



A Review on the Fate of Emerging Contaminants in Landfill Leachate: Insights from Conventional Treatment Approaches

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Abstract Landfill leachate is a dark-colored, complex liquid formed by the percolation of water through municipal solid waste, containing diverse array of emerging contaminants. Reported concentrations include pharmaceuticals such as ibuprofen (2–1,500 µg/L) and carbamazepine (up to 800 µg/L), personal care products like triclosan (50–3,200 µg/L), pesticides (50–1,200 µg/L), phthalates such as Di(2-ethylhexyl) phthalate (up to 5.3 mg/L), polycyclic aromatic hydrocarbons (20–600 µg/L), polychlorinated biphenyls (0.1–50 µg/L), per- and polyfluoroalkyl substances (up to 6,200 ng/L), microplastics (10^2 – 10^4 particles/L), and endocrine disruptors such as bisphenol A (0.5–1,800 µg/L). These contaminants persist in the environment, resist natural degradation,

and thereby posing significant ecological and health risks. The conventional biological treatments, including activated sludge and anaerobic digestion, achieve only partial removal (20–60% for pharmaceuticals; <30% for per- and polyfluoroalkyl substances). Physico-chemical processes such as coagulation-flocculation, advanced oxidation, and membrane filtration provide higher removal rates (60–95%) but remain energy-intensive, costly, and prone to secondary pollution. There is no single treatment that ensures complete elimination, underscoring the inadequacy of traditional methods. Recent advances, including hybrid membrane bioreactors, advanced oxidation processes, and bioelectrochemical technologies, achieve more than 90% removal of selected contaminants. The

Highlights

- Conventional treatments only partially remove emerging contaminants (ECs) in leachate.
- EC removal depends on physicochemical properties and applied treatment process.
- Fate of ECs includes adsorption, partial biodegradation, and environmental persistence.
- Hybrid and integrated treatments achieve higher EC removal than standalone methods.
- Treatment limitations indicate the need for optimized hybrid systems and monitoring.

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study focuses on the occurrence and fate of emerging contaminants in landfill leachate, evaluates the performance of existing treatment technologies, and compares regulatory frameworks across different countries. The insights aim to guide the development of sustainable and integrated strategies for effective leachate management.

Keywords Emerging Contaminants · Endocrine disruptors · Microplastics · Phthalates · Policy framework · Polycyclic aromatic hydrocarbons

Abbreviations

AC	Activated Carbon
AFs	Anaerobic Filters
ARGs	Antibiotic Resistance Genes
ASP	Activated Sludge Process
BOD	Biological Oxygen Demand
CECs	Contaminants of Emerging Concern
CPCB	Central Pollution Control Board (India)
DBP	Dibutyl Phthalate
DDT	Dichlorodiphenyltrichloroethane
DEHP	Di(2-ethylhexyl) Phthalate
DEP	Diethyl Phthalate
DIBP	Diisobutyl Phthalate
DMP	Dimethyl Phthalate
DO	Dissolved Oxygen
ECs	Emerging Contaminants
GC	Gas Chromatography
HCH	Hexachlorocyclohexane
HMBR	Hybrid Membrane Bioreactor
HRMS	High-Resolution Mass Spectrometry
IARC	International Agency for Research on Cancer
LC	Liquid Chromatography
LL	Landfill Leachate
MAP	Magnesium-Ammonium-Phosphate
MBBR	Moving Bed Biofilm Reactor
MPs	Microplastics
MS	Mass Spectrometry
MS/MS	Tandem Mass Spectrometry
MSW	Municipal Solid Waste
NH ₃ -N	Ammoniacal Nitrogen
NH ₄ -N	Ammonium Nitrogen
NMR	Nuclear Magnetic Resonance
NPs	Nanoparticles
OCPs	Organochlorine Pesticides
PAEs	Phthalate Esters
PAHs	Polycyclic Aromatic Hydrocarbons

PCBs	Polychlorinated Biphenyls
PFAS	Per- and Polyfluoroalkyl Substances
PFOA	Perfluorooctanoic Acid
PFOS	Perfluorooctanesulfonic Acid
POPs	Persistent Organic Pollutants
PPCPs	Pharmaceuticals and Personal Care Products
RO	Reverse Osmosis
SBR	Sequencing Batch Reactor
STPs	Sewage Treatment Plants
TF	Trickling Filter
TN	Total Nitrogen
UASB	Upflow Anaerobic Sludge Blanket
USEPA	United States Environmental Protection Agency
WHO	World Health Organization

1 Introduction

Rapid urbanization, population growth, and industrialization generate vast quantities of diverse waste materials, much of which ultimately accumulate in landfills (Sabba et al., 2025; Saha & Handique, 2023). Within these landfills, heterogeneous wastes undergo complex biological, physical, and chemical transformations, producing landfill leachate (LL) (Yuksekdag et al., 2023). The formation of LL occurs through the percolation of rainwater, the release of intrinsic moisture from waste, and the physicochemical degradation of organic and inorganic constituents (Prajapati et al., 2023). LL typically exhibits high concentrations of organic matter, ammonia, alkalinity, heavy metals, and xenobiotic organic compounds (Karagozoglu & Asar, 2023). It also serves as a significant reservoir of emerging contaminants (ECs), including phthalates, pharmaceuticals and personal care products (PPCPs), pesticides, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), per- and polyfluoroalkyl substances (PFAS) and microplastics (MPs), thereby increasing the contaminant load in influents entering treatment facilities (Surampalli et al., 2023). The persistence, bioaccumulation potential, and ecological and human health risks associated with these contaminants have drawn increasing scientific attention in recent years. Although modern landfills are engineered to minimize environmental damage (Vaish et al., 2019), the generation of EC-enriched leachate remains unavoidable. Untreated or insufficiently

treated LL contaminates nearby aquatic environments, leading to the deterioration of surface and groundwater quality and posing substantial risks to both human and animal health (Khatrī & Tyagi, 2015).

Conventional leachate treatment methods encompass physico-chemical processes such as precipitation, flotation, coagulation-flocculation, adsorption, oxidation, and air stripping, along with biological processes including sequencing batch reactors (SBR), activated sludge process (ASP), moving bed bio-film reactors (MBBR), upflow anaerobic sludge blanket (UASB), and trickling filters (TF) (Bhambore & Suresh Kumar, 2022). These methods generally achieve partial contaminant removal but fail to completely mineralize complex pollutants. Their long-term application is further constrained by high operational costs, continuous chemical and energy requirements, and poor removal efficiency when treating high-strength leachate (Prajapati et al., 2025). Researchers are developing integrated treatment strategies that combine multiple technologies to overcome these limitations and effectively manage ECs in landfill leachate (Rout et al., 2021). The present study reviews the composition and characteristics of LL, evaluate the performance and limitations of conventional treatment methods, and analyze the occurrence, behavior, and fate of ECs following treatment. In addition, it explores recent advancements in innovative treatment technologies, compares discharge standards across countries, and outlines relevant policy frameworks. Future perspectives and research priorities are also identified to support the development of sustainable LL management strategies. Regulatory frameworks vary widely across countries, like chemical oxygen demand (COD) discharge limits ranging from 100 mg/L in the EU, whereas, it exceeds 1,000 mg/L in several developing nations. Critical gaps persist in monitoring microplastics and PFAS transformation products, long-term field performance, and enforcement of regulations. Addressing these gaps is essential to develop sustainable and integrated leachate management strategies.

2 Landfill Leachate

Landfilling remains the most widely adopted method for municipal solid waste (MSW) disposal worldwide; however, its major drawback is the generation

of LL, which poses significant risks to surrounding aquifers (Das & Raj, 2025; Pisharody et al., 2022). LL is generated through rainwater infiltration, release of intrinsic moisture, and biodegradation of waste, and is typically enriched with organic matter, salts, heavy metals, and xenobiotic compounds (Song et al., 2025; Teng et al., 2021). It primarily forms due to percolation of water through waste and subsequent chemical transfer of contaminants. Studies estimate that 0.05–0.2 tonnes of leachate are generated per 907 tonnes of MSW over the operational lifespan of a landfill (Narayan et al., 2019; Nath & Debnath, 2022).

2.1 Leachate Composition

The composition of LL is notably complex and heterogeneous; encompassing nearly 200 identified hazardous substances as reported in prior research (Hamid et al., 2018). The physicochemical characteristics of LL are influenced by multiple interrelated factors, including the landfill's age, the nature and density of the waste deposited, the stage of biodegradation, precipitation inputs, and ambient temperature conditions (Chen et al., 2025). LL typically contains dissolved organic matter including alcohols, humic and fulvic acids, and volatile fatty acids; inorganic ions including Ca^{2+} , Mg^{2+} , Fe^{2+} , Mn^{2+} , Na^+ , and K^+ ; heavy metals such as Cd, Hg, Cu, Pb, Cr, Ni, and Zn; and xenobiotic organic compounds like phenols, pesticides, and chlorinated or halogenated organics (Ganjian et al., 2018; Luo et al., 2020). In addition, LL is enriched with persistent organic pollutants (POPs), pharmaceuticals, pathogens, ammonia nitrogen ($\text{NH}_3\text{-N}$), cyanides, solvents, and other toxic or carcinogenic substances (Michalska et al., 2020; Yong et al., 2018). A diverse range of ECs, including phthalic acid esters (PAEs), PCBs, PAHs, PPCPs, MPs, PFAS, and steroidal compounds, has also been detected (Kumar et al., 2020; Nika et al., 2020). Even at trace concentrations ($\mu\text{g/L}$ to ng/L), these ECs exhibit toxic and bioaccumulative behavior. They disrupt aquatic organisms, ecosystems, and food webs. They also pose severe risks to human health through carcinogenicity, acutely toxicity, and genotoxic effects (Derco et al., 2021).

