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Ecotoxicological impacts of landfill sites: Towards risk assessment, mitigation policies and the role of artificial intelligence

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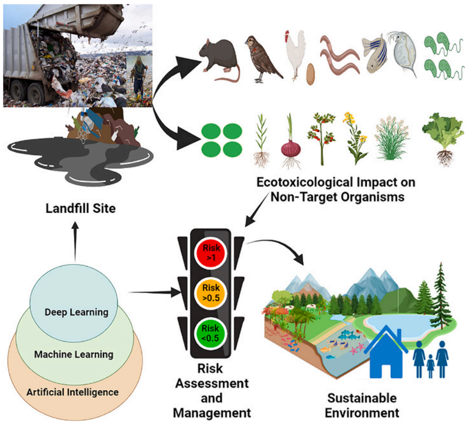
HIGHLIGHTS

- Scientometric analysis of pollutants emanating from landfills undertaken
- Chemical nature and toxicity of pollutants analysed systematically
- Diverse toxicities on humans and biota highlight intricate composition of leachates
- Persistent organic chemicals, metals and microplastics of greatest concern
- Potential role of artificial intelligence in risk assessment explored

GRAPHICAL ABSTRACT



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ABSTRACT

Waste disposal in landfills remains a global concern. Despite technological developments, landfill leachate poses a hazard to ecosystems and human health since it acts as a secondary reservoir for legacy and emerging

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Abbreviations: AI, Artificial Intelligence; AOPs, adverse outcome pathways; ARGs, antibiotic resistance genes; ANN, artificial neural networks; BPA, bisphenol A; CFD, computational fluid dynamics; DT, decision tree; DFT, density functional theory; EC_{50}, effective concentration (50 %); e-waste, electrical and electronic waste; GBRT, gradient boosting regression tree; KNN, k-nearest neighbour; LC_{50}, lethal concentration (50 %); MDS, molecular dynamics simulation; ML, machine learning; MSW, municipal solid waste; OPFRs, organophosphate flame retardants; PEC, predicted environmental concentration; PFAS, *per*- and polyfluorinated substances; PNEC, predicted no-effect concentration; POPs, persistent organic pollutants; PPCPs, pharmaceuticals and personal care products; RQs, risk quotients; QSAR, quantitative structure-activity relationship.

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pollutants. This study provides a systematic and scientometric review of the nature and toxicity of pollutants generated by landfills and means of assessing their potential risks. Regarding human health, unregulated waste disposal and pathogens in leachate are the leading causes of diseases reported in local populations. Both *in vitro* and *in vivo* approaches have been employed in the ecotoxicological risk assessment of landfill leachate, with model organisms ranging from bacteria to birds. These studies demonstrate a wide range of toxic effects that reflect the complex composition of leachate and geographical variations in climate, resource availability and management practices. Based on bioassay (and other) evidence, categories of persistent chemicals of most concern include brominated flame retardants, *per*- and polyfluorinated chemicals, pharmaceuticals and alkyl phenol ethoxylates. However, the emerging and more general literature on microplastic toxicity suggests that these particles might also be problematic in leachate. Various mitigation strategies have been identified, with most focussing on improving landfill design or leachate treatment, developing alternative disposal methods and reducing waste volume through recycling or using more sustainable materials. The success of these efforts will rely on policies and practices and their enforcement, which is seen as a particular challenge in developing nations and at the international (and transboundary) level. Artificial intelligence and machine learning afford a wide range of options for evaluating and reducing the risks associated with leachates and gaseous emissions from landfills, and various approaches tested or having potential are discussed. However, addressing the limitations in data collection, model accuracy, real-time monitoring and our understanding of environmental impacts will be critical for realising this potential.

1. Introduction

Globally, the production of municipal solid waste (MSW, including domestic, commercial and industrial wastes) is rapidly escalating due to the combined effects of modernisation, increasing industrialisation, growing populations and changing lifestyles (Wijekoon et al., 2022). Approximately 4.3 billion inhabitants of urban areas presently produce an average of 1.42 kg MSW/individual. This rate is predicted to escalate to a daily MSW production of 6.1 million tonnes by 2025 (Anand et al., 2021). In the Asian and Pacific regions alone, projections indicate that by 2050, India, China and Nigeria will gain an additional 416 million, 255 million and 189 million urban residents, respectively (Sharma and Jain, 2020), who will contribute significantly to the global increase in solid waste generation. In addition, electronic and electrical waste (e-waste) generation will escalate to 74.7 million metric tonnes by 2030, which is a cause for concern as it is still frequently disposed of at unauthorised sites (Houessionon et al., 2021). Moreover, industrial diversification and the expansion of health-care facilities have added hazardous industrial and biomedical wastes to landfills.

A well-designed ground depression utilised for dumping solid waste is a landfill. MSW is a complex assortment of food waste, grass clippings, paper, metals, wood, plastics, packaging, construction and demolition wastes, electronics, textiles, rubbers, ashes, oils, paints and chemical by-products (Charis et al., 2019; Gupta et al., 2015; Iravanian and Ravari, 2020). Globally, organic waste (food and green garbage) constitutes 44 % of MSW, followed by paper and cardboard (17 %), plastics (12 %), glass (5 %), metal (4 %), wood (2 %), rubber and leather (2 %) (Kaza et al., 2018; Sharma and Jain, 2020). However, this distribution varies by region and country, with the highest percentages of organic waste reported for Bangladesh (75 %), Afghanistan (70 %), Nigeria (64 %), China (60 %), India (54 %), Turkey (50 %) and Zimbabwe (47 %) (Bhat et al., 2022).

As a result of rapid globalisation, landfilling continues to be a widely used yet outdated method that leads to soil, groundwater and surface water pollution due to the percolation of harmful leachate (Mohanty et al., 2023). Landfills also cause air pollution by emitting dusts, volatile metalloids (As and Sb; de Oliveira et al., 2022), and, through the decay of organics by microorganisms, gases. The latter may have high global warming capacities (mainly CO_2 and CH_4; Luo et al., 2020) or may present a fire hazard.

As such, the nature of the waste, environmental circumstances, the age and position of the landfill and the management system in place lead to an intricate interplay of physical (*e.g.*, seepage, absorption, rainfall, evaporation, runoff), chemical (*e.g.*, oxidation, precipitation, complexation, dissolution, photooxidation) and biological (*e.g.*, nitrification, methanogenesis, acetogenesis) processes. These processes combine to convert waste materials into a diverse range of pollutants in leachate (Fig. 1), including metals and metalloids, organic substances, persistent organic micropollutants (POPs, like pesticides, flame retardants and polycyclic aromatic hydrocarbons), microplastics (MPs), and pharmaceutical and personal care compounds (PPCPs). All these pollutants have the potential to harm both the environment and human health, and they must be identified and assessed for their respective ecological risks in order to be adequately managed (Gautam et al., 2020; Gautam and Anbumani, 2020; Wijekoon et al., 2022; Zhang et al., 2022a). Since many antibiotic-resistance genes have been produced in bacteria present in landfill leachate, facilities may also be regarded as antibiotic-resistant reservoirs.

