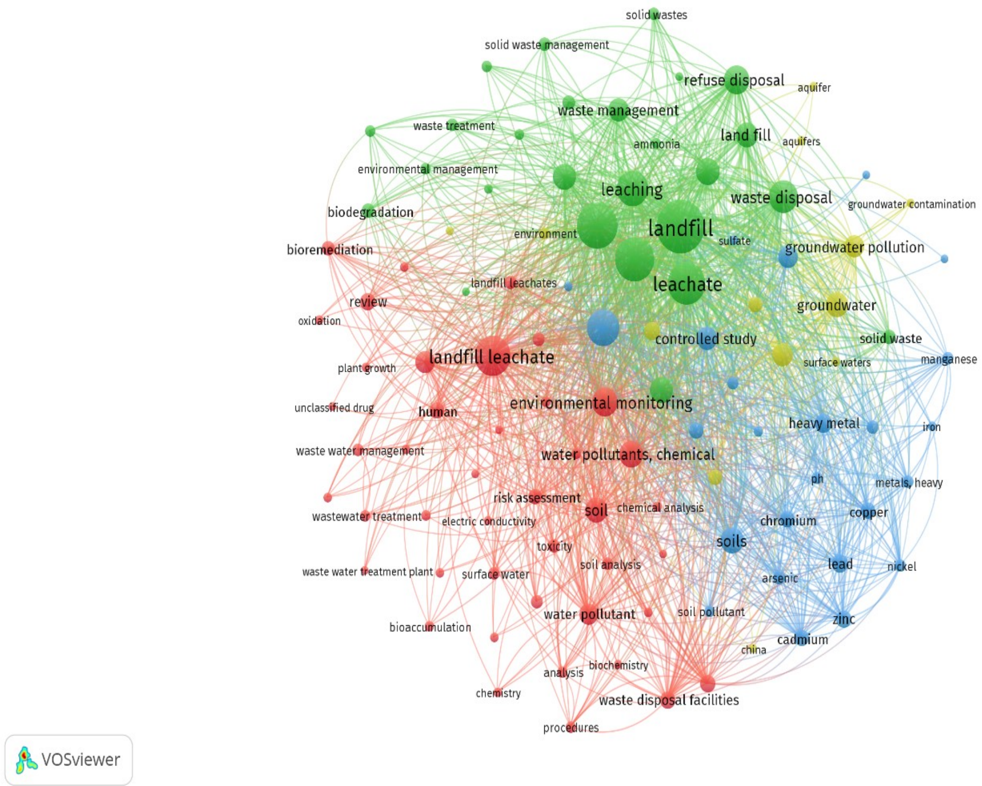

Figure 3. Vosviewer network visualization on recent hotspots

greater soil porosity, forming an unstable honeycomb structure and reducing particle uniformity. The specific surface area rapidly increased, stabilizing between 500 and 650 kg/m^2. Additionally, higher leachate levels caused a significant decrease in particle size and a sharp rise in pore volume (29).

Compaction

(30) found that soil contaminated with leachate exhibits lower dry density, likely due to chemical interactions between the leachate and soil pore fluid properties. The study suggests that incorporating leachate into the soil could improve compaction efficiency, potentially reducing soil volume in landfill cells. Nayak et al. (31) observed a decrease in maximum dry density is likely due to these chemical reactions between the acidic leachate and the soil. At high leachate concentrations, an excessive amount of leachate in the soil can trigger further chemical reactions between the acidic leachate and the soil particles. The compaction study showed that as the percentage of liquid leachate increased, both the maximum dry unit weight and the optimum moisture content decreased (32). Adding moisture facilitates compaction by making the soil easier to knead and capable of achieving higher dry density. However, the dry density decreases at higher moisture content as the soil becomes more saturated with water. Liquid leachate increases soil saturation, contributing to the observed reductions in maximum dry unit weight and optimum moisture content (33).

Hydraulic conductivity

According to Zheng et al. (34) an increase in leachate concentration results in an increase in the soil's hydraulic conductivity; high ion content in leachate causes an increase in mass loss due to the dissolving of clay minerals; channels emerge in the soil; and adequate pore space expands. The more significant permeability channel formed by the soil particles and the infiltration of heavy metal ions into the soil causes an increase in hydraulic conductivity. A summary of studies on the impact of heavy metals on hydraulic conductivity found in the literature is furnished in Table 3 (35).

