Treatment of landfill leachate with different techniques: an overview

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ABSTRACT

Landfill leachate is characterised by high chemical and biological oxygen demand and generally consists of undesirable substances such as organic and inorganic contaminants. Landfill leachate may differ depending on the content and age of landfill contents, the degradation procedure, climate and hydrological conditions. We aimed to explain the characteristics of landfill leachate and define the practicality of using different techniques for treating landfill leachate. Different treatments comprising biological methods (e.g. bioreactors, bioremediation and phytoremediation) and physicochemical approaches (e.g. advanced oxidation processes, adsorption, coagulation/flocculation and membrane filtration) were investigated in this study. Membrane bioreactors and integrated biological techniques, including integrated anaerobic ammonium oxidation and nitrification/denitrification processes, have demonstrated high performance in ammonia and nitrogen elimination, with a removal effectiveness of more than 90%. Moreover, improved elimination efficiency for suspended solids and turbidity has been achieved by coagulation/flocculation techniques. In addition, improved elimination of metals can be attained by combining different treatment techniques, with a removal effectiveness of 40–100%. Furthermore, combined treatment techniques for treating landfill leachate, owing to its high chemical oxygen demand and concentrations of ammonia and low biodegradability, have been reported with good performance. However, further study is necessary to enhance treatment methods to achieve maximum removal efficiency.

Key words | biological treatment, chemical treatment, landfill leachate, organic pollutants

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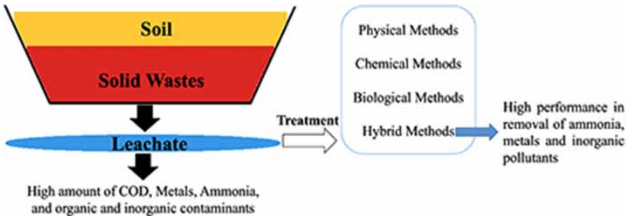
HIGHLIGHTS

- Membrane bioreactors and integrated biological techniques could remove up to 100% of ammonia.
- Enhanced elimination of metals can be gained by combining different treatment methods.
- Better elimination efficiency for suspended solids has been achieved by coagulation/flocculation.

doi: 10.2166/wrd.2020.079

GRAPHICAL ABSTRACT



INTRODUCTION

Urban solid waste landfills are commonly used for household, industrial nonhazardous and commercial solid wastes as well as nonhazardous sludge (Mojiri *et al.* 2016a). Sanitary landfilling continues to be employed in waste management plans despite its potentially hazardous effect on the environment (Mojiri *et al.* 2017). Compared with other methods, such as incineration, sanitary landfilling generally entails lower operation costs (Gotvajn & Pavko 2015). Waste may undergo a series of biological and physicochemical transformations after being landfilled, thereby producing extremely polluted wastewater called leachate. Such wastewater may pollute nearby ground and surface water as well as soil (Zamri *et al.* 2017).

Landfill leachate is characterised by high chemical and biological oxygen demand (COD, BOD) and often consists of high concentrations of organic contaminants, heavy metals, toxic materials, ammonia and inorganic materials as well as refractory compounds, such as humic substances (Chávez *et al.* 2019) as well as contaminants of emerging concern (Eggen *et al.* 2010). The characteristics of landfill leachate may differ depending on the degradation procedure, climate, hydrology conditions and age of a landfill. Ecological pollution and health issues are commonly connected to the insufficient treatment of landfill leachate (Mojiri *et al.* 2016a).

Minimising risks to the environment and human health is a serious concern in open dumping and sanitary landfills (Xaypanya *et al.* 2018). Appropriate key techniques for landfill leachate treatment consist of biological methods and chemical and physical processes. However, a comprehensive assessment of landfill leachate, including its characteristics, influences and treatment techniques, is lacking. Thus, this article serves to provide such a critical review.

LANDFILL LEACHATE AND ITS CHARACTERISTICS

Leachate forms when water penetrates waste in a landfill and transfers certain forms of contaminants (Mojiri *et al.* 2017). Municipal landfill leachate contains pollutants that can be categorised into four key groups, namely, organic contaminants and substrates, inorganic compounds, heavy metals, total dissolved solids (TDS) and colour (Mojiri *et al.* 2016a). Based on its age, landfill leachate may be divided into three key groups (Table 1), namely, young, intermediate and old (Aziz 2012; Tejera *et al.* 2019). Aziz (2012) and Vaccari *et al.* (2019) stated that in 'young' landfills (i.e. the acid phase),

Table 1 | Leachate characteristics and treatability based on the landfill age

Age (years)	Young 0–5	Intermediate 5–10	Old >10
pH	<6.5	6.5–7.5	>7.5
COD (mg/L)	>10,000	5,000–10,000	<5,000
BOD_5/COD	0.5–1.0	0.1–0.5	>0.1
NH_3–N (mg/L)	<400	–	>400
H.M	Medium to low	Low	Low
VFA/HFA	VFA (80%)	VFA (5–30%) + HFA	HFA (80%)
Biodegradability	High	Medium	Low

H.M, heavy metals; VFH, volatile fatty acids; HFA, humic and fluvic acids.
(Sources: Aziz 2012; Yadav & Dikshit 2017; Tejera *et al.* 2019).

leachate is characterised by low pH levels, high concentrations of volatile acids and simply degraded organic matter. In mature landfills (i.e. the methanogenic phase), leachate methane production and pH are high, and the organic materials present are mainly humic and fulvic fractions. However, there is a slightly difference in some other studies (Wang *et al.* 2018a, 2018b) due to the waste characteristics based on the countries. Table 2 shows the characteristics of landfill leachate around the world. Based on Table 2, most concentrated landfill leachates were located in China with COD (mg/L, 28,000) and in Riyadh (Saudi Arabia) with Fe (167.6 mg/L) for concentrated landfill leachate.