As an illustration of the complexity and changing composition of landfill leachate, between 1993 and 2018, a total of 172 pharmaceuticals and PPCPs, including stimulants, antibiotics, beta-blockers and anti-inflammatories, were found in leachates globally (Yu et al., 2020). As a preventive measure against COVID-19, the manufacturing and consumption rate of antibiotics and other drugs have increased further since 2019. Moreover, by including nylon polymers in facemasks following the outbreak of COVID-19, it is estimated that an additional 6 % (or 11 kg) of annual *per*- and polyfluorinated substances (PFAS) are discharged to United States waste streams, with 90 % ending up in landfill (Muensterman et al., 2022). Facemasks are also a potential source of microplastics to landfill leachate (Patrício Silva et al., 2021; Rahman et al., 2023). In the south-eastern region of Europe, a notable correlation was observed between the levels of bisphenol A (BPA; ranging from 0.70 to 2.72 mg L^{-1}) and microplastics (MPs; ranging from 0.64 to 2.16 mg L^{-1}) found in landfill leachate (Narevski et al., 2021), suggesting that MPs might also act as carriers of some POPs.

Chemicals emitted from landfill sites as gases, dusts and leachate pose both acute and chronic effects on human health (Baderna et al., 2019; Sharma et al., 2018). The presence of microbial contaminants is also a concern due to the risk they pose in transferring antibiotic-resistant genes (ARGs) among human pathogens through horizontal gene transfer (Anand et al., 2021; Kaza et al., 2018). Landfill pollutants have many detrimental effects on aquatic and terrestrial life (including birds). These include mortality and histopathological alterations in fish, decreased survival in water fleas (*Daphnia)*, reduced growth of algae, and increased mortality, altered cyto-genotoxic effects and antioxidant responses in earthworms (da Silva et al., 2022; Fauziah et al., 2019; Pratiwi et al., 2022; Junior et al., 2023; Shaari et al., 2021). Conversely, using recommended indicator organisms from various settings, ecotoxicological assessment of leachate ensures safe treatment and their disposal with minimal negative effects on the environment and human health.

With the increasing complexity and diversity of wastes and resulting landfill leachates, machine learning (ML), or artificial intelligence (AI), has gained widespread popularity as a valuable tool for both scientists and industry (Hoang et al., 2022). ML algorithms may examine big datasets, offer insights into the parametrisation and behaviour of landfill leachate, and improve predictive models and treatment methods for management and mitigation purposes. ML algorithms are also used to monitor landfill gas, forecast the production of landfill leachate, and estimate landfill areas using adaptive network fuzzy inference systems (ANFIS) and artificial neural networks (ANN) (Abunama et al., 2019; Abunama et al., 2018).

In light of the above information, this review aims to achieve the following objectives: (a) systematically summarise the available information pertaining to the characteristics and potential impacts of landfill leachates scientometrically (papers available online until 30th June 2023, (b) review information on the sources, contamination and disease burden in relation to landfill sites in both developed and developing countries, (c) evaluate the ecotoxicological impacts of landfill leachate in both aquatic and terrestrial ecosystems, (d) appraise risk characterisation and mitigation policies reported globally, (e) assess the role of machine learning in landfill leachate management, and (f) identify the priorities for future research directions.

2. Literature survey and methodology

Quantitative scientometric analysis was applied to the published landfill research domain between 1975 and 2023. The most extensive database, Scopus, was employed to search for pertinent publications using various keywords and combinations thereof within the title, abstract and keywords (Table S1), and yielded a total of 737 publications. Scientometric network keyword co-occurrence analysis was conducted using VOSviewer software (version 1.6.18) to compile existing research articles on landfill leachate, landfill gas and their toxicities in organisms (Chen et al., 2021; Gautam et al., 2023a). This software created a cluster-based scientific mapping, which was then explored and visually represented (Ghosh et al., 2023). In brief, out of the 7704 keyword data points from 737 publications retrieved from the Scopus database, 965 keywords satisfied the criteria. The total link strength with other keywords was calculated for all 965 words, and those with the highest total link strength were chosen (with a minimum keyword frequency of five). The analysis utilised the cluster-based approach, employing “association strength” as the normalisation strategy. The publishing trend for each year was also examined to understand the attention paid to landfill leachate and their effects on the environment.

Fig. S1a shows the overall network mapping of the landfill studies based on keyword co-occurrence, where all keywords used in studies between 1975 and 2023 related to chemical characterisation, aquatic toxicity, terrestrial toxicity and other variables are included. The dimensions of a keyword node inside the network representation serve as a measurable indicator of its relative frequency of occurrence throughout a range of scholarly articles. Larger nodes represent keywords that are more commonly found in the literature, and the spatial rise in node size serves as a powerful symbolic representation reflecting the increasing significance in the field of landfill research. The 20 top countries with the most publications have been selected based on the investigation to clearly show the current research in this domain (Fig. S1b). Here, we found that China (191) and the United States (105) have the highest number of studies, while Australia (14) and Malaysia (14) have the lowest. Among the emerging and developing nations, India published 40 waste management studies, just behind publications from the United Kingdom (47). Meanwhile, the number of articles reported on the toxicity end points related to landfills were gathered from 1975 to 2023 (Fig. S1c).

The number of studies related to plant (173) and animal (131) toxicity of landfill leachate was further categorised to select the relevant literature on ecotoxicological impact and risk assessment. Consequently, we conducted a literature search using the keywords “Toxicopathological impact” of landfill leachate on various species to gather data on the “Toxicity of Landfills.” Specifically, to assess the recent developments in research concerning the harmful effects of landfill sites on the environment and their influence on living organisms, we focused on studies conducted in the past five years (2018–2023). We judiciously filtered out articles from the PubMed database categorised as “Review” or written in languages other than English. This search yielded a total of 655 studies, of which 57 original research articles were directly linked to the *in vivo* toxicity of landfill sites or toxicity evidenced from effects or accumulation observed *ex situ*, and 12 studies addressed *in vitro* toxicity.