2.2 Characteristics of Landfill Leachate

Understanding the physicochemical properties of landfill leachate is fundamental for selecting effective

and appropriate treatment strategies. These characteristics vary with operational practices, waste type, age, climatic conditions and biodegradation stage (Remmas et al., 2018). Landfill age is particularly influential, as stabilization processes significantly alter leachate quality. Based on ageing, leachate is broadly categorized as young (<5 years), intermediate (5–10 years), and mature (> 10 years) (Luo et al., 2020). Young leachate, associated with the acidogenic phase, generally contains high organic load, volatile fatty acids, ammonia nitrogen (> 1000 mg/L), along with a low BOD₅/COD ratio (<0.1), indicating poor biodegradability. Intermediate leachate (5–10 years) typically shows a COD/TN ratio of 3–6 and retains partial biodegradability (Mousavi et al., 2015). Over time, stabilization processes gradually reduce biodegradable fraction, reflected in a reduced BOD₅/COD ratio and slightly elevated pH (Ranjan et al., 2016). Environmental conditions have a significant influence on LL; for instance, higher temperatures during summer decrease COD and DO levels due to accelerated biodegradation rate, whereas redox potential, metal concentration, total suspended solids, and volatile suspended solids remain largely unaffected (Poornima et al., 2022). The reported data (Table 1) further indicate that young tropical leachates (0.5–2 years) possess high alkalinity (3325–5015 mg/L), COD (1230–6027 mg/L), and ammonia (526–1787 mg/L), signifying intense organic degradation. In contrast, temperate landfills present wider COD ranges (164–21,137 mg/L) but generally lower biodegradability (BOD₅/COD < 0.3). Mature leachates (> 10 years) contain reduced BOD and COD yet sustain elevated ammonia levels, sometimes exceeding 3000 mg/L. Metal concentrations, including Ni, Cu, and Zn, vary across sites. Overall, tropical landfills generate stronger leachates at early stages, whereas temperate leachates evolve more gradually over time (Garbo et al., 2019; Surampalli et al., 2023).

2.3 Impacts of Landfill Leachate

MSW disposal poses critical challenges due to the large volumes of leachate generated at landfill sites. Untreated leachate rapidly infiltrate surrounding soil and groundwater, acting as a point source of contaminants with long-term ecological implications (Conte et al., 2021). It contains pesticides,

PPCPs, phthalates, and heavy metals that disrupt nervous, endocrine, and visceral functions (Deng et al., 2022). Ammonia concentrations often exceed 1000–4000 mg/L, far beyond the Central Pollution Control Board (CPCB) discharge limit of 50 mg/L and the World Health Organization (WHO) guideline of <0.5 mg/L, indicating significant nitrogen contamination requiring specialized treatment. Heavy metals including lead (up to 3.46 mg/L) and cadmium (0.1–1.2 mg/L) have been reported above WHO permissible limit for drinking water limits of 0.01 and 0.003 mg/L, respectively, posing risk of neurotoxicity and systemic toxicity. PAHs such as benzo[a]pyrene are reported at 0.2–3.5 µg/L, above the WHO limit of 0.7 µg/L. Leachate further exhibits biological toxicity, reducing earthworm reproduction by > 50%, when heavy metals exceed 1 mg/L (Deng et al., 2022; Qiu et al., 2016). Pathogenic microorganisms persist even at electrical conductivity values up to 25 mS cm⁻¹, far exceeding the CPCB permissible discharge limit of 2.25 mS cm⁻¹, thereby elevating infection risks in humans and animals (Chen et al., 2025; Dolatabadi et al., 2021). Leachate carries a high pollutant load, persistence, and biohazard risk. Therefore, landfill leachate poses a long-term risk to aquatic and terrestrial ecosystems, and its treatment requires multi-stage and integrated technologies.

3 Emerging Contaminants (ECs) in Landfill Leachate

Emerging Contaminants (ECs) include synthetic or naturally occurring substances and microbes that are not routinely monitored in the environment but may pose potential ecological and human health risks (Ali et al., 2022). The United States Environmental Protection Agency (USEPA) defines ECs as chemicals or materials that pose potential or actual environmental and health risks. These substances originate from recent sources or newly identified pathways. Currently, no established health standards exist for their regulation. Numerous ECs occur in LL, originating either as byproducts of waste degradation or through inputs from diverse waste streams (Bandala et al., 2021). ECs in LL (Table 2) include pesticides (e.g., glyphosate, atrazine), pharmaceuticals (e.g., diclofenac, ibuprofen, antibiotics, hormones), licit and illicit drugs (e.g., caffeine, cocaine, amphetamines),

Table 1 Characteristics of Landfill Leachate in reference to landfill age

Parameter	Landfill age (years) & leachate characteristics										
	Tropical region				Temperate region				Sub-tropical region		
	0.5–2	1.7–2.1	7.2–14.4	5–10	0–5	10–20	0–5	5–10	10–20	0–5	7.5–10
pH	7.80–8.50	6.2–8.3	7.3–8.4	7.34	8.44	8.0	3–6	6–7	>7.5	7.6	7.3
Colour (Pt.-Co)	-	-	-	2113	4510	-	-	-	-	-	-
EC (mS/cm)	8.9–10.8	6.77–14.59	3.9–25	-	24.9	-	15–41.5	6.0–14.0	-	14.0	71.2
Suspended solids (mg/L)	-	-	-	-	-	-	-	-	-	100	19883
Alkalinity ((mg/L)	3325–5015	-	-	-	-	-	8000–18000	4500–6000	-	123000	1900.5
BOD ₅ (mg/L)	275–453	1–7068	1–12766	285	1100	4500	10000–25000	1000–4000	50–1000	150	27300
COD (mg/L)	1230–6027	164–17440	576–21137	3018	6420	6500	15000–40000	10000–20000	1000–5000	2786	38769
BOD ₅ /COD	-	<0.006–0.3	<0.002–0.3	0.09	0.24	-	0.6–0.7	0.1–0.2	0.1–0.2	-	-
Ammonia-N (mg/L)	526–1787	21.1–1120	133–2808	49	1403	1000	1500–4250	250–700	50–200	800	2053
Total Nitrogen (mg/L)	-	-	-	-	-	1100	1500–4500	400–800	75–300	-	-
TKN (mg/L)	-	-	-	-	-	-	-	-	-	1100	2571.4
Nitrite-N (mg/L)	-	-	-	-	-	-	-	-	-	67	-
Nitrate-N (mg/L)	-	-	-	-	-	-	-	-	-	28	-
Total Phosphorous (mg/L)	3.81–7342	-	-	-	-	-	100–300	10–100	-	16.7	73.7
Nickel (mg/L)	-	-	-	29.67	0.46	-	-	-	-	-	-
Chloride (mg/L)	2499–4204	-	-	1280	-	-	1000–3000	500–2000	100–500	3200	-

Table 1 (continued)

Parameter	Landfill age (years) & leachate characteristics											
	Tropical region				Temperate region				Sub-tropical region			
	0.5–2	1.7–2.1	7.2–14.4	5–10	0–5	10–20	0–5	5–10	10–20	1.5–5	0–5	7.5–10
Copper (mg/L)	-	-	-	-	13.01	-	-	-	-	-	0.48	-
Sulphate (mg/L)	-	-	-	-	-	-	500–2000	200–1000	50–200	-	-	-
Barium (mg/L)	-	-	-	-	1.10	-	-	-	-	-	1.8	-
Total Iron (mg/L)	38–46	-	-	-	23.18	-	500–1500	500–1000	100–500	-	3	-
Lead (mg/L)	-	-	-	-	3.46	-	-	-	-	-	0.03	-
Zinc (mg/L)	0.5–13.7	-	-	-	7.51	-	100–200	50–100	10–50	-	3.7	-
Total Dissolved Solids (mg/L)	-	70–5885	310–3480	-	-	-	10,000–25000	5000–10000	2000–5000	-	-	-
Turbidity (NTU)	-	-	-	-	213	-	-	-	-	-	-	1982.6
References	Lebron et al., 2021	Mojiri et al., 2021	Yong et al., 2018	Yin et al., 2018	Lebron et al., 2021	Grosser et al., 2019	Narayan et al., 2019	Nhat et al., 2017	Pirsaheb et al., 2017			

preservatives (e.g., parabens, triclosan), personal care products (e.g., sunscreens, UV filters), surfactants, cleaning agents, and industrial chemicals (e.g., bisphenol A, chlorinated solvents, phthalates, plasticizers) (Morin-Crini et al., 2022). Other groups include polychlorinated naphthalenes (PCNs), PAHs, PCBs, dioxins, carbazoles, environmentally persistent free radicals, flame retardants, perfluorooctane sulfonate (PFOS), brominated dioxins, and pathogenic antibiotic-resistant bacteria. Additional pollutants detected in LL include alkylphenols, metalloids, radionuclides, rare earth elements, nanoparticles (NPs), MPs, and indoor pollutants. Even at trace concentrations, these contaminants can cause considerable ecological, economic, and human health impacts due to its persistence and bioaccumulative nature (Kumar et al., 2023; Nika et al., 2020). Studies have reported 17 types of MPs in LL, with concentrations ranging from 0.42 to 24.58 items/L (Singh et al., 2023), while phenolic compounds such as bisphenol A and 2,4-di-tert-butylphenol occur at levels exceeding 10 mg/L (Aziz et al., 2018). In addition, the detection of large quantities of antibiotic resistance genes identifies LL as a critical reservoir of antimicrobial resistance (Kumar et al., 2023; Teng et al., 2021). These findings establish LL as a significant source of ECs and emphasize the urgent need for effective treatment.

3.1 Identification and Classification of Emerging Contaminants

The comprehensive identification of ECs in landfill leachate relies on multiple advanced analytical strategies, including targeted analysis, non-targeted analysis, metabolomic profiling, toxicological assessments and monitoring strategies. Targeted analysis detects and quantifies known ECs using advanced techniques such as gas chromatography (GC), liquid chromatography (LC), mass spectrometry (MS), and tandem mass spectrometry (MS/MS), supported by standard reference materials and validated protocols (Hollender et al., 2017). Non-targeted analysis detects unidentified pollutants using high-resolution mass spectrometry (HRMS) combined with suspect and non-target screening, where mass spectra and fragmentation patterns are compared with databases and spectral libraries to improve identification accuracy (Menger et al., 2020). Toxicological assessments evaluate the potential risks of ECs by

determining ecotoxicity, genotoxicity, endocrine disruption, and other adverse biological effects through *vitro* and *in vivo* models including bioassays and toxicity experiments (Ghosh et al., 2017; Luo et al., 2020). Metabolomic profiling contributes further by identifying low-molecular-weight compounds and their transformation products using MS and Nuclear Magnetic Resonance (NMR) spectroscopy, thereby providing insights into contaminant dynamics within LL (Menger et al., 2020). Continuous monitoring and systematic analysis remain essential to track newly introduced contaminants arising from evolving waste streams and disposal practices. ECs are generally categorized based on chemical properties, sources, and potential impacts, although currently no such universally accepted classification system exists (Gogoi et al., 2018). A general classification of ECs into six broad categories is shown in Fig. 1 (Morin-Crini et al., 2022).