Colour and TDS

Colour is a common pollutant in landfill leachate. The decomposition of certain organic compounds, such as humic acid (HA), may cause water to turn yellow to dark brown (Naveen *et al.* 2016). Gotvajn & Pavko (2015) emphasised that substances and particles produce colour and turbidity. TDS display the integrative influence of certain cations and anions, such as calcium, chlorides, magnesium, sodium, potassium and bicarbonates, on water/wastewater. Furthermore, TDS can be produced from small amounts of dissolved organic matter (Sakizadeh 2019) and may inhibit or diminish the biological degradation of dissolved organic carbon (Hanson *et al.* 2019). Hussein *et al.* (2019) expressed that high electrical conductivity and TDS may specify dissolved organic and inorganic substances in samples.

Organic and inorganic pollutants, and heavy metals

The organic composition of leachate varies depending on waste characteristics, the age of a landfill and climatic conditions (Mojiri *et al.* 2016a). Urban solid waste and landfill leachate contain a wide variety of organic compounds (Scandelai *et al.* 2019). In landfill leachate, dissolved organic matter makes up 80% of total organic compounds and is generally composed of refractory humic substances and volatile fatty acids (Jiang *et al.* 2019). Such refractory organics may not be efficiently degraded by conventional biological treatments. Dissolved organics may be signified by BOD_5 and COD (Samadder *et al.* 2017). Moreover, persistent organic pollutants may be found in landfill leachate. Scandelai *et al.* (2019) indicated that various organic compounds with medium and low polarity, such as amines, alcohols, carboxylic acids, aldehydes, benzothiazolone, ketones, phenols, chlorinated benzenes, phosphates, nitrogen compounds, pesticides and aromatic and polyaromatic hydrocarbons, have been frequently noticed in leachate. Contaminants of emerging concern – pharmaceuticals, personal care products, surfactants, plasticisers, fire retardants, pesticides and nanomaterials – are also found in many municipal landfills, requiring attention on their management (Ramakrishnan *et al.* 2015; Qi *et al.* 2018).

Inorganic macro components, such as sulphates, chloride, iron, ammonia, aluminium and zinc, comprise anions and cations (Agbozu *et al.* 2015). Tałałaj (2015) argued that landfill leachate generally consists of large amounts of compounds, 80–95% of which are inorganic and approximately 52% are organic. Inorganic ions contain chloride (Cl^-), nitrites and nitrates, cyanide (CN^-), sulphides (S^-) and sulphates (SO_4^{2-}). Moreover, inorganic cations contain ammonia and ferrous (Tałałaj 2015).

One of the most toxic contaminants in landfill leachate is heavy metals. In most developing countries, the segregation of nonhazardous wastes from hazardous wastes before disposal into a landfill is uncommon (Edokpayi *et al.* 2018); therefore, several heavy metals in high concentrations have been reported in the landfill leachates (Chuangcham *et al.* 2008). Removal of heavy metals is a difficult task; consequently, we pay more attention to the removal of metals from landfill leachate in this study. Dan *et al.* (2017a) reported that the most common heavy metals in landfill leachate are chromium (Cr), manganese (Mn), cadmium (Cd), lead (Pb), iron (Fe), nickel (Ni) and zinc (Z). Metal concentrations in young (acetogenic) leachate are generally higher than those in old leachate (Dan *et al.* 2017a).

LANDFILL LEACHATE TREATMENT METHODS

The different landfill leachate treatment methods are shown in Figure 1 and Table 3.

Biological treatment methods

The biological degradation of contaminants results from the metabolic activities of microorganisms (Gotvajn &

Table 2 | Characteristics of landfill leachate around the world

Remarks	COD (mg/L)	BOD_5	BOD_5/COD	Ammonia (mg/L)	Heavy metals (mg/L)					Location	References
					Fe	Mn	Zn	Cd	Ni		
Concentrated leachate	28,000	950	0.04	3.50	30.00	4.03	17.80	NR	3.70	MSW incineration plants, China	Ren *et al.* (2018)
Semi-aerobic	935	83	0.09	483	7.9	NR	0.6	NR	NR	Pulau Burung, Malaysia	Kamaruddin *et al.* (2015)
–	6,140	558	0.09	1,856	NR	NR	NR	0.01	NR	Heimifeng, Changsha, China	Hu *et al.* (2016)
Covered landfill	24,040	15,021	0.59	2,281	10.37	NR	0.96	NR	0.95	Istanbul Kömürcüoda Landfill, Turkey	Akgul *et al.* (2013)
–	2,350	NR	NR	310	NR	NR	0.05	0.02	0.54	Sivas, Turkey	Atmaca (2009)
Sanitation landfill	2,305	105	0.04	1,240	NR	NR	NR	NR	NR	Beijing, China	Wang *et al.* (2016)
Semi-aerobic	1,343	96	0.07	NR	3.41	0.17	2.3	NR	0.17	Matuail landfill, Bangladesh	Jahan *et al.* (2016)
–	10,400	1,500	0.14	NR	11.16	NR	3.00	0.03	1.33	Mavallipura landfill, India	Naveen *et al.* (2014)
–	17,003	NR	NR	NR	167.61	10.83	0.18	NR	0.50	Riyadh City, Saudi Arabia	Al-Wabel *et al.* (2011)
Semi-sanitary	3,380	760	0.22	1,150	NR	NR	1.35–1.60	0.13–0.3	NR	Nonthaburi Landfill, Thailand	Xaypanya *et al.* (2018)
Concentrated landfill leachate	1,281	NR	–	14.2	NR	0.692	–	–	0.233	Jiangsu Province, China	Cui *et al.* (2018)
	7,700	1,300	0.16	1,780	10.03	NR	1.06	NR	NR	Xiangtan, China	Hu *et al.* (2011)
–	3,308–3,540	823–1,274	0.24–0.35	1,006–1,197	NR	NR	NR	NR	NR	Nam Binh Duong, Vietnam	Luu (2020)
–	781	1,16	0.14	212	21	NR	NR	NR	NR	Jones County Municipal Landfill, Iowa, USA	Nivala *et al.* (2007)
Sanitation landfill	4,737	NR	NR	1,897	NR	NR	NR	NR	NR	Virginia, USA	Iskandar *et al.* (2017)
NR	765	70	0.09	342	2.6	NR	0.07	NR	NR	Saint-Rosaire's City, Québec, Canada	Oumar *et al.* (2016)
Old and active landfill	1,380	NR	NR	665.2	NR	NR	NR	0.004	NR	Jakuševec landfill, Zagreb, Croatia	Dolar *et al.* (2016)
Operated for 2 years (very young). Non-hazardous wastes, no fermentable wastes	260	47	0.18	187	NR	NR	NR	NR	NR	France	Ricordel & Djelal (2014)
–	3,847	388	0.11	3,158.98	21.50	NR	NR	1.70	NR	Ouled Fayet landfill site, Algeria	Boumechhour *et al.* (2012)
Sanitation landfill	4,425–4,860	433–588	0.09–0.12	NR	NR	NR	NR	NR	NR	Sao Carlos, Brasil	Ferraz *et al.* (2014)
–	1,013	NR	NR	398.02	6.84	0.42	NR	6.26	NR	Guaratinguetá, Brasil	Peixoto *et al.* (2018)