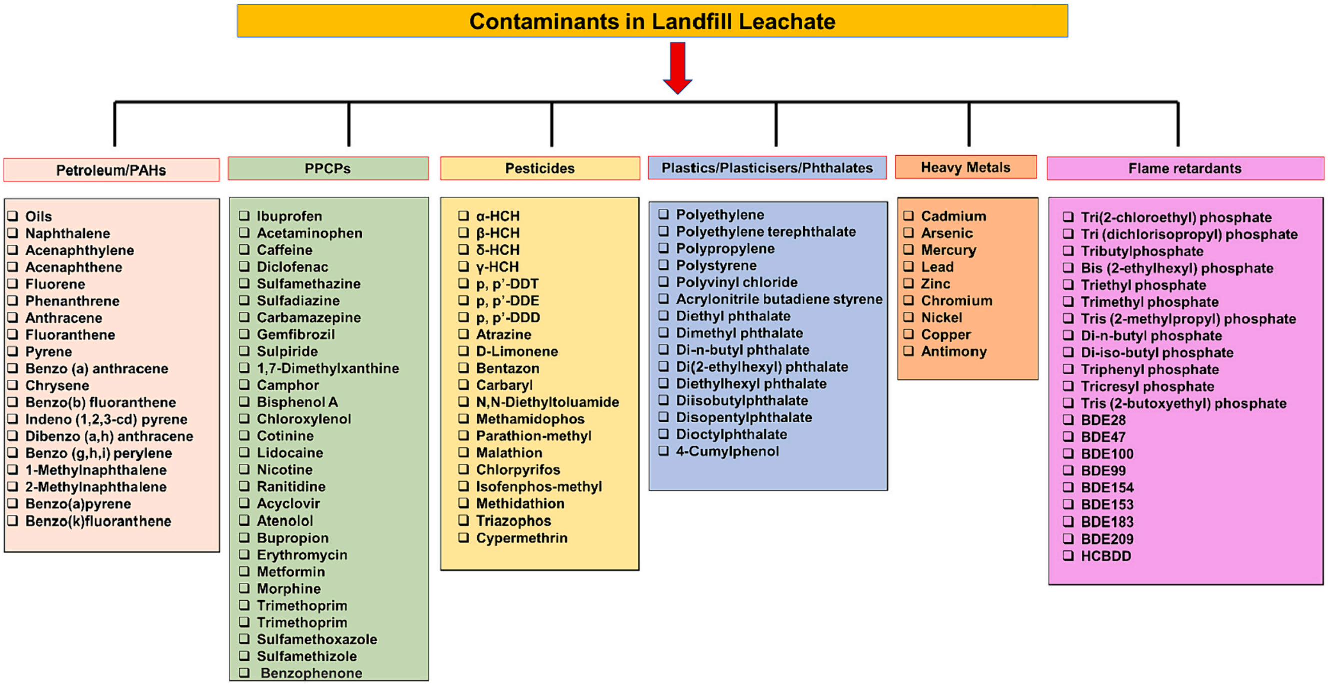

Fig. 1. Examples of major contaminants commonly encountered in landfill leachate.

While there is no clear trend for toxicological research, observations suggest a significant data gap and the need for further studies.

3. Impacts of landfills on human health

Exposure to hazardous chemicals derived from landfills can occur through various pathways, and particular pollutants can cause a wide range of health impacts. Extended latency durations and cumulative exposures to different pollutants complicate the investigation of connections between environmental pollution and health. Nevertheless, various attempts have been undertaken in recent years to assess the worldwide impact of diseases attributable to environmental pollution from landfill sites in terms of mortality or disability. For example, in Indonesia, India and the Philippines, 828,722 DALYs (disability-adjusted life years) were attributed to chemical exposures at 373 hazardous waste sites, with lead (Pb) and hexavalent chromium (Cr IV) identified as the significant culprits (Chatham-Stephens et al., 2013). In another study, it was assessed that 189,725 children in seven Asian countries were exposed to Pb from unregulated hazardous waste dumps that were high enough to cause neurological effects (Caravanos et al., 2013). In populations living near individual toxic waste sites, an increase in specific effects or diseases (such as fatigue, nausea, vomiting, chronic lymphatic leukaemia, total lymphoma, kidney and bladder tumours, cirrhosis, diabetes, asthma, adverse reproductive effects, infectious respiratory diseases and congenital anomalies) has been reported (Fazzo et al., 2014).

An epidemiological investigation conducted in Italy has revealed a significant link between the proximity of residents to illegal waste disposal sites and the incidence of various types of cancer, such as stomach, liver, kidney, bladder and lung. Additionally, there is a correlation with congenital anomalies affecting the central nervous and internal urogenital systems (Fazzo et al., 2017; Hussain et al., 2024; Triassi et al., 2015). Overall, compared to the general population, casual or professional waste pickers face an elevated susceptibility to acquiring various infections and illnesses (Made et al., 2020).

There are also significant concentrations of pathogens in landfill leachates, such as the avian influenza virus (H6N2), which can continue to be contagious for up to 600 days and pose a life-threatening risk (Patrício Silva et al., 2021). Due to the possibility of horizontal gene transfer spreading the ARGs in human diseases, the microbial burden in landfills also seriously threatens ARGs, antibiotic-resistant bacteria and metal-resistance genes (Kaza et al., 2018). The breakdown of food wastes also produces organic leachate, which, depending on the temperature and duration, can significantly alter the microbial community and introduce pathogenic organisms, including *Salmonella* sp., *Pseudomonas* sp., *Enterobacter* sp. and *Clostridium* sp., respectively (Kalwasińska and Burkowska, 2013; Wu et al., 2018).

4. Ecotoxicological impact of landfills

Based on the literature pertaining to the ecotoxicological impact of landfill sites (and predominantly landfill leachate) on both aquatic and terrestrial organisms, it is evident that most studies have focused on two main aspects. Firstly, the characterisation of leachate to assess the presence of pollutants that have been mobilised from waste. This approach is advantageous in understanding the contamination levels and their potential to exert adverse effects on biota. Secondly, conducting toxicity bioassays of leachate, primarily using short-term endpoints rather than long-term sub-chronic and chronic impacts on organisms. The following subsections are concerned with the second aspect.

4.1. Aquatic biota

Aside from the presence of toxic chemicals, like heavy metals and POPs, leachate produced from landfill waste contains varied concentrations of chemical components with BOD in the range of 2×10^4–2.7×10^4 mg L^{-1} and COD in the range 3.4×10^4–3.8×10^4 mg L^{-1}, which are considered to be generally detrimental for the health of recipient aquatic ecosystems (Bhat et al., 2022). Leachate can also alter water temperature, accelerating bacterial and phytoplankton growth, creating algal blooms, and affecting freshwater organisms' metabolic and reproductive processes (Bhat et al., 2022; Ho and Frenzel, 2012).