Nayak et al. (31) observed changes in soil structure after leachate contamination. They found that replacing pore water with leachate increased the void ratio of the soil. The increase in pore fluid volume and hydraulic conductivity was attributed to the leachate's capacity to dissolve clay minerals within the soil. Xie et al. (36) studied soil compacted with various concentrations of leachate and observed that hydraulic conductivity to leachate was consistently higher than that to demineralized water across all compacted samples. This difference was primarily attributed to the lower viscosity of leachate than water. Long-term soil exposure to leachate led to a notable decrease in hydraulic conductivity to both leachate and water, especially in samples with more significant voids. This decrease was due to reduced active pore space, influenced by thicker diffuse double layers, clay particle rearrangement, chemical precipitation and biofilm formation within soil pores. Microbial activity significantly reduces soil hydraulic conductivity (37-39). This reduction occurs as biofilms and colonies form on mineral particle surfaces and grow within soil pores, obstructing them and contributing to decreased hydraulic conductivity (40,41).

Table 3. Impact of Heavy metals on Hydraulic conductivity of soil

Contaminants	Hydraulic conductivity (cm/s)	Change in hydraulic conductivity	Reference
Pb Cu Pb + Cu Pb + Cu + Cd	4.7×10^{-9} 4.8×10^{-9} 4.3×10^{-9} 2.4×10^{-9} (m/s)	Hydraulic conductivity was found to be close to each other because the soil samples were mainly composed of sand.	(34)
0-4 mg/L Pb^{+2}	~Increase from 1.25×10^{-9} to 2.2 10^{-9}	As the concentration increased, hydraulic conductivity also increased	(69)
0-40 mg/L Pb^{+2}	Decrease from 2×10^{-5} to 7.8 x 10^{-7}	As the concentration increased, hydraulic conductivity decreased	(70)
0-10 mM Pb^{+2}	Increase from 10^{-9} to 10^{-7}	As the concentration increased, hydraulic conductivity also increased	(71)
0 mg/kg Pb or Zn^{+2} 1,000 mg/kg Pb^{+2} 1,000 mg/kg Zn^{+2}	2.2×10^{-8} 5×10^{-8} 4.8×10^{-8} (m/s)	As the concentration increased, hydraulic conductivity also increased	(34)
0-10 g/L Cu^{+2}	3.54×10^{-6} 42.25×10^{-6}	As the concentration increased, hydraulic conductivity also increased.	(72)
0-100 ppm Cu^{+2} 0-1,000 ppm Cu^{+2} 0-100 ppm Pb^{+2} 0-1,000 ppm Pb^{+2} 0-100 ppm Zn^{+2} 0-1,000 ppm Zn^{+2}	1.7 times increase 2.6 times increase one time increase 1.2 times increase 1.4 times increase 2.2 times increase	As the concentration increased, hydraulic conductivity also increased.	(73)

Soil Nutrient Imbalance

Changes in soil pH can limit nutrient availability (42). Rahman et al. (43) reported that copper, zinc and nickel are crucial micronutrients for plants in small amounts but become toxic in excess.

Rao (44) reported that nitrogen levels in the contaminated soils were notably high, ranging from 115 to 262 kg/acre, with the control soil sample showing a lower value of 62 kg/acre. The phosphorus content in the dump yard soils varied between 73 and 91 kg/acre, while the control site had a lower 34 kg/acre value. The elevated nitrogen and phosphorus levels in dump site soil are likely due to the high organic matter (45). Potassium levels in the dump site soils ranged from 157 to 363 kg/acre, compared to a low of 15 kg/acre at the control site. Although potassium is essential for plant growth, anthropogenic activities can elevate its levels, potentially contaminating groundwater. According to Agbeshie et al. (46), the high nutrient content at the dump site, mainly the organic carbon and exchangeable bases, significantly affected soil bulk density, porosity and nutrient availability. High concentrations of calcium, magnesium, sodium, potassium, ammonium, iron, chloride, sulfate, nitrate and hydrogen carbonate ions in leachate and soil increase osmotic pressure, hindering water uptake by plant roots and impairing growth (47). Letsoalo (48) suggests that essential nutrients and chromium affect plants' absorption of calcium (Ca^{2+}) and magnesium (Mg^{2+}) through soil interactions. Dimethyl arsenic acid in soil reduces concentrations of essential macronutrients (P, K, Ca, Mg) and micronutrients (B, Cu, Fe, Mn) in plants (49).