NR, not reported.

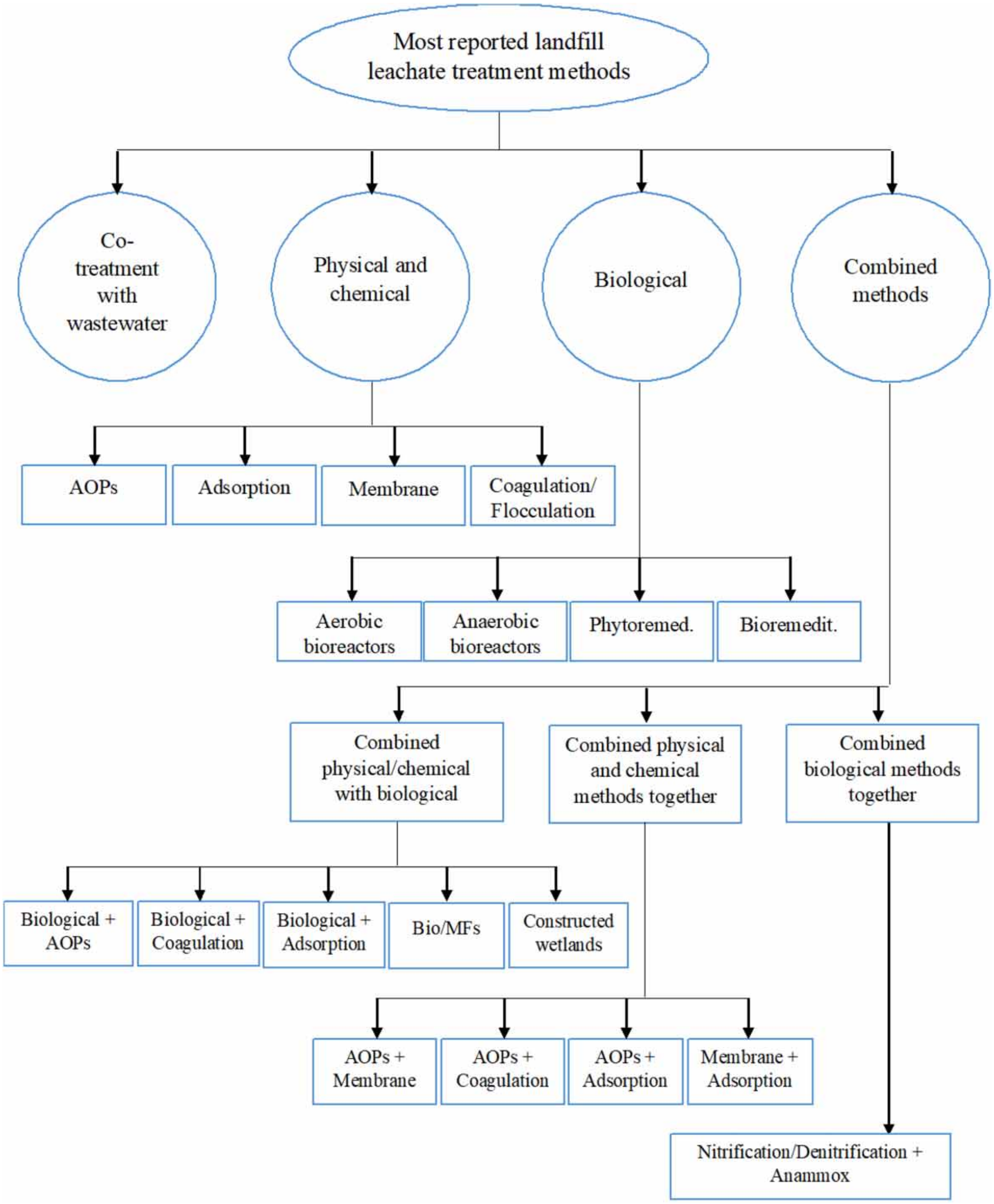


Figure 1 | Common landfill leachate treatment methods.

Pavko 2015). Owing to their cost effectiveness, biological techniques are commonly used to eliminate nutrients (e.g. ammonia) and organic compounds; however, such techniques may not be able to efficiently remove heavy metals and nonbiodegradable organics (Miao *et al.* 2019). Biological methods are classified into two main groups: (i) aerobic biological procedures and (ii) anaerobic biological procedures (Dabaghian *et al.* 2019).