Over the last 30 years, the use of bioassays as screening tools has grown substantially, including applications for landfill leachate hazard assessment (Baderna et al., 2019). Numerous techniques are available for undertaking these assessments *in vivo* and *in vitro*. The present review primarily focussed on the application of experimental (mainly in *in vivo*) model systems and *ex situ* analyses to assess landfill leachate toxicity, and scientific work published using *in vitro* systems during the last ten years and which has not, thus far, been included in any critical review (Table 1). It is noted that most of the work carried out with cytotoxicity assays has been restricted to human cells (Alimba et al., 2022; Gupta et al., 2019; Jabłońska-Trypuć et al., 2021; Khalil et al., 2018). Regarding the experimental systems and *ex situ* analyses, 57 studies from developed and developing nations that have been published over the last five years have been critically assessed, and the findings are summarised in Tables 2 and S2.

Apart from bacteria, test organisms include microalgae, invertebrates, fish, birds and mammals. Two studies reported no observable effects (Benguit et al., 2022; Jabłońska-Trypuć et al., 2021), and one reported a better nutritional status and body condition in birds (Pineda-Pampliega et al., 2021). However, more often toxicity has been reported as percentage concentration of raw leachate in terms of EC_{50} or LC_{50} (Bastos et al., 2021; Costa et al., 2023; Costa et al., 2019; Da Costa et al., 2018; da Silva et al., 2022; Dantas et al., 2020; Fernandes et al., 2019; Junior et al., 2023; Nika et al., 2020; Sackey et al., 2020; Sales Junior et al., 2021b; Tripathy and Kumar, 2019) or lowest observed effective concentration (LOEC) (Białowiec et al., 2019), with various end points monitored in plants and animals, and as summarised in Tables S2 and 2. These include germination rate or index (Anand and Palani, 2022; Bożym, 2022; Colombo et al., 2019; Ghanbari et al., 2021; Khavari Kashani et al., 2023; Kwarciak-Kozłowska and Fijałkowski, 2021; Poblete and Pérez, 2020; Wang et al., 2023), photosystem efficiency (Palm et al., 2022), haematological damage, somatic and germ cell mutations and tissue damage morphology (Alimba et al., 2022), biomass change (Ančić et al., 2020; Fasani et al., 2019; Hussain et al., 2023), growth rate or survival (Przydatek, 2019; Shaari et al., 2021; Silvestrini et al., 2019; Wang et al., 2023; Wilk et al., 2022; Zainal et al., 2022). Also observed have been alterations in antioxidant status and generation of ROS (Arojojoye et al., 2022; Ogunlaja et al., 2019; Prestes et al., 2020; Sales Junior et al., 2021a; Yildirim et al., 2019), retarded development (Escalante-Mañe et al., 2022) and reproduction impairment (Ademola et al., 2020), DNA damage (Anand and Palani, 2022; Ančić et al., 2020; Khalil et al., 2018; Neeratanaphan et al., 2020; Torres-González et al., 2021), and locomotion inhibition (de Sousa et al., 2023; Makaras et al., 2020; Wdowczyk and Szymańska-Pulikowska, 2021). In some of the *ex situ* studies, bioaccumulation of toxic chemicals like metals or polybrominated diphenyl ethers was also monitored (Bożym, 2020; Hard et al., 2019; Oloruntoba et al., 2019; Vongdala et al., 2019).

Clearly, the range of organisms impacted and diversity of end points observed reflect the highly complex composition of landfill leachate and the diversity of toxicants present at elevated concentrations, coupled with geographical variations in the nature of waste generated and sorted and its precise means of disposal and treatment. As noted above, climatic effects may also have an impact on leachate characteristics or its detrimental impacts.

4.2. Terrestrial biota

The soil environment in the vicinity of landfill sites may be

Table 1
Representative *in vitro* studies examining the cytotoxicity of landfill leachate. Studies are shown in reverse chronological order and all landfills are municipal or sanitary unless otherwise stated.

Landfill location	Leachate type	Test model	Test type	Test duration	Toxicity impact	Reference
Olusosun, Nigeria Bhandewadi Nagpur, India	Simulated from soil	Lymphoma (jurkat) cells	Agarose gel electrophoresis, Hoechst 33258-PI staining, and real-time PCR	24 h	DNA fragmentation increased, and morphological apoptotic traits. Altered p53 protein, caspase-2/6, BID, BAD gene expression	Alimba et al. (2022)
Hryniewicze, Poland	Raw	Melanoma A-375 cell line Human skin fibroblasts	CFU, luminescence assay, H_2DCFDA measurement assay, MTT assay, bioluminescent test	24 and 48 h	Cell viability increases at lower concentrations and decreases at higher concentrations. Similarly, dose-dependent decrease in caspase 3/7 activity and increase in ROS generation	Jabłońska-Trypuć et al. (2021)
Bhanpur, Bhopal, India	Prepared from landfill soil	Human peripheral blood lymphocytes	Mitochondrial deregulation and inflammatory response assay. Immunofluorescence analysis, cytogenetic analysis using Giemsa method	0–24 h	Enhanced DCF fluorescence, elevated 8-oxo-dG, nrf-2 levels. Reduced mitochondrial potential, genome alterations, heightened NF-κB, inflammation, and DNA damage. Induced mitochondrial apoptosis	Gupta et al. (2019)
Tripoli, Zahle, Ghazeer, Lebanon	Zahle old Zahle new Tripoli Ghazeer	Human modified keratinocyte cells	MTS and comet assay	2–24 h	Significant toxicity in terms of cellular organelles and DNA damage	Khalil et al. (2018)
Longgang, Shenzhen, China	Membrane-concentrated raw	HepG2 MCF-7	Cytokinesis-block micronucleus assay Comet assay Estrogenicity assay	24 h	Micronuclei increased; leachate had genotoxic and cytotoxic potency Increased % DNA in tails Increased proliferation effect	Hong et al. (2017)
Xingfeng, Guangzhou, China	Raw	HepG2	MTT assay EROD assay Comet assay γH2AX flow cytometry assay	24 h	Cell viability reduction: 78.5 % and 90.4 % at 20 and 30 % leachate Increased EROD activity Increased 66.84 % DNA in the tail and 31.36 (OTM) Concentration-dependent increases in mean intensity of γH2AX	Cheng et al. (2017)
Okhla, Bhalswa, Ghazipur, India	Prepared from landfill soil	HepG2	MTT and comet assays	24 h	EC_{50} values: 7.58–12.9 g Significant DNA damage	Swati et al. (2017)
Espírito, Santo, Brazil	Raw	Ovary (CHO-k1)	MTT and Trypan blue assay Nuclear division index Cytokinesis-block micronucleus assay	12 h	Decreased Increased Mutagenicity increased	Morozesk et al. (2016)
Xiaping, Shenzhen, China	Membrane-concentrated raw	MCF-7 BUS	*E*-Screen assay	5 days	Increased proliferation effect with estradiol equivalent concentration: 104 ± 24.6 ng L^{-1}	Wang et al. (2016)
Ghazipur, Okhla, Bhalswa, India	Raw	HepG2	MTT assay DNA damage using comet assay	24 h	EC_{50}: 15.04 % (Okhla), 20.44 % (Bhalswa) and 11.58 % (Ghazipur) % DNA in tail: 80.22 ± 14.56 (Okhla), 37.24 ± 23.02 (Bhalswa), 72.17 ± 18.01 (Ghazipur)	Ghosh et al. (2015)
Aigeira, Greece	Raw	Mussel haemocytes	Genotoxicity and oxidative stress assay	72 h	Increased SOD activity and MDA level and increased levels of % DNA in tail and OTM	Toufexi et al. (2013)
Electronic waste dumpsite, Lagos, Nigeria	Prepared from landfill soil	NIH/3 T3	MTT assay Mitochondrial membrane potential Cell cycle analysis ROS (oxidative stress assay)	24 h	IC_{50}: 30 % concentration of leachate Decreased above 20 % concentration Increase in phase sub/G1 and decreased population of NIH/ 3 T3 cells in G2/M and G1/G0 cell phases Increase in dose-dependent manner	Alabi et al. (2013)