3.2 Presence and Behavior of Emerging Contaminants in Landfill Leachate

3.2.1 Pharmaceutical and Personal Care Products (PPCPs)

Pharmaceutical and Personal Care Products (PPCPs) exhibit a wide variability in their concentrations in landfill leachate. They are recognized as major emerging contaminants due to their persistence and ecological relevance. Studies report PPCP concentrations ranging from below detection limits (BDL) to 349 µg/L for certain compounds. Albendazole, an anthelmintic drug, often appears at levels up to 61.6 µg/L (Anand et al., 2022). Seasonal changes significantly affect these concentrations. During wet seasons, average PPCP levels rise to about 17 µg/L, compared to ~3.8 µg/L in dry periods. Seasonal variations strongly influence their levels, with higher concentrations typically observed during wet seasons due to enhanced surface runoff and leachate dilution (Reyes et al., 2021). Several studies have identified PPCPs from more than 17 therapeutic categories, including antibiotics, lipid regulators, analgesics, and antiparasitic drugs (Sui et al., 2017). Among them, erythromycin, gemfibrozil, and albendazole occur most frequently and at the highest concentrations. These compounds serve as indicator pollutants for LL contamination (Laiju et al., 2023). In untreated leachate,

Table 2 Sources, uses and toxic impacts of various persistent Emerging Contaminants (ECs) in Landfill Leachate across the Globe

EC Class	Primary Sources	Emerging Contaminants	Concentration/Range	Country	Use	Toxic Effects	References
PPCPs	Human/veterinary drugs, personal care products	Acetaminophen	42 µg/L	USA	Analgasic and antipyretic	Constipation, nausea, vomiting	Masoner et al., 2016
		Carbamazepine	0.19 µg/L	China	Anticonvulsant	Hypotension, edema, syncope, reduced cortisol levels (in fishes)	Sui et al., 2017
		Caffeine	3.36 µg/L	USA	Stimulant	Anxiety, disturbed sleep patterns, developmental toxicity (in fishes)	Masoner et al., 2016
		Diclofenac	898 µg/L	India	Anti-inflammatory	Gastrointestinal effects, embryo toxicity (in fishes)	Velpandian et al., 2018
		Diethyl toluamide	0.9–143 µg/L	USA	Insect repellent	Skin irritation (rash, itching, burning)	Clarke et al., 2015
		Gemfibrozil	0.11 µg/L	China	Lipid regulator	Vomiting, diarrhea, dyspepsia	Sui et al., 2017
		Ibuprofen	136 µg/L	India	Anti-inflammatory	Nephrotoxicity (aquatic species), nausea, vomiting, heartburn, immunosuppression	Velpandian et al., 2018
		Sulpiride	166.6 µg/L	Norway		Aggressiveness, behavioral changes	Eggen et al., 2010
		Sulfadiazine	0.12 µg/L	China	Antipsychotic	Breathing difficulty, asthma, impaired lung function	Sui et al., 2017
		Sulfamethazine	16 µg/L	China	Antibiotic	Dizziness, nausea, vomiting, headache	Sui et al., 2017
					Antibiotic	Endocrine disruption (hormonal imbalance)	Qi et al., 2018

Table 2 (continued)

EC Class	Primary Sources	Emerging Contaminants	Concentration/Range	Country	Use	Toxic Effects	References
Pesticides	Agricultural and household use	Bisphenol A	2923 µg/L	China	Monomer in plasticizers	Liver damage, nephropathy, kidney dysfunction	Qi et al., 2018
		Camphor	100–125 µg/L	Iran		Anemia (including haemolytic anemia)	Bahramifar et al., 2014
		Oxytetracycline	62.4 µg/L	USA	Fragrance & flavorant	Loss of appetite, nausea, vomiting	Masoner et al., 2016
			100.9 ± 141.81 µg/kg	China	Antibiotic	Allergic reactions (skin, respiratory, eye irritation)	Song et al., 2016
		Tetracycline	63.8 ± 37.7 µg/kg	China	Antibiotic	Fever, tiredness, nausea, vomiting	Song et al., 2016
		Triclosan	1.6–64 µg/L	USA	Antifungal & antibacterial	Neurotoxicity, carcinogenic effects, immunotoxicity	Masoner et al., 2014
		Pentobarbital	8–32 µg/L	USA	sedative	Blurred vision, abdominal pain	Masoner et al., 2014
		Organochlorine	0.03–0.20 µg/L	China	Control of weeds, termites, insects	Throat and nose irritation, lung irritation	Qi et al., 2018
		Endrin aldehyde	3–63 µg/L	Oman	Control insects & rodents	Reproductive toxicity (testicular dysgenesis, reduced fertility, developmental effects)	Raisi, 2022
		Atrazine	0.10–0.16 µg/L	Denmark	Control of broadleaf & grassy weeds	Genotoxicity (in fishes and lab animals)	Baun et al., 2004
		Carbaryl	0.3–12 µg/L	USA	Control aphids, fire ants, ticks, spider	Tumor formation (testicular, liver, thyroid cancers)	Masoner et al., 2014
		Bentazon	0.3–0.4 µg/L	Denmark	Control weed	Obesity, oxidative stress (altered antioxidant enzyme activity)	Kjeldsen et al., 2002

Table 2 (continued)

EC Class	Primary Sources	Emerging Contaminants	Concentration/Range	Country	Use	Toxic Effects	References
PAHs	Combustion residues, industrial waste	Acenaphthylene	58.47 µg/L	Turkey	Dye synthesis, insecticides, fungicides	Constipation, nausea, vomiting	Ates & Argun, 2018
			<0.01–0.09 µg/L	Sweden		<i>Hypotension, edema, syncope, reduced cortisol levels (in fishes)</i>	Kalmykova et al., 2013
			0.595 µg/L	China		<i>Anxiety, disturbed sleep patterns, developmental toxicity (in fishes)</i>	Yiping et al., 2008
			0.0029 µg/L	France		Gastrointestinal effects, embryo toxicity (in fishes)	Oturan et al., 2015
			25.40 µg/L	Turkey	Chemical intermediate in naphthalimide dye	Skin irritation (rash, itching, burning)	Ates & Argun, 2018
Naphthalene			1.0 µg/L	Kenya		Vomiting, diarrhea, dyspepsia	Shitandayi et al., 2019
			0.06 µg/L	Kenya	Ingredient in moth repellent, resin and dye manufacturing process	Nephrotoxicity (aquatic species), nausea, vomiting, heartburn, immune suppression	Shitandayi et al., 2019
			0.02–3.8 µg/L	Sweden		Aggressiveness, behavioral changes	Kalmykova et al., 2013
			9.6 µg/L	Thailand		<i>Breathing difficulty, asthma, impaired lung function</i>	Boonyaroj et al., 2012
			0.6–114.7 µg/L	Denmark		Dizziness, nausea, vomiting, headache	Baun et al., 2004
Benzo(a)pyrene			1.272 µg/L	France		Endocrine disruption (hormonal imbalance)	Oturan et al., 2015
			0.051 µg/L	France	As a laboratory reagent in various studies	Liver damage, nephropathy, kidney dysfunction	Oturan et al., 2015

Table 2 (continued)

EC Class	Primary Sources	Emerging Contaminants	Concentration/Range	Country	Use	Toxic Effects	References
		Fluoranthene	0.125 µg/L	France	Ingredients in dyes, pharmaceuticals, and insulation oils	Anemia (including haemolytic anemia)	Oturan et al., 2015
		Fluorene	1.1 µg/L	Sweden	Production of dyes, pesticides, and plastics	Loss of appetite, nausea, vomiting	Kalmykova et al., 2013
			0.206 µg/L	France		Allergic reactions (skin, respiratory, eye irritation)	Oturan et al., 2015
		Anthracene	16.93 µg/L	Turkey		Fever, tiredness, nausea, vomiting	Ates & Argun, 2018
			9.8 µg/L	Thailand	Production of dyes, pesticides, and plastics	Neurotoxicity, carcinogenic effects, immunotoxicity	Boonyaraj et al., 2012
		Phenanthrene	<40 µg/L	Central Oklahoma	Production of dyes, drugs, pesticides, plastics, and explosives	Blurred vision, abdominal pain	Andrews et al., 2012
		Pyrene	13.54 µg/L	Turkey	Production of dyes, pesticides, and plastics	Throat and nose irritation, lung irritation	Ates & Argun, 2018
		Chrysene	<0.01–0.38 µg/L	Sweden	Ingredients in wood preservatives	Reproductive toxicity (testicular dysgenesis, reduced fertility, developmental effects)	Kalmykova et al., 2013

Table 2 (continued)

EC Class	Primary Sources	Emerging Contaminants	Concentration/Range	Country	Use	Toxic Effects	References
Phthalates	Plastics, cosmetics, inks, adhesives	Diethyl phthalate (DEP)	<0.10–22 µg/L	Sweden	A solvent for cosmetics and fragrances	Genotoxicity (in fishes and lab animals)	Kalmykova et al., 2013
		Dimethyl phthalate (DMP)	2.46–24.6 µg/L	Poland	Ingredients in insect repellants, moulding powders, lacquers, solid rocket propellants	Tumor formation (testicular, liver, thyroid cancers)	Kotowska et al., 2020
		Di(2-ethylhexyl) phthalate (DEHP)	<LOD–249 µg/L	Poland	Furnishing, construction materials, PVC medical devices, raincoats, toys	Obesity, oxidative stress (altered antioxidant enzyme activity)	Kotowska et al., 2020
PCBs	Electrical equipment, paints, lubricants	Di-n-butyl phthalate (DBP)	384 µg/L	Thailand	Dyes, cellulose plastics, latex adhesives, nail products	Constipation, nausea, vomiting	Boonnorat et al., 2014
		Polychlorinated biphenyls	500–1400 µg/L	Oman	Coolants and lubricants in transformers, capacitors, and other electrical equipment	Hypotension, edema, syncope, reduced cortisol levels (in fishes)	Raisi, 2022
PFAS	Textiles, firefighting foams, coatings	Perfluorooctanoic acid (PFOA)	10 µg/L	USA	To make fluoropolymer coatings and products that resist heat, oil, stains, grease, and water	Anxiety, disturbed sleep patterns, developmental toxicity (in fishes)	Lang et al., 2017
		Perfluorooctanesulfonic acid (PFOS)	1 µg/L	USA	Stain-resistant fabrics, fire-fighting foam, food packaging, and as a surfactant in industrial processes	Gastrointestinal effects, embryotoxicity (in fishes)	Lang et al., 2017