Bioreactors

Bioreactors have been applied for treating wastewaters during several years because these methods are simple and

Table 3 | Reported landfill leachate treatment methods

Compounds	Removal (mg/L) or Removal efficiency (%)	Treatment method	Remarks	Category	References
Ammonia	94.5%	Adsorption/Photo-Fenton-Ozone	Pre-treatment was done via activated carbon (Sawdust) activated by H_3PO_4. After the adsorption process, the leachate was moved to a solar photo-Fenton/O_3 process.	Advanced oxidation process/Adsorption	Poblete & Pérez (2020)
COD	95.1%				
Colour	95.0%				
HA (ABS_{254})	97.9%				
COD	94%	Electrocoagulation/Fiber filtration	Anodic electrodes were arranged in parallel. After electrocoagulation with aluminium or iron electrodes, the treated landfill leachate was applied to two stages of fiber filters.	Advanced oxidation process/Coagulation/ Adsorption	Li *et al.* (2017)
As	87%				
Fe	96%				
P	86%				
COD	3,381.9 mg/L	Electro-catalytic ozonation	The current density was 42.1 mA/cm^2, and ozone concentrations varied 100–400 mg/h. This method increased biodegradability index from 0.27 to 0.45.	Advanced oxidation process	Ghahrchi & Rezaee (2020)
BOD	1,521 mg/L				
Ammonia	90%	Supercritical water oxidation (ScWO)/Zeolite	ScWO was operated under a pressure of 23 MPa at 600 and 700 °C, without the addition of oxidants. Zeolite was used by following ScWO.	Advanced oxidation process/Adsorption (ion-exchange)	Scandelai *et al.* (2020)
Nitrite	100%				
Nitrate	98%				
Colour	98%				
Turbidity	98%				
COD	74%				
COD	83.3%	Kefir grains/Ag-doped TiO_2 photocatalytic	Biological pre-treatment was done in 250 mL beakers containing 50 mL of leachate inoculated with Kefir grains. Then, leachate was moved for treatment by using Ag-doped TiO_2 photocatalytic.	Advanced oxidation process/biological method	Elleuch *et al.* (2020)
Ammonia	70.0%				
Cd	100%				
Ni	94.0%				
Zn	62.5%				
Mn	53.1%				
Cu	47.5%				
COD	68%	Coagulation/Photo-Fenton	Ferric chloride in acidic condition and Alum in neutral condition were used as coagulant. The photo-Fenton process was conducted using a high-pressure mercury immersion lamp of 450 W from ACE-Glass.	Advanced oxidation process/Coagulation	Tejera *et al.* (2019)
Colour	97%				
HA (UV-254)	83%				

(*continued*)

Table 3 | continued

Compounds	Removal (mg/L) or Removal efficiency (%)	Treatment method	Remarks	Category	References
COD	97.8%	Fenton process	The Fenton reaction was done by adding powdered ferrous sulphate and an appropriate H_2O_2:Fe^{2+} ratio.	Advanced oxidation process	Roudi *et al.* (2018)
COD HA	90.2% 93.7%	Coagulation-flocculation/ Microelectrolysis-Fenton processes	Landfill leachate was treated by chemical flocculation with polyaluminium chloride (PAC) as flocculant, and subsequently purified by microelectrolysis-Fenton process. Concentration of H_2O_2 (mg/L) varied 2.66–4.	Advance oxidation process/Coagulation-flocculation	Luo *et al.* (2019)
COD Colour Ni	88.2% 96.1% 73.4%	Electro-ozonation/adsorbent augmented SBR	At first stage, the raw concentrated leachate was treated by electro-ozonation reactor. The electro-ozone reactor was reinforced by a cross-column ozone chamber to develop ozone gas diffusion. Furthermore, the ozone reactor was supported with anode and cathode plates (Ti/RuO_2–IrO_2, 18 cm × 8 cm). After that leachate was moved to the second reactor (SBR + Composite adsorbent).	Advanced oxidation process/biological/ adsorption	Mojiri *et al.* (2017)
Colour Turbidity Ammonia	>90% >90% >90%	EO/Coagulation	$Al_2(SO_4)_3$ with dosage of 50 g/L was added as coagulant. And two stainless steel plates were applied as electrodes. Sodium sulphate 0.1 mol/L was added to the leachate in order to improve the conductivity of the solution.	Advanced oxidation process/coagulation	de Oliveira *et al.* (2019)
COD Ammonia	36% 99%	UV_{solar}/O_3/H_2O_2/$S_2O_8^{-2}$/ Zeolite	Ozone, hydrogen peroxide and UV_{solar} were considered in the same reactor with leachate to produce a high amount of hydroxyl radicals, which have a short life. The $S_2O_8^{-2}$ was added directly. Then, treated leachate was treated by zeolite.	Advanced oxidation process /adsorption	Poblete *et al.* (2019)
COD	91%	UV-based sulphate radical oxidation process/ Coagulation-flocculation	For coagulation-flocculation (pre-treatment), ferric chloride ($FeCl_3$) was used, with COD: $FeCl_3$ ratio = 1:1.3, as the coagulant. Then, leachate was treated by UV-based sulphate radical oxidation process (UV-SRAOP). For UV/SRAOP, the sulphate radical was produced using UV-activated persulphate (UV/PS) and peroxymonosulphate (UV/PMS).	Advanced oxidation process/Coagulation-flocculation	Ishak *et al.* (2018)
Colour COD Ammonia	100% 88% 79%	Ozone/catalyst ($ZrCl_4$)	Zirconium tetrachloride was added, dosage 1.2 g (COD/$ZrCl_4$), as a catalyst to ozone reactor.	Advanced oxidation process	Abu Amr *et al.* (2017)