IC_{50} = half maximal inhibitory concentration; 8-oxo-dG = 8-oxo-2′-deoxyguanosine; CFU = colony forming units; CHO-k1 = Chinese hamster ovary; DCF = dichlorodihydrofluorescein; DNA = deoxyribonucleic acid; EROD = ethoxyresorufin-*O*-demethylase; γH2AX = phosphorylated histone; HepG2 = hepatoblastoma cell line; MCF-7 BUS = Human invasive ductal carcinoma cell line; MTS = 3-(4,5-dimethylthiazol-2-yl)-5-(3-carboxymethoxyphenyl)-2-(4-sulfophenyl)-2H-tetrazolium; MTT = 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl-2H-tetrazolium bromide; NF-κB = nuclear factor binding to the κ-light-chain-enhancer B site; NIH/3 T3 = mouse embryonic fibroblast cell line; nrf-2 = nuclear factor erythroid 2–related factor 2; OTM = Olive tail moment; PCR = polymerised chain reaction; ROS = reactive oxygen species.

contaminated by percolating leachate and the deposition of fugitive dusts and waste. However, relative to aquatic biota, there have been few studies that have examined toxicity to soil biota, and the range of organisms considered has been limited (including over the past five years). Similar tests and end points noted above for aquatic organisms have been employed with terrestrial plants exposed to dilutions of raw landfill leachate, with a reduction in germination, growth inhibition, and genotoxicity reported (Anand and Palani, 2022; Szymańska-Pulikowska and Wdowczyk, 2021). Regarding invertebrates, most studies in the terrestrial setting have focussed on the impacts of leachate on earthworms. Here, leachate-amended soils result in the bioaccumulation of various toxins (and the consequent use of worms as biomonitors) and lead to adverse effects that include fluid leakage, loss of habitat, alteration of reproductive potential (by decreasing the production of juveniles and cocoons), modulation of antioxidant response and various cyto-genotoxic effects (da Silva et al., 2022; He et al., 2018; Sales Junior et al., 2021a, 2021b; Singh et al., 2018).

About 250 avian species have been observed utilising landfills and their corresponding environments (including wastewater treatment facilities) for foraging and reposing. In this context, they face potential exposure to a range of waste-related chemicals and debris and have the potential to transfer ingested pollutants to other environments through

Table 2

Studies of the toxicopathological impacts of and chemical bioaccumulation from landfill leachate performed *ex situ*. Studies are shown in reverse chronological order and landfills are municipal or sanitary unless otherwise stated.

Landfill location (type)	Samples	Species studied	Test type	Effects	Reference
Ojokoro, Nigeria	Wild black rats	*Rattus rattus*	Haematological, histological, and reproductive toxicity	Teratozoospermia significantly impacts haematological parameters and causes abnormal erythrocytes, somatic and germ cell mutations, and tissue damage.	Alimba et al. (2021)
Ciudad Real, Spain	White stork nestlings	*Ciconia ciconia*	Body condition, blood parameters, oxidative stress balance, and the presence of pathogens	Improved nutrition, body condition, and varied antioxidant response, higher metHb levels, and *E. coli* resistance in landfill-fed stork nestlings	Pineda-Pampliega et al. (2021)
Vientiane, Laos	Samples from wastewater or leachate area	*Ipomoea aquatica*	Bioaccumulation assay	Accumulation of Cr, Pb, Cu, and Zn	Vongdala et al. (2019)
Anjanta and Karmo, Abuja, Nigeria	Food samples collected from near landfill site animals	Chicken eggs	Bioaccumulation assay	$\sum_7$ PBDEs: 262.3 to 313.4 (ng g^{-1} lw)	Oloruntoba et al. (2019)
		Cow milk		Median PBDE level: 49.1 and 81.5 (ng g^{-1} lw)	
Harrison, Arizona, US (closed)	Plants collected from landfill leachate	*Pennisetum ciliare*	Bioaccumulation assay	Lower bioaccumulation of metal	Hard et al. (2019)
		Baccharis sarothroides		BAFs: 1.4 and 1.7 for Zn and Se	
		Salsola tragus		BAFs: 1.6, 2.0, 2.9, and 1.7 for Zn, Se, Cd, and Sn	
		Larrea tridentata		Lower bioaccumulation of metal	
		Tamarix ramosissima			
		Atriplex canescens		BAFs: 1.3, 2.4, 1.3, and 1.1 for Zn, Se, Cd, and Sn	

BAF = bioaccumulation factor; lw = lipid weight; metHb = methemoglobinemia; PBDEs = polybrominated diphenyl ethers.

their droppings, regurgitated pellets and remains (López-Calderón et al., 2023; Herrero-Villar et al., 2023). Plastics have been consumed by gulls at landfill sites in Portugal (Lopes et al., 2021), with ingested material having the potential to block intestines, reduce nutrient uptake, increase susceptibility to infections and disrupt metabolic processes (Wang et al., 2021b). Among the pollutants studied, flame retardants are of greatest concern (Tongue et al., 2019). The bioaccumulation of these chemicals, including many toxic brominated compounds that have been restricted, such as hexabromocyclododecane and polybrominated diphenyl ethers, has been documented in the tissues and eggs of wading birds, gulls and raptors from Europe, Asia and North America that spend time within or in the vicinity of landfill sites (Abbasi et al., 2019; Blanco et al., 2018; Gewurtz et al., 2018; Verreault et al., 2018). The exposure to flame retardants raises significant concerns about the chronic effects on bird populations and their overall health and reproductive success. Further research and conservation efforts are necessary to mitigate the risks posed by landfill sites to avian communities.