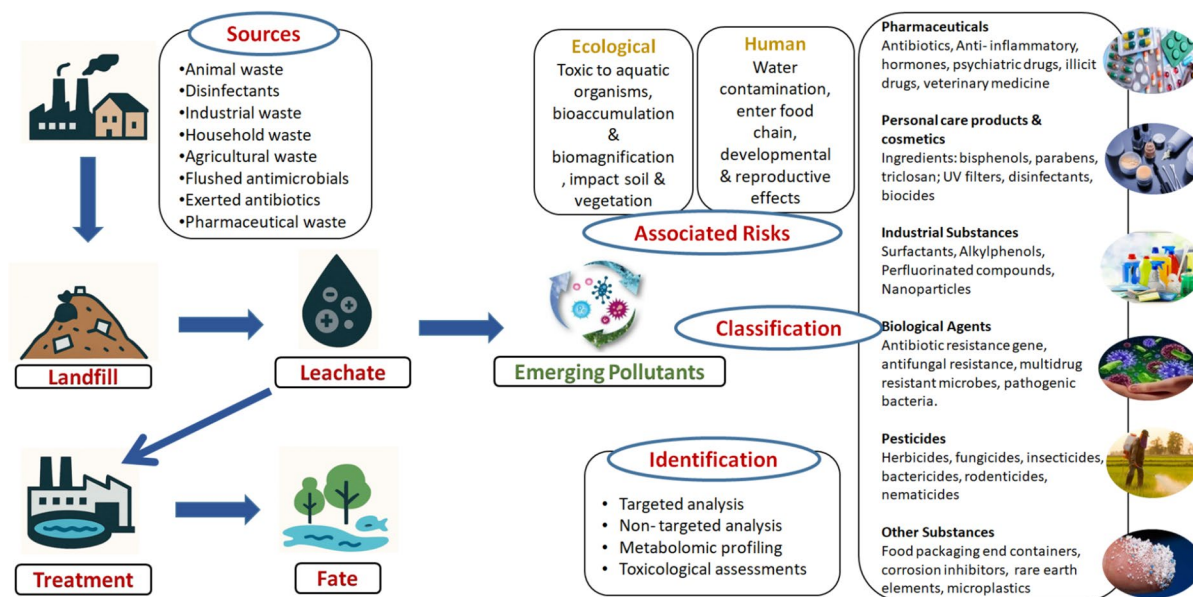


Fig. 1 Origin, detection, and potential hazards of emerging pollutants in landfill leachate

concentrations can reach up to 349 µg/L. After treatment (Yu et al., 2021), levels generally drop below 10.6 µg/L, depending on the technology used. PPCPs can also migrate from landfills into groundwater. Their concentrations decline with distance from the landfill, yet the same compound profiles persist (Lekshmi & Anand, 2024). Moreover, their low biodegradability and high polarity make PPCPs resistant to conventional treatment methods, often resulting in partial removal and environmental persistence.

3.2.2 Phthalates

Phthalates are synthetic chemicals widely used as plasticizers to enhance the flexibility, durability, and processability of plastics, particularly polyvinyl chloride. Concentrations of PAEs in LL typically range from 114 to 303 µg/L (He et al., 2019). Among these, di(2-ethylhexyl) phthalate (DEHP) is the most dominant compound, detected at concentrations up to 73.9 µg/L in some samples (Sardon & Dove, 2018). DEHP occurs in nearly 65% of analyzed leachate samples, indicating its widespread presence. Other phthalates such as diethyl phthalate (DEP), dibutyl phthalate (DBP), diisobutyl phthalate (DIBP), and dimethyl phthalate (DMP) are detected at lower levels, often below quantification limits or within

0.6–4.7 µg/L (Giuliani et al., 2020). Due to their hydrophobicity, phthalates strongly absorb to organic matter and solid particles within landfill matrices (Bandala et al., 2021). Such sorption behavior leads to prolonged persistence, allowing these compounds to remain even after site remediation or landfill closer. Their accumulation in sludge presents disposal challenges and increases the risk of secondary pollution.

3.2.3 Per and Polyfluoroalkyl Substances (PFAS)

Per and Polyfluoroalkyl Substances (PFAS) are synthetic organic compounds composed of a hydrophobic fluorinated alkyl chain and a hydrophilic functional group. This unique molecular structure, dominated by strong carbon–fluorine (C–F) bonds, makes PFAS extremely resistant to degradation in the environment (Lu et al., 2023). PFAS exposure has been associated with thyroid disorders, asthma, reduced lung function, and several cancers (Qin et al., 2017). In LL, PFAS concentrations often exceed those in other environmental matrices. Reported total PFAS levels can reach up to 93.1 µg/L, demonstrating their significant contamination potential in landfill systems. Their amphiphilic nature enhances mobility in aqueous environments and facilitates bioaccumulation in organisms. Long-chain PFAS compounds,

such as perfluorooctanoic acid (PFOA) and PFOS, are particularly bioaccumulative and toxic, posing greater environmental and health risks (Solo-Gabriele et al., 2020). PFAS exhibit high water solubility but very low biodegradability, which allows them to persist in groundwater, surface water, and soil impacted by LL (Lin et al., 2024). Their widespread detection in water, sediments, and biota confirms their global distribution and persistence. Due to their exceptional persistence, PFAS are classified as ‘forever chemicals’ and require advanced degradation technologies such as electrochemical oxidation, plasma treatment, or photocatalysis.

3.2.4 Pesticides

Pesticides continue to be produced and used on a massive scale worldwide. Global consumption is estimated at around 18 million tons annually, with the pesticide market projected to reach approximately USD 283 billion by 2025 (Wang et al., 2020). The Asia-Pacific region dominates this market, primarily due to high usage in China and India, which together account for a substantial proportion of global pesticide consumption. LL frequently contains residues of both legacy and modern pesticides (Kalliora et al., 2018). Organochlorine pesticides (OCPs) such as dichlorodiphenyl-trichloroethane (DDT) and hexachlorocyclohexane (HCH) remain detectable in LL, with DDT concentrations reported between 2.16 and 3.38 µg/L in Jordan (Raisi, 2022). In Muscat, endrin aldehyde and endosulfan sulphate occur at 0.003–0.063 mg/L and 0.011–0.016 mg/L, respectively. Other OCPs, including aldrin and dieldrin, appear at levels up to 1.1 µg/L and 0.35 µg/L (Wang et al., 2018). In addition, organophosphate pesticides such as chlorpyrifos have been detected at 0.01–5 µg/L in municipal landfill leachate. Although pesticide concentrations in LL are typically lower than those of PFAS or phthalates, but even low concentrations remain environmentally significant due to high persistence and bioaccumulation potential. These compounds can disrupt endocrine and neurological functions, causing biodiversity loss and ecosystem imbalance (Alimi et al., 2022). The presence of both banned OCPs and newly introduced synthetic pesticides in LL highlights the long-term environmental legacy of pesticide use and the urgent need for effective leachate management. Moreover, the coexistence of legacy pesticides such as

DDT and modern synthetic pesticides in LL reflects both historical contamination and ongoing agricultural dependence.

3.2.5 Polycyclic Aromatic Hydrocarbons

PAHs are organic compounds composed of two or more fused aromatic benzene rings. They are lipophilic, chemically stable, and highly persistent in the environment. Several PAHs, such as benzo[a]pyrene, are classified by the International Agency for Research on Cancer (IARC) as carcinogenic or possibly carcinogenic, raising serious public health concerns (Abdel-Shafy & Mansour, 2016). In LL, PAH concentrations vary widely depending on landfill age, waste composition, and operational conditions (Patel et al., 2020). Total PAH concentrations have been reported at 10–58 µg/L in Turkey’s Konya province and 5.81–1263 µg/L in China (Ateş & Argun, 2023; Qi et al., 2018). Common compounds such as naphthalene and phenanthrene frequently occur at concentrations ranging from 1 to over 100 µg/L, indicating their widespread presence in LL. Compared with phthalates and pesticides, PAHs often occur at higher concentrations in LL (Lin et al., 2024). Their hydrophobicity and thermal stability contribute to strong sorption to organic matter and resistance to degradation, resulting in long-term persistence (Balati et al., 2015).

3.2.6 Polychlorinated Biphenyls

PCBs are synthetic organochlorine compounds consisting of up to 209 congeners derived from anthropogenic sources such as electrical equipment, lubricants, and paints (Robey et al., 2024). These compounds are highly persistent, hydrophobic, and toxic, making them significant environmental contaminants. In LL, PCB concentrations typically range from 0.01 to 3.1 µg/L (Arp et al., 2020). Studies from China have reported PCBs concentrations in between 0.1 and 1.5 µg/L, whereas investigations in India found levels up to 2.8 µg/L. In Europe, LL from Norway contained PCB congeners in the range of 0.05–0.8 µg/L (Kaya et al., 2018). Lower-chlorinated congeners show greater mobility in the aqueous phase, while higher-chlorinated congeners strongly adsorb to organic matter and sediments, limiting their transport but increase their persistence (Sabba et al., 2025). Although PCBs

generally occur at lower concentrations than PAHs or pesticides, they pose serious ecological and health risks due to their toxicity, persistence, and bioaccumulation potential (Das & Raj, 2025). Bioaccumulation coefficients exceeding 1 have been reported in certain plant species, indicating active uptake and retention. Under anaerobic landfill conditions, PCBs can persist for months to years, undergoing slow reductive dechlorination into less chlorinated and relatively less toxic congeners (Ali et al., 2022).

3.2.7 Microplastics

MPs, defined as plastic particles smaller than 5 mm, are increasingly recognized contaminants in LL, with untreated municipal leachate in Suzhou, China, containing MPs at concentrations of 11.4 ± 0.8 $\mu\text{g/L}$ (Sun et al., 2021). Larger MPs greater than 1000 μm have also been detected in LL from Iran (Mohammadi et al., 2022). In Sweden, LL samples contained MPs at concentrations up to 15.2 $\mu\text{g/L}$, demonstrating regional variability. Globally, an estimated 5 trillion MPs, weighing roughly 243,000 tonnes, jeopardize aquatic ecosystems and pose risks to marine organisms due to their widespread environmental presence (Eriksen et al., 2014; Lin et al., 2024). MPs in LL originate both as primary particles manufactured for industrial and commercial use, and secondary particles resulting from the breakdown of larger plastics (Cheng et al., 2021). The variable physicochemical properties of LL, such as pH ranging from 4.5 to 9, accelerate transformation of MPs into hazardous byproducts, compounding their toxic effects on organisms through disruption of endocrine, cytoskeletal, and metabolic functions (Anand et al., 2021).