COD Colour	16.5% 40.5%	Vermiculite/Ozonation	Rotating packed bed reactor was used to provide greater gas diffusion to the medium. Optimum operation conditions were as follows: rotation of 915 rpm, pH of 5.8 and ozone flow of 3.9 L/min. Biodegradability was increased (BOD_5/COD), from 0.13 to 0.49 by this treatment method.	Advanced oxidation process	Braga *et al.* (2020)
COD HA	72% 91%	MAC/Ozonation	MnCe-ACs were produced by impregnating Mn and Ce oxides onto granular activated carbon surfaces. MnCe-AC was added to a cylinder and ozone was added from bottom of the reactor.	Advanced oxidation process/Adsorption	Wang *et al.* (2015a, 2015b)
COD Colour	100% 100%	Activated carbon (Oat hulls)	Oat hulls adsorbents were activated with phosphoric acid and pyrolysed (N_2 atmosphere) at 350 and 500 °C.	Adsorption methods	Ferraz & Yuan (2020)
COD Ammonia Chlorine Bromine Copper	51.0% 32.8% 66.0% 81.0% 97.1%	Activated carbon (Coffee wastes)	The washed coffee was oven-dried at 105 °C for 24 h prior to activation. And then it was activated via H_3PO_4.	Adsorption methods	Chávez *et al.* (2019)
COD Ammonia	93.6% 84.8%	Zero-valent iron nanofibers/ reduced ultra-large graphene oxide (ZVINFs/rULGO)	At the optimum condition, pH, dosage of ZVINFs/rULGO and reaction time were 3, 1.6 g/L and 45 min.	Adsorption methods	Soubh *et al.* (2018)
COD Colour	77.3% 82.5%	Silica nanoparticle	At the optimum condition, pH and dosage of adsorbent were 6 and 90 min.	Adsorption methods	Pavithra & Shanthakumar (2017)
COD Ammonia	49% 45%	Zeolite Feldspar Mineral Composite Adsorbent	Samples were shaken for 5 h with 200 rpm at pH 7.	Adsorption methods	Daud *et al.* (2016)
COD	65.5–92.1%	Amino acid modified bentonite	Batch experiments were done under contact time 20–100 min, pH 2–11 and bentonite dosage of 10–40 g/L.	Adsorption methods	Hajjizadeh *et al.* (2020)
Pb	99.2	MS@GG	MS@GG was produced by modification of melamine sponge (MS) with polydopamine (PDA) and then coat with glutathione/ graphene oxide.	Adsorption methods	Feng *et al.* (2019)

(*continued*)

Table 3 | continued

Compounds	Removal (mg/L) or Removal efficiency (%)	Treatment method	Remarks	Category	References
COD	53.5%	Tannin-Based Natural Coagulant	Tannin dosage and pH were 0.73 g and 6, respectively.	Coagulation/flocculation	Banch *et al.* (2019)
Ammonia	91.3%				
TSS	60.2%				
Fe	89.7%				
Zn	94.6%				
Cu	94.1%				
Cr	89.9%				
Cd	17.2%				
Pb	93.7%				
As	86.4%				
COD	61.9%	Polyaluminium chloride and *Dimocarpus longan* Seeds as Flocculants	A coagulation–flocculation process using a combination of Polyaluminium chloride (PACl) as a coagulant and *Dimocarpus longan* seed powder (LSP) as coagulant aid was done.	Coagulation/flocculation	Aziz *et al.* (2018)
Colour	98.8%				
SS	99.5%				
COD	66.9%	Red earth as coagulant	The optimal pH and the optimal coagulant dosage were 5.0 and of 9,000 mg/L, respectively.	Coagulation/flocculation	Zainol *et al.* (2018)
Ammonia	43.3%				
Turbidity	96.2%				
COD	45%	Ferric chloride as coagulant and a cationic flocculant AN 934-SH polyelectrolytes as flocculant	The pH was fixed at 6.3. Optimum condition was 7.2 g/L $FeCl_3$ and 0.2 mL/L Flocculant.	Coagulation/flocculation	Taoufik *et al.* (2018)
COD	94.6%	Using membrane processes of NF and RO	A working pressure and flow rate were set at 15 bar and 750 mL/min. The surface area of the membranes was 10.7 cm.	Membrane	Košutić *et al.* (2015)
Ammonia	Up to 88.9%				
COD BOD Ammonia	17.5–48.5% 45.4–81.6% 50–98.8%	Using *Aspergillus flavus*	The *A. flavus* strain were isolated form leachate contaminated soil.	Bioremediation with the fungi	Zegzouti *et al.* (2020)
COD	40%	Using *Brevibacillus panacihumi* strain ZB1	The pure colonies of *B. panacihumi* strain ZB1 were grown in sterile nutrient broth in the incubator shaker for 24 h. About 10% (v/v) of the *B. panacihumi* strain ZB1 was used to treat the raw leachate sample in the 200 mL conical flask. The leachate sample was treated anaerobically for 21 days and followed by 21-days aerobic treatment.	Bioremediation	Er *et al.* (2019)
Ammonia	50%				
Mn	40%				
Cu	60%				
Se	52%				

Ammonia	90%	Using *Chlorella* sp.	After growing the *Chlorella* sp., it was inoculated for experimental studies.	Bioremediation with microalgae	Ouaer *et al.* (2017)
COD	60%				
Ammonia	83%	Using *Chlamydomonas* sp. SW15aRL	The *Chlamydomonas* sp. strain SW15aRL, previously isolated from a sample of raw leachate in 2014 from a landfill site, was maintained in raw leachate or diluted raw leachate samples with a phosphate concentration adjusted to a molar N:P ratio ~ 16:1 prior to the experiments.	Bioremediation with microalgae	Paskuliakova *et al.* (2018a)
Leachate Pollution Index	74.7%	Using garbage enzyme	The garbage enzyme (fermented mixture of jaggery, organic waste and water in the ratio 1:3:10) was applied.	Bioremediation/Enzyme	Rani *et al.* (2020)
COD	67%	Using *Colocasia esculenta*, *Gynerium sagittatum* and *Heliconia psittacorum*.	Plants were transplanted in a constructed wetland with a gravity flow ($Q = 0.5$ m^3/d).	Phytoremediation/ wetland	Madera-Parra (2016)
Cd	80%				
Pb	40%				
Hg	50%				
COD	75%	Using *Imperata cylindrica*	Contact time was ranged from 0 to 30 days.	Phytoremediation	Moktar & Tajuddin (2019)
Pb	56.3%				
Cd	16.2%				
Zn	6.5%				
COD	81.0%	Using *Typha latifolia*	Flow rate of 5 L/day and a HRT of 22 days were used.	Phytoremediation/ wetland	Yalçuk & Ugurlu (2020)
Ammonia	60.0%	Using *Canna indica*			
COD	84.0%				
Ammonia	56.0%				
COD	86.7%	Using *Typha domingensis*	Plants in a reactor with two kinds of substrates including zeolite and ZELIAC. 20% of landfill leachate was mixed with 80% of domestic wastewater at optimum condition.	Wetland/co-treatment	Mojiri *et al.* (2016b)
Ammonia	99.2%				
Colour	90.3%				
Ni	86.0%				
Cd	87.1%				
COD	93%	Membrane bioreactor + Activated sludge	Membrane sequenced batch bioreactors were inoculated indigenous leachate bacteria or activated sludge.	Bioreactor/Membrane	Azzouz *et al.* (2018)
Fe	71%				
Zn	78%	Membrane bioreactor + Indigenous leachate bacteria			
COD	95%				
Fe	71%				
Zn	74%				