Soil microbes

(50) reported that bacteria found at waste or leachate dumpsites can include Arthrobacter, Bacillus, E. coli, Klebsiella, Micrococcus, Proteus, Serratia marcescens, Klebsiella aerogenes, Staphylococcus aureus, Alcaligenes sp., Proteus mirabilis and Salmonella. Fungi isolated from waste dumpsites include *Aspergillus, Fusarium, Mucor, Penicillium, Rhizopus* and *Saccharomyces*. *Aspergillus niger, Aspergillus flavus, Rhizopus* and yeast species were explicitly isolated from dumpsite leachates. Wydro et al. (51) experimented using soil treated with different doses of leachate (50 LL and 100 LL). They found that the highest total number of bacteria was observed in pots treated with 50 LL (1.05 x 10^7 cfu/g DM, T1), while the lowest number was in the control pots (1.43 x 10^6 cfu/g DM, T3). According to (52), leachate (LL) contains a mixture of soluble organic matter, heavy metals, PAHs and other toxic substances, which, when introduced into the soil, can affect its activity and reduce the number of microorganisms (Fig 4.) (53). The presence of these toxic substances can interfere with the adaptability of some organisms, resulting in a decrease in their numbers (54). Wydro et al. (51) also reported that leachate alters the structure of the microbial community, as indicated by the T-RFLP approach, affecting microbial richness and relative abundance in the soil. Daniel et al. (55) suggested that heavy metals indirectly impact soil enzymatic activities by altering the microbial community responsible for enzyme synthesis. These heavy metals affect soil microorganisms by modifying their diversity, population size and overall activity within the soil microbial communities. Heavy metals like lead, silver and cadmium penetrate bacterial plasma membranes and generate superoxide ions in the cytosol. These ions, converted by Super Oxide Dismutase (SOD) into hydrogen peroxide or hydroxyl radicals, oxidize lipids, proteins and DNA. Reactive Oxygen Species (ROS) and other oxidative intermediates further damage cellular components. Cells produce antioxidant enzymes such as catalase, SOD and glutathione peroxidase to mitigate ROS. However, the oxidative stress caused by heavy metals can result in apoptosis, necrosis, tissue damage and malignancy (53).