The behavior of ECs in LL depends on waste composition, landfill design, leachate characteristics, management practices, and environmental conditions. Their leaching potential is governed by solubility, hydrophilicity, and chemical structure. Highly soluble compounds, such as PPCPs, readily dissolve and migrate through leachate. In contrast, poorly soluble pollutants, including nanoplastics and MPs, show limited mobility but remain consistently detectable (Li et al., 2021; Yu et al., 2021). Within landfills, ECs undergo various degradation and transformation processes influenced by temperature, moisture, microbial activity, and sunlight exposure. Some compounds degrade partially, whereas others persist

or transform into byproducts of equal or greater toxicity (Ramakrishnan et al., 2015; Tan et al., 2022). MPs contribute 70–90% of the hydrophobic pollutant load in LL. Microplastics also act as vectors for ECs by promoting sorption and transport of hydrophobic pollutants, thereby intensifying ecotoxicity and bioaccumulation in food webs (Lekshmi & Anand, 2024; Rahman et al., 2022; Valderrama et al., 2023). Leachate often infiltrates surrounding soils, contaminating surface water and groundwater systems. The transport and fate of ECs are largely controlled by soil properties, hydrogeological conditions, and the proximity of receiving water bodies (Anand et al., 2021; Andrews et al., 2012). Overall, the behavior of ECs in landfill leachate is governed by their physicochemical properties, landfill age, climatic conditions, and treatment systems. Persistent compounds such as PFAS, phthalates, PPCPs, and microplastics demonstrate strong resistance to conventional treatment, indicating the need for enhanced or hybrid technologies for their effective removal.

4 Conventional Treatment Methods for Landfill Leachate

In the present study, the term “conventional treatment methods” refers to well-established and widely implemented biological and physicochemical processes traditionally used for landfill leachate treatment. These include activated sludge process (ASP), sequencing batch reactor (SBR), trickling filter (TF), moving bed biofilm reactor (MBBR), upflow anaerobic sludge blanket (UASB), coagulation-flocculation, chemical precipitation, air stripping, and adsorption. These systems primarily aim to remove bulk organic matter (COD, BOD), ammoniacal nitrogen, and suspended solids, and are characterized by mature operational designs and long-standing application histories.

4.1 Overview of Conventional Treatment Processes

4.1.1 Leachate Transfer

Recirculation and discharge to sewage treatment plants (STPs) are widely used conventional strategies for leachate management. Recirculation relies

on microbial degradation and dilution mechanisms that occur within the waste matrix. Leachate reintroduction increases moisture content, accelerates hydrolysis, and enhances the solubilization of organic compounds, which promotes anaerobic digestion and methanogenesis (Jain et al., 2014; Patel et al., 2020). However, excessive recirculation can lead to the accumulation of refractory compounds such as humic substances and persistent organic pollutants (POPs). These compounds inhibit microbial activity and induce acidification (Abbas et al., 2009; Anand et al., 2021). When pH drops below 5, methanogenesis declines, volatile fatty acids accumulate, and COD levels rise. Waste bed saturation and ponding further restrict oxygen diffusion and reduce biodegradation efficiency (Teng et al., 2021). Discharging leachate to municipal STPs provides a low-cost option but often disrupts biological processes due to inhibition of nitrification by high ammonia levels. High concentrations of refractory organics, ammoniacal nitrogen, and heavy metals inhibit nitrification and hinder sludge floc formation (Masoner et al., 2020). Many ECs including pharmaceuticals, endocrine-disrupting compounds, and surfactants are highly polar and chemically stable, making them resistant to biodegradation in conventional STPs. Overall, both recirculation and co-treatment strategies primarily redistribute contaminants rather than eliminate them, leading to continued release of ECs into aquatic environments (Rehman et al., 2018; Alimi et al., 2022). Therefore, leachate transfer should only be considered as a short-term management option and must be coupled with secondary or tertiary treatment systems.

4.1.2 Biological Treatment

The biological treatment of LL operates under aerobic or anaerobic conditions depending on oxygen availability and leachate characteristics. In aerobic systems, oxygen serves as the terminal electron acceptor, enabling breakdown of biodegradable organics through enzymatic oxidation, mineralization, and nutrient assimilation (Torretta et al., 2016). These systems are effective for young leachates with high BOD₅/COD ratios (>0.5), where biodegradable organics predominate (Luo et al., 2020). However, refractory compounds such as humic substances, long-chain hydrocarbons, and ECs persist due to their low biodegradability (Teng et al., 2021). Aerated lagoons,

among the simplest aerobic setups, can remove 80–88% of phenols and 55–64% of COD (Panter et al., 2016). Their mechanism primarily involves aerobic oxidation of biodegradable carbon and partial volatilization of phenolic compounds. Yet, large land requirements, odor issues, and poor temperature tolerance limit their operation (Payandeh et al., 2017). The ASP enhances microbial oxidation through continuous aeration and suspended biomass contact. It achieves up to 52.5% COD removal in leachates with a BOD₅/COD ratio of 0.17 (Abbas et al., 2009), and 3.6–42.9% removal of micropollutants such as ketoprofen and gemfibrozil (Teng & Chen, 2023). However, ASP produces large quantities of sludge and exhibits limited removal of hydrophobic ECs, that tend to adsorb onto sludge rather than degrade, leading to secondary contamination (Wang et al., 2018). SBR improves treatment efficiency through time-controlled aeration and alternating aerobic-anoxic phases that promote nitrification–denitrification. They effectively reduce COD (76%), BOD₅ (84.06%), and ammonia (64.83%) while achieving over 60% removal of metals such as Cd, Fe, and Zn (Torretta et al., 2016). The swim-bed biofringe configuration further enhances simultaneous nitrogen and organic removal (Aziz et al., 2011). Despite such performance, hydrophilic ECs like carbamazepine and diclofenac remain refractory (<30% removal), as they resist enzymatic cleavage and have low affinity for biomass (Lebron et al., 2021). TFs and MBBRs utilize attached-growth biofilms for stable microbial activity. TFs remove up to 97% of ammonia (Abbas et al., 2009) but are prone to clogging when treating young leachates with high organic loads (Torretta et al., 2016). MBBRs combine suspended carriers with aeration to achieve 60–85% nitrification and around 80% COD removal at 16 h retention time (Xiong et al., 2018). These systems stabilize long-term performance but remain inefficient for ECs due to limited microbial adaptation and lack of co-metabolic pathways.

Anaerobic systems function through sequential hydrolysis, acidogenesis, acetogenesis, and methanogenesis, converting organic matter into methane (CH₄) and CO₂. The UASB reactor achieves 65–80% COD removal under 20–35 °C (Mainardis et al., 2020), with efficiency increasing with temperature due to enhanced methanogenic activity (Loupasaki & Diamadopoulos, 2013). Nevertheless, ECs often inhibit methanogenic enzymes, reducing biogas

yield and overall stability. Anaerobic filters (AFs) achieve up to 90% COD removal at 1.26–1.45 kg COD m⁻³ day⁻¹ (Renou et al., 2008), while hybrid filters integrating AF and UASB designs improve solid retention and gas–solid separation. These systems remove 81–97% of COD depending on loading rate (Abou-Elela et al., 2013), but remain restricted by slow biomass growth, long start-up times, and poor degradation of toxic ECs. Thus, biological processes are effective for carbon and nitrogen removal but insufficient for eliminating persistent emerging contaminants.

4.1.3 Physico-Chemical Treatment

Various common physico-chemical processes include flotation, coagulation-flocculation, adsorption, precipitation, and air stripping (Gao et al., 2015; Mojiri et al., 2013), are widely used as either standalone or integrated treatment processes (Tripathy & Kumar, 2017). Their primary role is to improve the removal of refractory organics, suspended solids, metals, and colloidal matter that resist biological treatment. However, their performance varies significantly depending on leachate characteristics, especially during treatment of aged or EC-rich leachates.

Flotation separates particles based on density and surface hydrophobicity. Air bubbles attach to solids, colloids, and microbial cells, lifting them to the surface. This process effectively removes colloids, ions, macromolecules, microbes, and fibers. However, its application in LL treatment remains limited (Renou et al., 2008). Column flotation removed nearly 60% of humic acids from simulated leachate under optimal conditions (Gao et al., 2015). Coagulation-flocculation destabilizes colloidal and dissolved particles through charge neutralization and adsorption bridging. Floc formation allows subsequent removal by sedimentation or filtration. This mechanism removes heavy metals and organic pollutants efficiently but performs poorly for ammoniacal nitrogen (Fang et al., 2021). Common coagulants include Al₂(SO₄)₃, FeSO₄, FeCl₃, and Fe₂(SO₄)₃. Ferric salts outperform aluminum salts because of wider pH tolerance and lower solubility (Moradi & Ghanbari, 2014). FeCl₃ reduces COD by 25–38% in fresh leachates at low pH and achieves >75% COD removal at pH 10 in partially stabilized leachates (Ghafari et al., 2009; Torretta et al., 2016). Metal hydroxide flocs also adsorb

humic substances, improving color and turbidity removal.

Chemical precipitation removes dissolved metals by forming insoluble hydroxides or sulfides (Pohl, 2020). The precipitates are separated by sedimentation or filtration. Commonly used as pretreatment, this method effectively eliminates ammonium nitrogen and heavy metals (Mojiri et al., 2013). Sulphide and hydroxide precipitation achieve 92–100% metal removal (Pohl et al., 2020). Magnesium-ammonium-phosphate (MAP) and lime are widely used. MAP removes up to 85% NH₄⁺-N (Pesonen et al., 2022; Teng et al., 2021), while lime precipitation efficiently removes metals in young leachates (Luo et al., 2020). Adsorption relies on surface binding and pore diffusion, driven by van der Waals forces, electrostatic attraction, and hydrogen bonding. Activated carbon (AC) is the most common adsorbent for removing dissolved organics and ammonium nitrogen. In aged leachates, AC improves biodegradability but limits organic removal to 40% at 10 g/L, increasing the BOD₅/COD ratio from 0.18 to 0.56 (Gotvajni et al., 2009). AC derived from sewage sludge and cabbage using ZnCl₂ activation achieved 85.61% COD removal. Phosphoric acid-activated rice husk biochar achieved ~80% COD removal (Zeng et al., 2020). Coagulation combined with adsorption enhanced removal to 80% COD reduction in biologically treated leachates (Papastavrou et al., 2009). Air stripping transfers volatile and semi-volatile contaminants from liquid to gas at the air–water interface (Yuan et al., 2016). At high pH, NH₄⁺ converts to gaseous NH₃, which is stripped out of the solution. The process removes methane, ammonia, and VOCs effectively. Efficiency depends on pH, temperature, and retention time. Ammonia decreased from 800 mg/L to <5 mg/L after 96 h, while a 36-h retention achieved 51.5% COD, 74.6% BOD₅, and 97.6% NH₄⁺-N removal, followed by Fenton oxidation and coagulation (De et al., 2019).