(*continued*)

Table 3 | continued

Compounds	Removal (mg/L) or Removal efficiency (%)	Treatment method	Remarks	Category	References
COD TOC Ammonia Phosphorous	63% 35% 98% 52%	Membrane bioreactor	Organic load rate of 1.2 gCOD/L/day and sludge retention time of 80 days were selected.	Bioreactor/Membrane	Zolfaghari *et al.* (2016)
Ammonia TN	>98% >90%	Membrane bioreactor	DM filtration was conducted in a submerged configuration inside the aerobic bioreactor.	Bioreactor/Membrane	Saleem *et al.* (2018a)
COD Ammonia	80% 78%	Air stripping, and aerobic and anaerobic biological processes	For aerobic reactor, the activated sludge system was applied. And for anaerobic reactor, the upflow anaerobic fixed bed reactor was used.	Bioreactor/Air Stripping	Smaoui *et al.* (2020)
Colour COD Ammonia TSS	85.8% 84.8% 94.2% 91.8%	SBR and coagulation	Sequential treatment via SBR followed by coagulation was applied. Aluminium Sulphate was used as coagulant.	Bioreactor/Coagulation	Yong *et al.* (2018)
COD	>70%	Anaerobic Sequencing Batch Biofilm Reactor	Biomass from the bottom of a landfill leachate stabilisation pond was immobilized in polyurethane foam cubes as inoculum.	Bioreactor	Contrera *et al.* (2018)
COD Ammonia	30% 65%	Aerobic sequencing batch reactor (ASBR)	Air upflow velocity was set at 1.0–1.2 cm/s.	Bioreactor	Lim *et al.* (2016)
TN	95.0%	Partial-denitrification and Anammox	Firstly, leachate diluted with municipal sewage. And two USB reactors were used.	Integrated bioreactor	Wu *et al.* (2018)
TN	98.7%	Partial nitrification, simultaneous anammox and denitrification	During the aerobic phase, the DO was maintained below 0.5 mg/L.	Integrated bioreactor	Zhang *et al.* (2019)
Ammonia TN	98% 90%	DM bioreactor	DM filtration was conducted in a submerged configuration inside the aerobic bioreactor provided with a hydrostatic water head of 8 cm. And the initial inoculum was collected from the aerobic bioreactor in a municipal wastewater treatment plant.	Bioreactor/Membrane	Saleem *et al.* (2018b)
COD Ammonia	99% 99%	Activated sludge process/RO	Biological pre-treatments followed by RO.	Bioreactor/Membrane	Tałałaj *et al.* (2019)

reliable, and highly cost-effective (Gotvajn & Pavko 2015). But, the main drawbacks of bioreactor treatments involve temperature issues and leachate toxicity for microbial communities (Lippi et al. 2018).

Aerobic bioreactors. Aerobic treatments are the most commonly applied biological procedures. Aerobic reactors involve sustained aeration with large pre-established bacterial populations (i.e. activated sludge) (Torreta et al. 2017). The activated sludge process requires high concentrations of microorganisms, mainly bacteria, fungi and protozoa, to eliminate organic matter from wastewater (Rajasulochana & Preethy 2016). According to Wang et al. (2018a, 2018b), the activated sludge process may efficiently eliminate biodegradable organic material by completely transforming it into carbon dioxide and water. The sequencing batch reactor (SBR) is the most common method for treating landfill leachate. The SBR consists of several time-oriented periodic stages, and its batch operation may enhance process efficacy (Yong et al. 2018).

One of the main drawbacks of this technique involves the need for high concentrations of dissolved oxygen in biofilm reactors for denitrification (Payandeh et al. 2017).

Anaerobic bioreactors. Anaerobic methods generally demonstrate better landfill leachate treatment performance than aerobic treatment techniques owing to the high COD and high BOD/COD ratio of landfill leachates (Azreen & Zahrim 2018). Anaerobic approaches are effective biotechnological treatments for concentrated organic wastewater. Such methods are energy efficient and environmentally friendly owing to their low production of sludge and biogas (Gamoń et al. 2019). Anaerobic treatment involves the biological decomposition of organic or inorganic matter without oxygen molecules. Key drawbacks of this technique include long retention time, its sensitivity to temperature changes and low elimination efficiency (Azreen & Zahrim 2018). The anaerobic activated sludge process may require upflow anaerobic sludge blanket (UASB) and expanded granular sludge blanket (EGSB) reactors for the purification of landfill leachate. In a UASB reactor, wastewater flows through a sludge bed with high microbial activity (Gotvajn & Pavko 2015). Meanwhile, an EGSB is a third-generation anaerobic bioreactor that is characterised by high volumetric loading (Wang et al. 2018a, 2018b).

Anaerobic ammonium oxidation (anammox). Anammox bacteria transform ammonium (an electron donor) and nitrite (an electron acceptor) into nitrogen gas, using CO_2 as the carbon source for growth (Torreta et al. 2017). The most commonly applied mechanism of the anammox process is presented by the following equation (Gamoń et al. 2019):

$$NH_4^+ + 1.3H^+ + 1.32NO_2^- + 0.06HCO_3^- \rightarrow 1.02N + 0.26NO_3^- + 2.03H_2O + 0.06CH_2O_{0.5}N_{0.15} \quad (1)$$

Anammox bacteria are considered monophyletic and comprise six candidate genera, namely, *Candidatus jettenia, Candidatus anammoxoglobus, Candidatus brocadia, Candidatus scalindua, Candidatus anammoximicrobium* and *Candidatus kuenenia* (Mojiri et al. 2020). Remarkably, other types of contaminants, such as high COD and heavy metals, can affect anammox activities. Therefore, the anammox reactors are often combined with other treatment methods (Kumar et al. 2016).