5. Ecological risk characterisation

Risk assessment is still an emerging and rapidly evolving field of study, both in terms of its application to environmental challenges as a formalised analytical process and as a quantitative tool for policymakers to help regulators make decisions. Environmental legislation has also begun to impose risk analysis as a technique for complying with legal obligations related to waste hazards (Butt et al., 2014). Predicting the ecological risk linked to landfill locations requires understanding the potential hazards posed by (mainly) leachate when it enters the environment beyond laboratory conditions. Risk considers various factors, including toxicity values derived from laboratory studies, potential pathways through which the leachate can reach the environment and the vulnerability of different ecosystems or habitats.

The risk assessment guideline published by the European Commission (EC) defines risk quotients (RQs) as the relationship between the measured environmental concentration (MEC) or predicted environmental concentration (PEC) and the predicted no-effect concentration (PNEC) (Downs et al., 2022; European Commission, 2003; Gautam et al., 2022).

$$RQ = \frac{MEC \text{ or } PEC}{PNEC}$$

with the following classifications: $RQ \geq 1$ = risk potential "high"; $0.1 \leq RQ < 1$ = level of risk considered "medium"; $RQ < 0.1$ = risk "low" or "negligible".

In a recent review paper, the acute toxicity risk was analysed for various emerging organic pollutants, including PPCPs, BPA, phthalates and various flame retardants, in treated landfill leachate in China (Qi et al., 2019). Calculated RQ values were highly variable for different types of organisms (algae <0.1–142,300; invertebrates <0.1–39.80; fish <0.1–761,500). RQs were also calculated for raw leachate from six sites in China for ten targeted organophosphate flame-retardants (OPFRs) at three trophic levels (green algae, daphnia and fish) (Qi et al., 2019). Although an estimated annual emission of between 170 and 7094 g of OPFRs into the aquatic environment from municipal landfills across China is reported, the majority of OPFRs, except for tris (2-chloroethyl) phosphate (considered of medium to high risk) and tributyl phosphate (medium risk), were determined to have a negligible impact. For raw leachates collected in northern Greece, the most significant RQ values were calculated for BPA in fish (RQ = 49,367) and nicotine in daphnids (RQ = 10,983). In contrast, RQ values exceeding 100 were found for five additional compounds, including 2OH-BTH, sucralose, saccharine, fluometuron and lincomycin (Nika et al., 2020). In an inactive landfill site located in Brazil, Junior et al. (2023) identified elevated risks across all specified scenarios for both aquatic (Risk Quotient, RQ = 375–909) and terrestrial (RQ > 140,000) environments.

Assessing risk to terrestrial biota is critical if leachate is to be used to irrigate agricultural land. For instance, a harmless leachate concentration limit of 5.87 % was determined in a phytotoxicity assessment involving the germination of triticale seeds (*Triticum* sp.) that corresponded to a PEC for soil equivalent to 117,400 L ha^{-1} (Cretescu et al., 2013). A strategy recommended by Singh et al. (2017) suggested applying 450 mL of leachate to pots with 6.0 kg of soil (equivalent to a PEC for soil of 150,000 L ha^{-1}) in order to optimise the growth of wheat (*Triticum aestivum*). Using the PEC values from these studies, Sales Junior et al. (2021a) estimated RQ values for these application rates of 3354 and 4286, respectively, using a PNEC value for the soil of 0.0175 mL kg^{-1} for the earthworm, *Eisenia Andrei,* and a 35 L ha^{-1} application. As a more general safety limit, landfill leachate application rates of 685 L ha^{-1} day^{-1} applied to soils over ten years were suggested by Jones et al. (2006). Based on this advice, however, one day of leachate results in an RQ of 20, underscoring the importance of recognising highly affected taxonomic species in the context of environmental risk assessments.

6. Mitigation policies

Policies and practices directly or indirectly related to the following four strategies are required to mitigate the risk associated with landfills.

1. *Modern landfill technologies:* Lining the landfill with impermeable materials or treating leachate (electrochemically or *via* ozonation, fenton oxidation, membrane filtration, reverse osmosis or coagulation) can reduce the leakage of hazardous materials into soil and surface and groundwater, potentially removing harmful pollutants from the leachate (Kumar et al., 2023; Naveen et al., 2017; Rubinos and Spagnoli, 2018). However, some technologies, such as membrane separation and advanced oxidation processes, have the potential to generate more concentrated streams and residues that require assessment for toxicity (Ganiyu et al., 2015).
2. *Covering and sealing landfills properly:* The landfill can be covered and sealed to minimise or control the airborne discharge of toxins, hazardous gases and dust (Nanda and Berruti, 2021; Ozbay et al., 2021). Once capped, land can be reclaimed with an amenity value (Cahill and Plant, 2011).
3. *Alternative use or disposal of waste:* By reducing the volume of waste through compositing, recycling and energy recovery, or by more efficiently removing waste that generates hazardous chemicals, the more general risks associated with landfills can be decreased (Nanda and Berruti, 2021; Weng et al., 2015).
4. *Education and public awareness:* Reducing the amount of landfill waste generated by lifestyle changes and reuse and recycling of materials, as above, in addition to the hazards and environmental impacts of landfill disposal, can be achieved by educating the general public (Debrah et al., 2021).

Of course, the success of these mitigation efforts relies on local, national, and international rules, policies, and practices and their enforcement. In the European Union Directive 2018/850 of the European Parliament and the Council amending Directive 1999/31/EC, some guidelines must be followed for effective landfill management. The measures comprise (a) the restriction of landfilling for all recyclable or recoverable waste from 2030 onwards, (b) the target of reducing the proportion of municipal waste sent to landfills to 10 % by 2035, (c) the establishment of a robust quality control and traceability system for landfilled municipal waste, and (d) the mandate for the European Commission to cooperate with the European Environment Agency.