Despite their efficiency, physico-chemical processes generate large sludge volumes and incur high costs. Coagulation-flocculation produces 0.5–1.5 kg sludge/m³ enriched with 200–500 mg/kg of heavy metals, contributing 20–30% of total disposal cost (Das & Raj, 2025). Treatment costs range from US\$ 25–75/m³, while advanced oxidation consumes 1–2 kWh/m³ and US\$ 10–20/m³ in reagents for mature leachates (COD > 3,000 mg/L;

$\text{NH}_4^+\text{-N} > 1,000 \text{ mg/L}$). These processes also form toxic by-products such as trihalomethanes ($\leq 120 \text{ }\mu\text{g/L}$), aldehydes ($50\text{--}150 \text{ }\mu\text{g/L}$), and residual iron ($10\text{--}50 \text{ mg/L}$) (Zhang et al., 2024). Although COD removal reaches $50\text{--}70\%$, toxicity reduction remains below 30% , highlighting the need for integrated or sequential treatment strategies (Luo et al., 2020; Teng et al., 2021). The advantages and limitations of these conventional methods are summarized in Table 3.

4.2 Role of Conventional Treatment in the Removal of Emerging Contaminants

Recent studies demonstrate that the highly variable composition of LL poses significant challenges to the effective remediation of ECs. Despite their wide application, conventional treatment systems show inconsistent removal, partial degradation, and operational inefficiencies for emerging contaminants due to variable leachate composition and the complex physicochemical properties of ECs (Goukeh et al., 2025). For instance, Fenton oxidation achieves up to 99% removal of free antibiotic resistance genes (ARGs), but its performance decreases to below 30% for ARGs adsorbed onto MPs due to their physical shielding effects (Luo et al., 2020). Anaerobic sludge digestion shows variable ARG removal ranging from 22 to 89% . Free ammonia pretreatment enhances this efficiency to about 95% , highlighting the need for effective pretreatment to ensure consistent pathogen control (Zhang et al., 2022). SBR efficiently remove more than 95% of biodegradable antibiotics. However, they show limited effectiveness against recalcitrant compounds. In contrast, UASB reactors primarily reduce COD but achieve minimal antibiotic removal (Qian et al., 2020).

Membrane filtration also faces major operational challenges such as fouling, particularly caused by MP-induced pore blockage. This fouling can reduce flux and filtration efficiency by up to 40% , requiring frequent cleaning and membrane replacement (Mukherjee & Pal, 2024). However, integrating membrane bioreactors with biochar filters achieves more than 95% removal and immobilization of MPs sized around $10 \text{ }\mu\text{m}$. This hybrid approach helps reduce fouling but increases capital and operational complexity (Shen et al., 2020; Wang et al., 2020). ASP removes a wide range of ECs more efficiently than

TF. They achieve over 80% degradation for carboxylic pharmaceuticals such as ketoprofen and gemfibrozil. In contrast, amide compounds like crotamiton and carbamazepine often persist above 50% after treatment. The removal of beta-blockers such as atenolol and propranolol remain poor, with reductions frequently below 40% . Metabolite reformation further complicates removal, indicating reversible biotransformation pathways (He et al., 2020; Huang et al., 2024). Sequential TF-ozonation systems achieve more than 80% removal of ECs such as atenolol and triclosan. This performance highlights the complementary benefits of combining biological and oxidative processes (Shukla & Ahammad, 2023). Chemical oxidation methods including chlorination, ozonation, and $\text{UV}/\text{H}_2\text{O}_2$ photolysis also show strong degradation capabilities. They remove pharmaceuticals such as furosemide ($> 71\%$), saluamine ($> 80\%$), and pyridinium ($> 85\%$) (Rahman et al., 2022). However, these processes often result in incomplete mineralization. The transformation and intermediate products formed may persist in the environment (Sandre et al., 2023).

Integrated in-situ ozonation coupled with ceramic membrane filtration further enhances removal efficiency. It reduces pharmaceutical, endocrine-disrupting, and odorous compound concentrations from 12 ng/L to 28 ng/L for pharmaceuticals (Zhou et al., 2025). Despite its high efficacy, the integrated system requires significant energy input and close monitoring to avoid secondary pollution (Chen et al., 2021). Persistent contaminants such as PFAS remain highly resistant to conventional biological and physicochemical treatments. Their removal rarely exceeds 15% , posing continued ecological and human health risks (Qiu et al., 2016; Goukeh et al., 2025). PAEs frequently accumulate in sludge through partial degradation and sorption, reaching concentrations as high as $89.6 \text{ }\mu\text{g/L}$ in certain leachates (Goukeh et al., 2025). MPs also persist, worsening membrane fouling and operational costs. Their removal efficiency seldom surpasses 30% in conventional systems (Shen et al., 2020). Furthermore, the variability in leachate composition complicates process optimization. Conventional parameters such as COD and BOD do not accurately predict EC removal, hindering real-time control and regulatory compliance (Zhang et al., 2025). Overall, conventional LL treatments rely mainly on partial degradation, adsorption, and transformation

Table 3 Principle, advantages and limitations of physical, chemical, and biological treatment systems for emerging contaminants (ECs)

Methods	Principle	Focused Pollutants	Advantages	Limitations	References
Leachate Transfer	LL is treated with the sewage	BOD, COD, NH_4^+ -N, suspended solids	Integration with SBR facilitated a cost-effective solution for eliminating 95% of BOD and 50% of nitrogen. The BOD/COD ratio was also elevated. Nitrogen and phosphate in LL and sewage work synergistically during the treatment process	Presence of organic compounds and heavy metals reduces the effectiveness of the treatment and leads to increased sludge formation	Luo et al., 2020; Kamaruddin et al., 2017
Recirculation	The landfill system functions as a biofilter by redirecting the collected leachate back to the landfills	COD, BOD	Accelerate the stabilization process of waste in landfills, enhance the breakdown of garbage, and reduce the volume of leachate generated from landfills	The challenge of treatment intensifies as resistant dissolved organic matter accumulates	Kamaruddin et al., 2017; Renou et al., 2008
Biological Treatment	Application of the principles of sedimentation, filtration, nitrification, denitrification, and biodegradation	Organic & inorganic matters, phenolic compounds, pathogens	Cost-effective installation and operation, rapid startup, straightforward and efficient, effective removal of $\text{NH}_3\text{-N}$	Low efficiency needs to be combined with other processes to meet launch standards, has a broad range of efficiency, requires a lot of space, is sensitive to temperature changes, is not good for mature LL, and has unpleasant odors	Nawaz et al., 2020; Costa et al., 2019

Table 3 (continued)

Methods	Principle	Focused Pollutants	Advantages	Limitations	References
ASP	employs aeration and biological floc made up of microorganisms for the treatment of sanitary and industrial wastewater	Organic Carbon, nutrients, ammonia	Offers a more intensive treatment compared to lagoons, is cost-effective, suitable for any community size, and produces stabilized sludge	Challenges in sludge separation, reduced effectiveness in faecal coliform elimination, susceptibility to toxicity, microbial suppression caused by elevated levels of ammoniacal nitrogen, ongoing monitoring, and expertise needed	Gao et al., 2015; Michalska et al., 2020
SBR	employs a fill-and-draw activated sludge method	COD, BOD, ammonia, nitrogen	Removal of 76% of COD, 84% of BOD, and 65% of NH ₃ -N	Presence of ammonia affects the COD removal rate	Renou et al., 2008
TF	An attached growth technique, in which the microorganisms that treat the water are attached to an inert packing material	Suspended solids, COD, BOD, turbidity, Ammonia- Nitrogen	Affordable media filters are capable of simultaneously eliminating nitrogen and carbon, along with 75% of NH ₃ -N	Less effective for young leachate as well as wastewater with high organic content, possible clogging & growth of fungi or algae	Kamaruddin et al., 2017; Abbas et al., 2009
MBBR	Utilizes floating plastic carriers within the aeration tank to increase the abundance of microorganisms present for the treatment of wastewater	COD, Organic matter	Adds challenges in sludge separation, reduces sludge settling duration, tolerates elevated levels of ammoniacal nitrogen, and exhibits low sensitivity to toxic substances	Higher capital and operating cost	Luo et al., 2020; Kamaruddin et al., 2017
UASB	A highly effective integration of biomass and wastewater, resulting in swift anaerobic decomposition	Organic Matter	Emphasizing technical simplicity, cost-effectiveness, minimal sludge production, high treatment efficiency, and the conversion of organic matter into methane and carbon dioxide	Low efficiency and ammonia toxicity resulting from the leachate, along with a short hydraulic retention time	Gao et al., 2015; Kurniawan et al., 2021

Table 3 (continued)

Methods	Principle	Focused Pollutants	Advantages	Limitations	References
Anaerobic Filters	As water flows through the filter, particles become trapped, and organic matter is decomposed by the biomass adhering to the filter material	Organic matter	Ease of operation	Issues related to clogging arise when there is a high organic load, leading to bacterial inhibition of nitrifiers, particularly as the upper section of the filter is exposed to elevated levels of N-NH_3	Abbas et al., 2009
Physico-chemical Treatment	Coagulation-flocculation	Compression double layer, neutralization, adsorption bridge, and net trapping	Non-biodegradable organic matter, clays, colloids, surfactants, suspended solids, acids, and heavy metals are critical components in various environmental studies	Cost-effective, highly efficient, streamlined method, operationally straightforward, successfully eliminates humic acid, organic substances, and heavy metals	Renou et al., 2008; Kamaruddin et al., 2017
	Chemical precipitation	Soluble metal compounds undergo a chemical reaction with the precipitating reagent, resulting in the conversion of ionic metals into an insoluble form (particle)	$\text{NH}_3\text{-N}$, $\text{NH}_4^+\text{-N}$, heavy metals, and non-biodegradable organic compounds	Facilitates the retrieval of byproducts as fertilizers, offers reduced costs relative to alternative physical-chemical methods, and operates more swiftly than biological processes	Narayan et al., 2019; Kamaruddin et al., 2017
Adsorption	Pollutants migrate from the liquid phase to the surface of a solid via physical and/or chemical interactions	Pollutants of both organic and inorganic nature, persistent organic compounds, and heavy metal contaminants	Economically viable, highly efficient, possessing significant adsorption capacity and enhanced thermal stability	Rejuvenation of adsorbents, The extensive use of adsorbents cannot serve as the exclusive treatment approach for leachate	Kamaruddin et al., 2017
	Air Stripping (Ammonia stripping, Methane stripping)	The transfer of $\text{NH}_3\text{-N}$ from the liquid phase to the gas phase occurs as air or water vapor moves through the leachate	Methane, ammonium $\text{NH}_3\text{-N}$, and VOCs	Simple, stable, adaptable, cheap investment, efficient ammonia removal at high beginning concentrations	Narayan et al., 2019; Kurniawan et al., 2021

mechanisms. Such processes are insufficient for complete remediation of ECs. Therefore, ECs like PFAS, phthalates, PPCPs, and MPs require advanced hybrid or specialized degradation technologies.