Nitrification and denitrification process. The denitrification and nitrification processes involve the microbial elimination of ammonium. Ammonia is transformed into nitrate under an aerobic condition, which in turn is reduced to N_2 by an anoxic condition during a conventional nitrification–denitrification process (Thakur & Medhi 2019). In the process, firstly, ammonia is oxidised by ammonia-oxidising bacteria into nitrite (NO_2^-). Secondly, NO_2^- is converted into nitrate by nitrite-oxidising bacteria. Finally, the denitrification of nitrate into N_2 is performed by heterotrophic bacteria during the anoxic step (Miao et al. 2019). Generally, this step is integrated into other treatment techniques owing to the effects of other pollutants on the process.

Phytoremediation

Phytoremediation methods employ the capability of plant-soil systems to degrade and inactivate potential toxic elements in leachate (Song et al. 2018). The benefits of phytoremediation include (1) low-cost installation and energy consumption and (2) the elimination of the pollutants from landfill leachate (Madera-Parra 2016).

Daud *et al.* (2018) used *Lemna minor* to treat landfill leachate. More than 70% of metals, 39% of COD and 47% of BOD are removed during a 15-day contact time. Daud *et al.* (2018) and Song *et al.* (2018) said that several aquatic plants, such as *Colocasia esculenta*, *Pistia stratiotes*, *Eichhornia crassipes, Phragmites australis*, *Azolla filiculoides*, *Typha domingensis*, *Hydrilla verticillata, Azolla caroliniana*, *Salvinia Cucullata*, *Heliconia psittacorum*, *Azolla pinnata*, *L. minor*, *Lemna gibba*, *Lemna aequinoctialis*, *Gynerum sagittatum* and *Spirodela polyrhiza* can be used to treat leachate. Plants with a remarkable metal-accumulating ability are categorised as hyperaccumulator (Tangahu *et al.* 2011). Hyperaccumulation is a vital factor for the success of phytoremediation (Alaboudi *et al.* 2018). Hyperaccumulator plants can be recognised by the translocation factor (TF) and the bioconcentration factor. TF (Equation (2)) is an indication of the plant's capability to translocate metals from its root to its shoot (Ndimele *et al.* 2014). BCF (Equation (3)) shows the accumulation of metals in plant tissues. Plants with BCF values of more than 2 or TF values more than 1 are considered as hyperaccumulator (Mellem *et al.* 2009). Table 4 illustrates the concentration of metals in roots and shoots of plants during removing metals by phytoremediation or constructed wetlands.

$$\mathrm{TF} = \frac{\text{Concentration of metals in aerial parts}}{\text{Concentration of metal in roots}} \quad (2)$$

$$\mathrm{BCF} = \frac{\text{Concentration of metal in plant tissues}}{\text{Concentration of metal in substrate (water)}} \quad (3)$$

Bioremediation

Moris *et al.* (2018) stated that bioremediation involves biologically removing contaminants from the environment. Its benefits include cost-effective and environmentally-friendly techniques. The use of microalgae, algae and other fungi and bacteria for the bioremediation of landfill leachate has been reported in the literature (Moris *et al.* 2018; Spina *et al.* 2018). Paskuliakova *et al.* (2018a) claimed that algae can eliminate inorganic and simple organic compounds, whereas a few complex substances may undergo a certain degree of biotransformation. According to Paskuliakova *et al.* (2018b), microalgae that have been employed to treat landfill leachate include the *Scenedesmus*, *Chlamydomonas* and *Chlorella* genera as well as cyanobacteria and other phylogenetic. Moreover, major bacteria that have been utilised for landfill leachate treatment include *Firmicutes*, *Actinobacteria*, *Proteobacteria*, *Brevibacillus panacihumi* strain ZB1 and *Pseudomonas putida* (Moris *et al.* 2018; Michalska *et al.* 2020).

Co-treatment of landfill leachate and urban wastewater with biological methods

To enhance the biodegradability of landfill leachate and BOD/COD ratios, researchers have mixed domestic wastewater with landfill leachate before treatment (Mojiri *et al.* 2016a). Ranjan *et al.* (2016) used an SBR for the co-treatment of urban wastewater and landfill leachate. With a hydraulic retention time (HRT) of 6 days and a landfill leachate concentration of 20% v/v, 93, 83, 70 and 83% of ammonia, nitrite, COD and turbidity, respectively, were removed.

Mojiri *et al.* (2017) emphasised that owing to high COD and BOD/COD ratios, comparing landfill leachate treatments with methods used for domestic wastewater is difficult. Thus, a combined system should be applied to treat leachate. Li *et al.* (2020) employed denitrification/partial nitrification–anammox to eliminate nitrogen from intermediate landfill leachate. At optimum conditions, total nitrogen (TN) removal rate and TN elimination efficacy were 0.45 m^3/d and 96.7%, respectively. The denitrification–nitrification–anammox process demonstrates two vital points, that is, the improvement of degradable COD in wastewater to realise nitrate removal and the improvement of autotrophic bacteria growth. Pirsaheb *et al.* (2017) utilised a combined aerobic–anaerobic/biogranular activated carbon SBR for landfill leachate treatment. This biodegradable landfill leachate treatment demonstrates high performance.

Physical and chemical treatment methods

Adsorption and ion-exchange

Erabee *et al.* (2018) expressed that adsorption has been broadly applied for the treatment of landfill leachate.