Countries like Sweden, Germany, Canada and Japan have achieved outstanding results regarding resource utilisation and solid waste management. However, India has a very low waste processing and recycling rate, an issue exacerbated by improper disposal practices. In 2016, India introduced the MSW Management Rules, Guidelines and Legislation (Ministry of Environment and C.C, 2016). This encompasses crucial government departments tasked with efficient management of MSW and landfills, which include the Ministry of Environment, Forest and Climate Change (responsible for overseeing the nationwide enforcement of MSW regulations), the Ministry of Urban Development (collaborating with State Governments and Union Territory Administrations), the Ministry of Chemicals and Fertilizers (offering support for market development of urban compost), the Ministry of New and Renewable Energy (promoting the establishment of waste-to-energy plant infrastructure) and the Ministry of Agriculture (supervising testing laboratories for compost quality and advocating its application in agriculture).

Critically, and at the international level, the problem of waste disposal and its impacts is often shifted from higher- to lower-income countries through transboundary shipments. For example, countries such as the United Kingdom, Canada, the United States, Australia, the Netherlands and Germany have exported large quantities of e-waste, a source of many harmful metals and organic chemicals (including brominated flame retardants), to several Asian and west African nations (notably China, India, Ghana and Nigeria; Patil and Ramakrishna, 2020; Sthiannopkao and Wong, 2013). However, current or forthcoming e-waste regulations in numerous nations, combined with the concept of Extended Producer Responsibility (EPR), are designed to minimise or eliminate the exportation and importation of such waste (Patil and Ramakrishna, 2020; Thakur and Kumar, 2022).

7. Role of artificial intelligence (AI) in landfill risk management

Recently, artificial intelligence (AI), including machine learning (ML), has been playing a crucial role in the evaluation of hazards and risks against environmental pollutants (Krishnan et al., 2023). Several AI techniques that are frequently employed in contaminated soil and leachate management are molecular dynamics simulation (MDS), quantitative structure-activity relationship (QSAR) models and adverse outcome pathways (AOPs) (Pandit et al., 2022; Pandit et al., 2021; Stuart et al., 2012). ML-based approaches include gradient boosting regression trees (GBRT), decision trees (DTs), random forests (RFs), support vector machines (SVMs), artificial neural networks (ANNs), deep learning (DL), genetic algorithms (GAs), density functional theory (DFT) and computational fluid dynamics (CFD) (Gautam et al., 2023b; Ihsanullah et al., 2022; Qambar and Al Khalidy, 2022; Vyas et al., 2023) (Fig. 2).

Since these approaches afford a wide range of options for evaluating the risks associated with chemical exposure, they are beneficial tools for assessing indirect exposure. For example, QSAR models are essential for predicting the behaviour and fate of pollutants in cases where landfill waste is at risk of producing highly contaminated soil and leachate (Stuart et al., 2012), thereby helping to identify toxicological properties and potential impacts on surrounding ecosystems and water bodies. Researchers are now focusing on generating descriptors using various

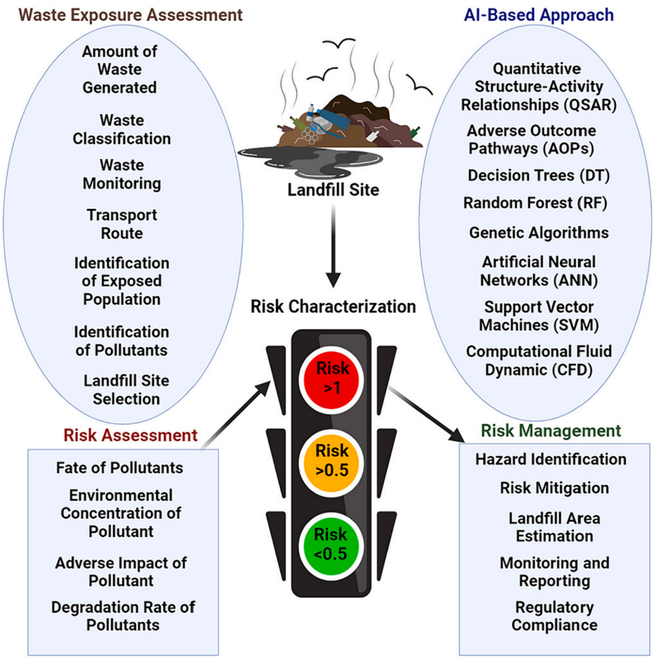

Fig. 2. The roles of artificial intelligence (AI) involved in the characterisation, risk assessment and management of landfill waste.

methods in QSAR technology to develop more accurate three-dimensional models for understanding chemical characteristics. A recent trend involves generating numerous descriptors (up to a hundred), leading to data complexity. To tackle this, dimensionality reduction techniques, like Mahalanobis distance, Canberra distance, partial least square regression and principal component analysis, are used to select the essential features (Santos et al., 2015; Tang et al., 2014).

Recent research has also emphasised the importance of understanding the mechanisms of action of chemicals in landfill sites, given their vast diversity and complexity (Ravichandran et al., 2022). This understanding is crucial for addressing potential threats and developing alternative management approaches (Gupta et al., 2015). However, there is a shortage of available AOPs for identifying hazards related to municipal waste. To bridge this gap, Pandit et al. (2021) focused on benzene and its derivatives as significant model constituents of chemicals in municipal waste, presenting a framework for understanding their mode of action using AOPs. Subsequently, Pandit et al. (2022) demonstrated the applicability of MDS to assess the risk associated with landfill sites by considering bisphenols and quinone metabolites found in waste (Watanabe et al., 2012).

Currently, the municipal waste sector utilises ML techniques extensively to sort waste, forecast emissions and understand movement within landfills. Table 3 presents a summary of the ML techniques used to investigate landfill waste sites for risk assessment and risk management. GBRT is a machine learning technique that combines the power of DT and boosting to create a robust predictive model and can predict various outcomes related to landfill management, such as the rates of waste decomposition, production of methane or leachate generation (Liu et al., 2022; Xia et al., 2022). DTs are preferred for their profound insights (Reichel and Haarstrick, 2008; Soroudi et al., 2018), while RFs at pattern generation (Malmir and Tojo, 2016; Rosecký et al., 2021) and have been effectively utilised to investigate the spatial distribution of metals in MSW (Ji and Pei, 2019; Luo et al., 2019). ANN is valuable for studying odour emissions, waste status and energy generation (Xu et al., 2022), SVM is used to predict gas heating values and segregate mixed waste at dumping sites (Abbasi et al., 2014; Qambar and Al Khalidy, 2022) and has proven highly impactful with an accuracy of about 90 % (Hanbal et al., 2020), and GAs aid in chemical transportation and waste management network modelling (Njoku et al., 2019; Yousefloo and Babazadeh, 2020; Zhang et al., 2022b). DFT is a highly effective technique for understanding atomic-scale properties and assessing the toxicity of chemical compounds through their interaction with biological molecules and has been successfully used to study chemicals like chlorophenols and benzene derivatives in municipal waste, providing valuable insights into their ecotoxicity (Giri et al., 2012; Padmanabhan et al., 2006).