4.3 Fate of Emerging Contaminants in Landfill Leachate after Conventional Treatment

Various studies demonstrate that conventional LL treatments including bioprocesses (ASP, SBR, TF, MBBR) and physicochemical methods (coagulation-flocculation, precipitation, adsorption) are insufficient for complete EC mitigation. PPCPs and pesticides in LL undergo partial transformation and adsorption during conventional treatment (Enfrin et al., 2019). Effluent frequently contains residues of 0.01–10 µg/L for PPCPs and up to 5 µg/L for pesticides, with metabolite formation complicating toxicity monitoring. During primary leachate transfer or lagooning, most PPCPs, pesticides, phthalates, PAHs, PFAS, and PCBs remain largely persistent, with only minor settling or natural attenuation (Bandala et al., 2021; Silva et al., 2021).

Biological processes, ASP, SBR, TF, MBBR, and anaerobic systems like UASB and AFs, achieve partial biodegradation or transformation of low molecular weight compounds (Kurre & Samantaray, 2025). Hydrophobic and high molecular weight contaminants, such as phthalates, PAHs, and PCBs, preferentially adsorb to biofilms, sludge, and solids, retaining 25–75% of the contaminant load (Kelkar et al., 2019; Zhou et al., 2025). Effluent still contains 0.1–8 µg/L PAEs and 0.01–2 µg/L PAHs. Coagulation–flocculation and chemical precipitation remove mainly hydrophobic or floc-associated compounds, while adsorption captures some hydrophobic ECs (Gunaratne et al., 2024). PFAS and PCBs remain largely unchanged across all treatments, with PFAS sometimes exceeding 6000 ng/L post-treatment and PCBs accumulating in solids. MPs exhibit minimal retention, with 0.4–25 items/L remaining in treated leachate or solids. Air stripping is largely ineffective due to low volatility (Kurre & Samantaray, 2025). Overall, the fate of ECs in landfill leachate under conventional treatment is driven by incomplete biodegradation, selective adsorption, and chemical persistence. The fate of individual EC classes across treatment processes is summarized in Table 4.

The fate of ECs after conventional treatment is predominantly governed by several factors including adsorption, partial biodegradation, volatilization, or physical persistence. Hydrophobic compounds such as phthalates, PAHs, and PCBs preferentially adsorb to sludge and solids, while polar compounds such as PPCPs and PFAS remain largely unaltered in the aqueous medium. Microplastics promote sorption of ECs and further complicate removal process. These trends in ECs removal through traditional methods indicate that these well-established treatments cannot fully eliminate ECs and should be complemented using hybrid, advanced oxidation, or membrane-integrated systems.

5 Case Studies and Innovative Approaches

5.1 Successful Case Studies of Landfill Leachate Treatment

Several full-scale and pilot-scale LL treatment systems have been developed worldwide, demonstrating the practical feasibility, operational limitations, and engineering adaptability of different technologies. Yaman et al. (2012) investigated the Odayeri landfill in Istanbul, Turkey, which receives MSW from 16 districts and generates approximately 2000 m³ of leachate daily. The treatment facility integrates a pre-anoxic biological system followed by UF and NF, achieving high removal efficiencies for COD (99%), total nitrogen (94.5%), NH₄⁺-N (99%), and total phosphate (93.8%). The biological pre-treatment effectively minimizes membrane fouling by reducing the organic load, while NF polishing ensures compliance with stringent discharge standards. The efficient integration of biological and membrane processes, supported by optimized pre-treatment and hydraulic control, represents a key success factor of the integrated system. The sequential configuration of anoxic-UF-NF stages forms a closed-loop modular treatment design adaptable to variable inflow conditions. Similarly, the Efford landfill treatment plant in Hampshire, UK, described by Last et al. (2005), is designed to treat up to 150 m³/day of concentrated leachate using an SBR system followed by reed bed polishing. The SBR enables controlled aerobic-anoxic cycles to achieve stable nitrification and

denitrification, while the reed beds serve as a passive polishing stage through plant uptake and microbial biofilm activity. This system highlights the effective use of natural treatment technologies as low-cost and sustainable polishing steps. The modular configuration of SBR followed by reed beds and final discharge to a rural sewage treatment plant makes this approach particularly suitable for decentralized and rural applications. Robinson et al. (2004) reported the modernization of the Deerplay landfill facility in Lancashire, UK, by Caird Ltd., which incorporated a roofed, above-ground SBR system with a treatment capacity of 130 m³/day for methanogenic leachate. The effluent from this plant is discharged via a gravity-fed pipeline into the urban sewer network. The weather-protected design of the SBR prevents dilution and temperature fluctuations, thereby maintaining consistent microbial activity even under cold climatic conditions. The closed-containment setup with automated sequencing control and direct connection to the sewer network minimizes both transportation and pre-treatment costs. In another study, Kashitarash et al. (2012) evaluated the application of nanosized zero-valent iron (nZVI) for the treatment of leachate from the Hamadan landfill in western Iran, which receives approximately 750 tonnes/day of municipal waste and 5 tonnes/day of hospital waste. The nZVI achieved an average removal of 53% for COD, BOD₅, total solids, and color within 10 min at an optimal pH of 6.5. Increasing the nanoparticle dose to 2.5 g/L further enhanced removal performance, while a higher pH (8.5) reduced efficiency. This study demonstrated the rapid redox-based degradation capability of nZVI due to its high surface reactivity. It highlights its potential use as a pre- or post-treatment step for improving biodegradability and color removal. Emerging technologies such as nZVI offer promising short contact-time treatments and serve effectively as pre-oxidation steps to enhance biodegradability; however, challenges related to nanoparticle recovery, regeneration, and large-scale implementation remain unresolved. From an energy and cost perspective, high-intensity systems such as UF/NF and AOPs deliver superior removal efficiencies but entail higher operational costs (US\$ 30–50/m³), whereas natural treatment systems are more economical but require extensive land area and longer retention times. Hybrid configurations that integrate with well-established existing approaches

can balance performance and cost through modular and adaptive integration.

5.2 Innovative Technologies for Enhanced Removal Efficiency

Innovative technologies for LL treatment encompass emerging or hybrid treatment strategies that enhance or complement conventional systems by targeting persistent and trace-level contaminants. In this review, innovative technologies refer to systems that complement conventional treatment technologies on targeting recalcitrant and trace level contaminations through degradation, transformation, or immobilization of ECs (Table 5). Wang et al. (2023) developed a novel LL treatment method based on selective adsorption of humic acids using carbon nitride, which not only reduced the impact of UV-quenching substances but also enabled recovery of humic acids for reuse as liquid fertilizers in agriculture and forestry. Zhang et al. (2022) introduced a system combining partial nitrification, in situ fermentation, and anammox for simultaneous treatment of mature LL and waste-activated sludge. After 200 days of continuous operation, the combined system is able to achieve nitrogen removal above 99%, reduced oxygen energy demand by 21.3%, eliminated the need for external carbon, and lowered CO₂ emissions by 38.9% compared with conventional nitrification–denitrification. Luu (2020) applied electrochemical oxidation for biologically leached waste using Ti/BDD and Ti/RuO₂ anodes. The Ti/BDD anode removed COD, TOC, NH₄-N, and TN by 95.17%, 91.89%, 81.18%, and 63.54%, respectively, while the Ti/RuO₂ anode achieved removals of 92.57%, 78.76%, 97.85%, and 72.12% within 8 h. Swar et al. (2023) reported that integrating physicochemical and algal treatment at the Sisdol landfill yielded COD removal of 62.93–72.43%, BOD₅ removal of 74.93–75.55%, ammonium-nitrogen removal of 87.58–93.40%, and phosphate removal of 73.63–86.73%, confirming the feasibility of the combined approach. Coertze (2020) showed that sulfate-calcined modified eggshell effectively adsorbed *E. coli* containing the gentamycin-resistance gene from artificial LL. Biochar from biomass pyrolysis at 500–600 °C removes nearly 80% of long-chain PFAS through selective adsorption and structural stability, while activated carbon achieves 70–99% PFAS removal, with powdered and fiber forms outperforming granular types due to higher surface area and faster sorption kinetics. Ibrar et al. (2023) designed a biodegradable kappa-carrageenan-vanillin

Table 4 Fate of Emerging Contaminants in Landfill Leachate after Conventional Treatment

EC Class	Leachate Transfer/Lagooning	ASP/SBR	TF/MBBR	UASB/Anaerobic Filters	Coagulation-Flocculation	Chemical Precipitation	Adsorption	Air Stripping	References
PPCPs	Largely persistent; minor settling	Partial biodegradation; some transformation; residues persist in effluent	Partial biodegradation; some transformation; sorption to biofilm/sludge	Limited anaerobic transformation; sorption to sludge	Partial removal via adsorption to floc; mostly persistent	Generally persistent; not co-precipitated	Sorption depends on hydrophobicity; partial retention	Not volatile; minimal effect	Luo et al., 2020; Zhang et al., 2022
Phthalates	Settle with solids/float	Partial biodegradation for low molecular weight (MW); higher MW persist; sorption to sludge	Sorption to biofilm; variable transformation; hydrophobic types retained	Anaerobic removal limited; strong sludge partitioning	Moderate sorption to floc; high MW enriched in sludge	Co-precipitation possible; often partition to solids	Hydrophobic PAEs well-adsorbed; persistence otherwise	Not volatile	Kamaruddin et al., 2017; Wang et al., 2020
PFAS	Highly persistent; little to no change	No biodegradation; remain in water phase	Remain in water phase; negligible transformation; limited to no adsorption	Strong persistence; minor partition to sludge	Moderate removal of long-chain compounds by floc/sediment	No effect; not co-precipitated	Partial adsorption, especially long-chain PFAS	Not volatile; minimal effect	Nawaz et al., 2020; Teng et al., 2021
Pesticides	Largely persistent; minor natural attenuation	Partial biodegradation; some transformation to metabolites	Partial transformation and sorption; metabolite formation	Anaerobic transformation variable; some are persistent	Partial sorption to floc; hydrophobic pesticides enriched	Limited effect unless polar; mostly persistent	Some removed by adsorption; others persist	Some volatilization (rare)	Gao et al., 2015; Michalska et al., 2020
PAH	Partition to solids/float	Partial biodegradation of low-MW; high-MW persistent, sorbed to sludge	Sorption to biofilm and media; minor biodegradation	Anaerobic removal limited; accumulate in solids	Sorption to floc; most remain in particulate phase	Some co-precipitation; hydrophobic PAHs partition to sludge	Good adsorption for hydrophobic PAHs; residual in solid phase	Low volatility; little effect	Fang et al., 2021; Teng et al., 2021
PCBs	Remain in solid/floating phase	Strong sorption to sludge; essentially persistent	Adsorb to biofilm and support; persistent due to hydrophobicity	Strong sorption to anaerobic sludge; largely persistent	Adsorb to floc and settle; not degraded	Sorbed to precipitates; persist in solids	Highly retained in adsorbents and biosolids	Non-volatile	Kamaruddin et al., 2017; Masoner et al., 2020