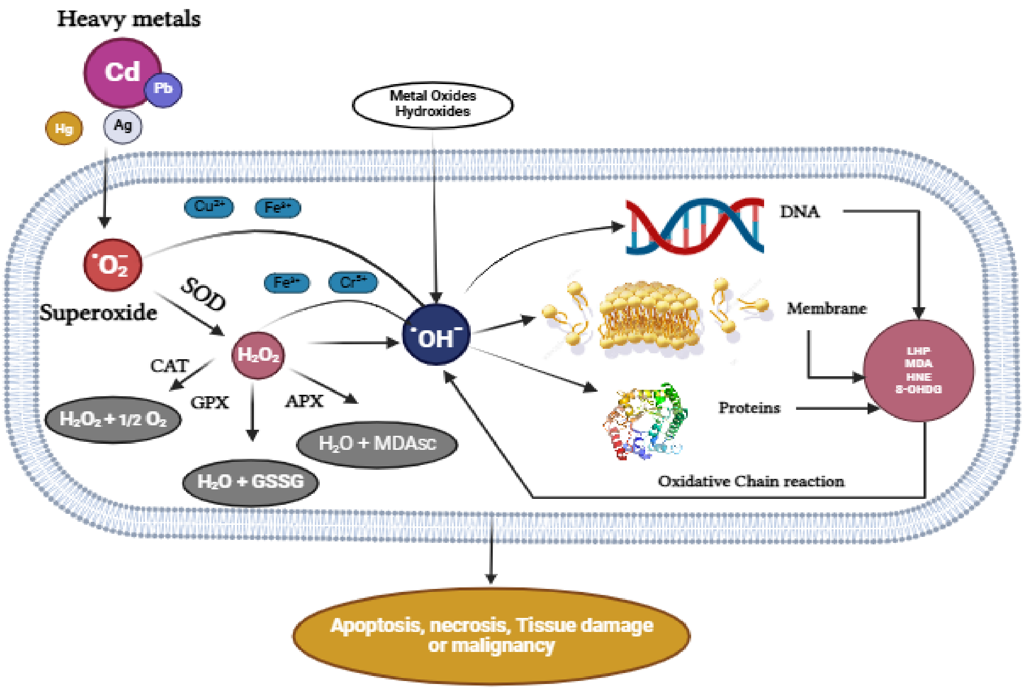

Figure 4. Mechanism of Heavy Metal Toxicity on Bacteria

Heavy metal

Heavy metals are major pollutants in landfill leachate and can remain in landfills for about 150 years if leaching occurs at 400 mm/year (56, 57). Their toxicity disrupts the biological balance and impairs natural purification processes (58). Leachate production and heavy metal mobility are influenced by rainfall (posing risks to soil, groundwater and surface water (59). Non-threshold pollutants like arsenic, chromium (VI), cadmium, mercury and lead are toxic even in small amounts (60,61). Torkashvand et al. (56) reported copper, cadmium, lead, iron, and nickel concentrations in landfill leachate from Iran as 1, 0.45, 0.85, 14 and 1.1 mg/L, respectively. Pasalari et al. (62) found manganese levels in Iranian landfill leachate ranging from 3.2 to 8.1 mg/L. Beinabaj et al. (63) indicated that iron concentrations in Nigeria were the highest among the metals, at 22.94 mg/L. Johar et al. (64) discovered the highest concentrations of cadmium (Cd) and silver (Ag) in soil samples from a landfill in New Delhi, India, highlighting the landfill as a significant source. The soil exhibited a higher Cd and Ag adsorption capacity than iron (Fe) and copper (Cu). The high level of transferable Cd is particularly concerning due to its potential for significant plant uptake and accumulation (65).

Mitigation measures

Landfill leachate significantly threatens soil and water resources, leading to degradation. Without adequate containment measures, leachate can directly contaminate surrounding soil and seep into groundwater, exacerbated by rainfall. Various industrial and scientific initiatives have been implemented to mitigate leachate release, each tailored to specific environmental conditions and with varying biomedical implications. The landfill liner is crucial to preventing leachate from seeping into the subsoil (66). The foundation of a landfill site should be designed to support the weight of the overlying waste and cover material. The foundation material must have sufficient compressive strength to bear this load.

In some cases, grouting or other techniques may be needed to reinforce the foundation. For a landfill liner to be effective, it must exhibit specific properties such as swelling behaviour, strength and low permeability. Clay with a higher content of Montmorillonite, combined with overburden pressure, needle punching density, and areal density, demonstrates better self-healing properties and low hydraulic conductivity. However, hydraulic conductivity increases with higher water pressure in clayey soil (67). Using nanotechnology, (68) discussed the application of nanoclay and nanofiber filters during the landfill stage for solid waste management to control leachate leakage from landfill liners.

Conclusion

Landfill operations are vital for waste disposal, but landfill leachate, produced by chemical and biological reactions within landfills, can contaminate soil and groundwater, posing environmental health risks. This review explored the effects of landfill leachate on soil structure, hydraulic conductivity and heavy metal impact. Recent innovations, such as advanced landfill liners with nanotechnology, are essential for preventing leachate contamination. Developing new bioinoculants shows promise in reducing heavy metals in landfills. Biochar and Hydrochar are effective for treating landfill leachate due to their customizable adsorption properties, though challenges like limited research and the difficulty of scaling laboratory methods to treat the average 167 million tonnes of leachate produced globally. Further research could enhance their effectiveness, mitigating waste and providing sustainable ecosystem services.

Acknowledgements

I sincerely thank the Department of Soils and Environment, Agricultural College and Research Institute, Madurai and the Department of Environmental Sciences, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India, for their support.

Authors' contributions

J K designed the study and wrote the protocol. S Jagasri and R J wrote the first draft of the manuscript. S S and C P managed the analyses of the study. K P performed the analysis. R M J and R M and S M managed the literature searches. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None.

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No AI tools are used for manuscript preparation

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