Similarly, DFT has been utilised to explore the harmful effects of polychlorinated biphenyls and dibenzofurans (Sarkar et al., 2006). By contrast, CFD is a versatile approach for studying gas and liquid flow in various objects or systems and has been particularly useful in understanding gaseous flow inside landfill sites and its interaction with other chemicals (Gollapalli and Kota, 2018). CFD simulations can also be applied to study the biochemical processes in landfills, such as biodegradability, biomass generation, and heat consumption/release (Padmanabhan et al., 2006).

Overall, these AI techniques are extremely useful for environmentalists, toxicologists, policymakers and stakeholders involved in the study, management and mitigation of contaminated soil and leachate. As such, they offer multiple benefits regarding the overall risk assessment and management of municipal waste.

8. Summary and areas for future research

Globally, landfills remain one of the most popular approaches to waste management, but further research, greater awareness and better education are required to address several challenges. Ultimately, research and investment are required to reduce the waste generated at source and disposal by alternative means, or at least in well-managed and adequately lined landfill sites. A general reduction in the volume of waste is desirable from a sustainability point of view but also requires less land use, with greater space than available for other activities like farming, urban development or conservation. Waste reduction solutions include using more sustainable materials, greater reutilisation and recycling of waste, and implementation of more efficient and robust collection, compaction and sorting practices. Recent research has also investigated the feasibility of biodegradation of landfill waste and the

Table 3

Machine learning (ML) models employed for the risk assessment (RA) and risk management (RM) of landfill sites.

ML models	RA/ RM	Major applications	References
DT	RA	Human health effects of landfill soil gases	Sabrin et al. (2020)
	RM	Safe management of landfill sites Landfill site selection	Abujayyab et al. (2016); Alanbari et al. (2014)
GBRT	RA	Predicting patterns of waste generation, NO_x emission, BOD demand	Ding et al. (2023); Johnson et al. (2017); Qambar and Al Khalidy (2022)
	RM	Projecting variability in waste quantity and quality Waste composition and recovery values as energy carriers or nutrient substituents	Adeogba et al. (2019)
RF	RA	Distribution of metals in landfill waste, BOD in municipal wastewater	Hu and Cheng (2013)
	RM	Intelligent waste management system	Uganya et al. (2022)
KNN	RA and RM	Municipal waste generation	Adedeji and Wang (2019)
ANN	RA	Odour emission rates, detection of waste status, waste classification	
	RM	Energy generation from landfill waste sites Prediction of response parameters (applicable to all ML methods)	Xia et al. (2022)
SVM	RA	Gas heating inside incineration at landfill sites Prediction of municipal waste generation Classification of waste	
	RM	Solid waste generation and classification. Forecasting frequency of garbage collection	Abbasi et al., 2013; Adedeji and Wang, 2019; Shahab and Anjum, 2022
DL	RA	Predictions based on remote sensing images	Shahab and Anjum (2022)
	RM	Waste classification, monitoring, and collection.	Wang et al. (2021a)
GA	RA	Assessment of transportation of chemicals inside landfill sites Gaseous release from landfill sites Identification of exposed population Prediction of MSW decomposition Optimisation of waste collection routes	Ozmen et al. (2020); Reichel and Haarstrick (2008)
	RM	Setting of garbage points and selection of collection routes	Zhang et al. (2022a)

DT = decision tree); GBRT = gradient boosting regression trees; RF = random forest; KNN = K-nearest neighbour; ANN = artificial neural network; SVM = support vector machine; DL = deep learning; GA = genetic algorithm).

variables that promote it to reduce volumes *in situ* (Li et al., 2022; Duodu et al., 2022). Regarding sorting, a particular problem relates to segregating potentially hazardous materials, and the global reduction or elimination of (transboundary) waste exportation is critical.

Leachate acts as a vehicle for environmental contamination of a plethora of emerging and legacy chemicals and materials (Fig. 1). Recent research has targeted various leachate treatments (biological, chemical and recirculation), but combining multiple treatment types might be optimal (Mohanty et al., 2023). At present, however, the environmental concentrations and pathways of many persistent chemicals, including certain brominated flame retardants, PPCPs, PFAs and alkylphenol ethoxylates, are poorly understood, as are their toxicities to aquatic and terrestrial biota and short-term and long-term impacts on human health. From a risk assessment perspective, there are uncertainties in extrapolating laboratory results to field scenarios and considering multiple leachate toxicants in combination rather than in isolation. These concerns are especially significant in developing nations where regulations dealing with the disposal and management of waste are often lacking, and resources and technology to deal with waste are generally limited.

Landfills also produce significant quantities of dusts and greenhouse (mainly methane) and hazardous gases, which pose a risk to human and biota health and global climate. Climate change itself is believed to be responsible for the collapse of many coastal landfill sites and the emission of significant quantities of untreated wastes into the aquatic environment (Nicholls et al., 2021). Studies have explored various methods for capturing and utilising landfill gas, including gas-to-energy systems and gas as a fuel for vehicles (Winslow et al., 2019). However, these novel techniques are not yet practical at an industrial scale. Machine learning has enormous potential for improving landfill management of leachate and gas emissions and responding to potential (*e.g.*, leakage) events. However, addressing the shortcomings of data collection, model accuracy, model interpretability, real-time monitoring and understanding environmental impact will be critical for realising this potential.

Overall, it is clear that a multifaceted strategy is required to address these challenges, which includes more sustainable product design, better waste management procedures, greater investments in cutting-edge research and technology, improved public education and awareness, and stricter and more enforceable national and international rules and regulations.

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CRediT authorship contribution statement

Krishna Gautam: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Namrata Pandey:** Visualization, Methodology, Investigation, Data curation. **Dhvani Yadav:** Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Ramakrishnan Parthasarathi:** Writing – review & editing, Supervision, Software, Methodology, Formal analysis, Data curation. **Andrew Turner:** Writing – review & editing, Validation, Methodology, Formal analysis, Conceptualization. **Sadasivam Anbumani:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Formal analysis, Conceptualization. **Awadhesh N. Jha:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.171804.

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