Table 4 (continued)

EC Class	Leachate Transfer/Lagooning	ASP/SBR	TF/MBBR	UASB/Anaerobic Filters	Coagulation-Flocculation	Chemical Precipitation	Adsorption	Air Stripping	References
Microplastics	Settling/floatation	Minor retention in sludge; most persist through bio-processes	Trapping in biofilm possible; most pass through media	Settle/float with solids; otherwise persistent	Trapping in floc; inefficient for small particles	No effect; remain in effluent	Physical adsorption onto granular/activated media; partial removal	Some volatilization for microfibers; negligible overall	Luo et al., 2020; Raissi et al., 2022

hydrogel for cost-effective LL treatment and brine management. The hydrogel filter rejects 77% TOC, 73% TDS, 95% turbidity, and 97% color, demonstrating strong potential for scalable, gravity-driven filtration. Constructed wetlands (CWs) have also emerged as sustainable systems for EC removal through synergistic interactions among substrates, plants, and microorganisms (Bakhshoodeh et al., 2020). Vertical-flow CWs achieved removal efficiencies above 90% for antibiotics and ARGs, while recent studies reported overall removal of 88–98% of MPs, 70% of PPCPs, and nearly 97% of nano-sized plastics (Teng & Chen, 2023). Yi et al. (2017) further demonstrated that hybrid CWs removed more than 90% of selected PPCPs, EDCs, and ARGs from LL. Hybrid membrane bioreactor (HMBR) systems combined with RO membranes show high efficiency in removing emerging contaminants from landfill leachate. They achieve over 90% removal of pharmaceuticals such as carbamazepine and diclofenac, and PFAS compounds like PFOA and PFOS. RO membranes reject more than 92% of PFOA and PFOS at influent concentrations of about 10 µg/L and 1 µg/L, respectively (Zhang et al., 2025; Zhou et al., 2025). Total organic carbon decreases by $92 \pm 8\%$, indicating effective removal of dissolved organic matter. Advanced HMBR systems that integrate UV disinfection and granular activated carbon adsorption remove over 95% of herbicides such as Ametryn, reducing concentrations from around 2 µg/L to below 0.1 µg/L (Das & Raj, 2025).

Findings from different scientific studies established these innovative techniques promising for mitigating persistent pollutants in LL. However, despite promising efficiencies, many advanced technologies lack prolonged field validation, especially under fluctuating leachate characteristics, economic feasibility studies, and full-scale operational feasibility, which limit their practical implementation for treatment of ECs from landfill leachate. Therefore, process optimization should include specific EC tracking, metabolite profiling, and energy-removal efficiency correlations to achieve scalable and sustainable treatment.

6 Policy and Regulatory Perspectives

6.1 Current Regulations for Landfill Leachate Management and Discharge

Effective collection and management of LL are essential prior to environmental discharge, as untreated

leachate poses significant risks of soil, subsoil, and water contamination (Chu et al., 2008; Zhang et al., 2025). Landfills produce diverse intermediate organic byproducts and inorganic contaminants through compression, water percolation, and microbial activity, leading to serious environmental and health concerns (Xiao et al., 2009). Regulatory frameworks, summarized in Table 6, mandate treatment of hazardous constituents in leachate before its final disposal (Trabelsi et al., 2013). Adherence to discharge standards remains crucial, although variations in environmental and economic conditions result in differences in permissible limit values across regions (Abubakar et al., 2016; Jagaba et al., 2020).

6.2 Policy Framework Recommendations for addressing Emerging Contaminants

The European Water Framework Directive stands as one of the most comprehensive legislative instruments on global water quality, recognizing water as a vital heritage that requires protection rather than a simple commodity. Chemical pollution poses a significant threat to aquatic ecosystems, often occurring due to coexistence of regulated, unregulated substances, transformational products, often forming complex mixture (Brack, 2019). Policy frameworks must allocate resources for research on Contaminants of Emerging Concern (CECs) at local, regional, and global levels, with programs designed to prevent rather than merely manage contamination (Altenburger et al., 2015; Wiener & Sandheinrich, 2010). Effective regulation of CECs requires integration of scientific evidence with policy development, supported by diverse stakeholders. A comprehensive framework should

prioritize key contaminants and their transformation products. It should evaluate human and ecological health impacts and consider major environmental matrices. The framework must assess toxicity and combined chemical effects (Gunarathne et al., 2024). Moreover, it should also analyze available technologies and analytical capacities. Additional components may include stakeholder engagement, development of innovative mitigation and remediation strategies, and establishment of standards encompassing prevention, operational guidelines, and screening protocols (Zhou et al., 2025). As information on CECs continues to evolve rapidly, therefore, global collaboration among regulators, industry, and experts for integrating advanced ecotoxicological assessment with emerging treatment technologies remains essential for developing advancing global policy and regulatory measures for sustainable landfill leachate management (Naidu et al., 2016).

7 Conclusion and Future Perspectives

Researchers increasingly recognize LL as a critical source of ECs, with concentrations spanning ng/L to mg/L depending on compound class and landfill conditions. This variability underscores the heterogeneous composition of landfill waste streams and poses significant challenges for treatment systems. Conventional biological processes such as ASP, SBR, UASB, and MBBR can achieve partial removal of several ECs; however, their effectiveness varies across classes of compounds. Integrated treatment trains that combine biological and physicochemical mechanisms exhibit higher removal potential. For instance, coupling

Table 5 Overview of emerging technologies for wastewater treatment

Technology	Main Mechanism	Removal Efficiency	Drawbacks	References
UASB-MBBR	Anaerobic + Aerobic co-metabolism	60–85% COD, partial EC removal	Slow biomass adaptation	Chen et al., 2018
AOPs (UV/H ₂ O ₂ , O ₃)	Hydroxyl radical generation	> 80% PPCPs	Incomplete mineralization	Dezotti et al., 2017
Membrane Bioreactor (HMBR)	Selective filtration + biodegradation	> 90% COD and MPs	Fouling and high cost	Oller et al., 2011
Electrochemical oxidation	Radical oxidation	> 90% TOC and NH ₄ ⁺ removal	Energy intensive	Rahman et al., 2022
CWs	Natural attenuation and biodegradation	> 90% PPCPs and MPs	Large area required	Yi et al., 2017

oxidation with biofilm reactors improves pharmaceutical degradation, while UASB-MBBR hybrids enhance the breakdown of phenolic compounds. However, researchers must rigorously evaluate advanced systems under pilot and full-scale conditions to establish reproducibility, operational stability, and economic feasibility when treating real leachate matrices. Effective management also requires advanced monitoring. Analytical tools capable of detecting contaminants at low ng L^{-1} enable precise evaluation of treatment performance, identification of transformation products, and detection

of persistent endocrine-disrupting compounds that impose acute ecological and human health risks. Future research must systematically investigate transformation pathways, persistence mechanisms, and cumulative ecotoxicological effects of ECs across different climatic and operational scenarios. By advancing optimized hybrid treatment technologies, deploying high-sensitivity monitoring frameworks, and enforcing stringent regulatory measures, the scientific community can significantly reduce EC burdens in LL and strengthen protection of environmental and public health.

Table 6 Standard Discharge Limits for Landfill Leachate in Different Nations. (Jagaba et al., 2020; Kamaruddin et al., 2017; Mojiri et al., 2017; Yong et al., 2018)

Parameters (Units)	Standards						
	Environmental Quality Regu- lations 2009, Malaysia	Australian guidelines for sewerage systems	Environmental Protection Agency 2005, USA	Chinese Dis- charge Stand- ards, 2008	Standard of Effluent Stand- ard for Coastal Aquaculture 2004, Thailand	Hazardous waste legisla- tion guide, British Colum- bia 2022	German standards 1996
pH	6–9	6.5–9	-	-	-	6.5–8.5	-
Temperature (°C)	40	-	-	-	-	32	-
Colour (Pt-Co)	100	-	-	40	-	-	-
Suspended Sol- ids (mg/L)	50	20	-	-	30	20	-
TDS (mg/L)	-	-	-	-	3000	-	-
COD (mg/L)	400	-	-	100	120	-	200
BOD ₅ (mg/L)	20	10	-	30	20	20	50
Ammonia-N (mg/L)	5	-	-	40	-	-	-
Nitrite-N (mg/L)	-	-	-	25	-	-	2
Nitrate-N (mg/L)	-	0.5	-	-	-	2	-
Mn (mg/L)	0.2	-	-	-	5	0.5	-
As (mg/L)	0.05	-	-	-	-	0.1	-
Cd (mg/L)	0.01	0.002	0.01	0.01	0.03	0.05	0.1
Pb (mg/L)	0.1	0.005	0.03	0.1	0.2	0.1	0.5
Cr (mg/L)	0.20	0.0044	0.05	0.05	-	0.5	0.5
Sulfide (mg/L)	0.5	-	-	-	-	-	1
Ag (mg/L)	0.1	0.0001	0.05	-	-	-	-
Se (mg/L)	0.02	0.005	-	-	-	0.05	-
Cu (mg/L)	0.20	0.01	0.07	-	2	0.1	0.5
Ni (mg/L)	0.20	0.15	0.013	0.1	1	0.5	1
Zn (mg/L)	2	0.05	0.3	-	5	0.2	2
Fe (mg/L)	5	1	-	-	-	-	-
Hg (mg/L)	-	0.0001	-	-	0.001	-	0.05

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