Table 4 | TF and BCF during remediation of metals by plants

Metal	Plant	Concentration in influent (μg/L)	Accumulation in root (μg/g)	Accumulation in shoot/leaves (μg/g)	TF	BCF	Remarks	References
Zn	*Water hyacinth*	1,420	1,100	600	0.58	1.3	Mixing ration of landfill leachate and tap water (75%)	Abbas *et al.* (2019)
Pb		770	600	360	0.68	0.7		
Cu		620	400	400	0.63	0.5		
Fe		1,120	800	650	0.53	1		
Ni		1,410	750	500	0.57	1.25		
Zn	*Water lettuce*	1,420	1,300	660	0.6	1.2	Mixing ration of landfill leachate and tap water (75%)	Abbas *et al.* (2019)
Pb		770	650	350	0.5	0.6		
Cu		620	520	250	0.58	0.5		
Fe		1,120	1,000	500	0.5	1		
Ni		1,410	1,200	470	0.5	1.1		
Zn	*Lemna minor* L.	1,470	NR	NR	NR	0.78	BCF reported after 3 days	Daud *et al.* (2018)
Pb		830				0.46		
Cu		690				0.63		
Fe		1,170				0.76		
Ni		1,210				0.58		
Zn	*S. globulosus*	106–887	49.98	82.81	NR	NR	After 15 days	Ujang *et al.* (2005)
Ni		17–96	20.37	12.5				
Cu		8–31	11.11	12.78				
Cr		30–123	26.11	24.65				
Pb		Jun-51	7.43	8.91				
Zn	*E. sexangulare*	106–887	124.93	206.32	NR	NR	After 15 days	Ujang *et al.* (2005)
Ni		17–96	6.58	21.28				
Cu		8–31	5.99	12.06				
Cr		30–123	28.52	38.68				
Pb		Jun-51	6.1	24.87				
Pb	*A. selengensis*	4,080	404.79 (10^3)	65.37 (10^3)	NR	NR	–	Wang *et al.* (2018a, 2018b)
Cd		790	24.71 (10^3)	2.90 (10^3)				
Cr		6,120	765.59 (10^3)	127.99 (10^3)				
V		14,180	645.21 (10^3)	156.57 (10^3)				
Mn	*Vetiveria zizanioides*	490	121.55 (10^3)	48.12 (10^3)	NR	NR	pH was set at 7.	Roongtanakiat *et al.* (2007)
Fe		16,150	1,430.07 (10^3)	62.31 (10^3)				
Cu		60	4.30 (10^3)	2.45 (10^3)				
Zn		4,090	82.31 (10^3)	14.27 (10^3)				
Pb		50	4.50 (10^3)	0.69 (10^3)				
Al	*Typha domingensis*	6,560	303,910	NR	0.14	46.3	Industrial wastewater was treated by phytoremediation.	Hegzay *et al.* (2011)
Fe		10,460	154,680	NR	0.18	40.4		
Zn		3,870	117,640	NR	0.11	30.3		
Pb		990	14,870	NR	0.35	15.2		

(*continued*)

Table 4 | continued

Metal	Plant	Concentration in influent (μg/L)	Accumulation in root (μg/g)	Accumulation in shoot/leaves (μg/g)	TF	BCF	Remarks	References
Cu	*Echhornia crassipus*	101.3	NR	NR	5.08	0.61	Contaminated water was treated by phytoremediation.	Pandey *et al.* (2019)
Zn		259.4	NR	NR	3.64	0.91		
Ni		7	NR	NR	7.63	1.83		
Pb		28.5	NR	NR	1.73	0.88		
Fe		1,026.8	NR	NR	1.04	0.92		
Cr	*Acorus calamus Linn.*	11,390	64,480	7,980	NR	NR	–	Sun *et al.* (2013)
Fe		20,350	22,310	4,860				
Cu		45	1,590	650				
Zn		7,720	9,970	3,930				
Cr	*Juncus effusus L.*	11,390	30,450	15,470	NR	NR	–	Sun *et al.* (2013)
Fe		20,350	77,290	14,090				
Cu		45	650	730				
Zn		7,720	13,290	540				

NR, Not Reported.

Advantages of this method include its ease of operation, the simplicity of its design, its insensitivity to toxic substances and its ability to remove a variety of contaminants (Chávez *et al.* 2019). Different adsorbents and their performance are shown in Table 5.

In adsorption, the pollutants can adhere to the surface of the adsorbent over several mechanisms (Figure 2). The surface of the adsorbent has specific characteristics that allow the attachment of the adsorbate. Adsorption occurs under certain conditions, a reversible phenomenon which is named desorption, is applicable. In desorption, the adsorbates can be released from the surface of the adsorbent and got back to the liquid (Bello & Raman 2019).

Modified activated carbon (MAC), which is produced by immersing granular activated carbon (2.0 g) in a $KMnO_4$ solution (30 mg/L) for 6 h, was created to treat landfill leachate. Approximately 99% of ammonia and 86% of zinc can be removed by MAC in a contact timespan of 120 min. The Langmuir adsorption capacity (mg/g) of this absorbent for the removal of ammonia and zinc is 0.16 (Erabee *et al.* 2018). Zamri *et al.* (2017) used an ion-exchange resin to treat landfill leachate, with a maximum adsorption capacity (mg/g) based on a pseudo second-order kinetic model of 13.4, 13.5, 14.2, 33,333.3, 10,000.0 and 50,000.0 for Cr^{6+}, Al^{3+}, Cu^{2+}, COD, ammonia and colour, respectively.

Advanced oxidation processes

Advanced oxidation processes (AOPs) that apply a combination of oxidants and catalysts to produce hydroxyl radicals (•OH) in solutions, such as ultraviolet (UV), Fenton, ozonation and electrochemical oxidation (EO) methods, have garnered interest for the degradation of hazardous organic compounds or biorefractory in wastewater (Särkkäa *et al.* 2015). However, the main drawback of AOPs is high capital and operating costs.

In an EO process, contaminants are eliminated either by (a) direct EO in which organics are oxidised by moving electrons to an anode directly or (b) indirect EO in which certain electroactive species that act as mediators are produced to conduct the degradation procedure (Mandal *et al.* 2017). The EO of organics in metal oxide anodes was described by Ukundimana *et al.* (2018) as follows (Equations (4)–(6)).

Water is electrolysed via anodic catalysis to generate adsorbed hydroxyl radicals.

$$MO_X + H_2O \rightarrow MO_X(OH)_{ads} + H^+ + e^- \quad (4)$$

Table 5 | Adsorbents reported for landfill leachate treatment

Pollutants in landfill leachate	Adsorbent	Adsorption isotherm	Adsorption capacity (mg/g)	Remarks	References
TSS	Activated carbon (AC)	Langmuir	1.77	AC was derived from coconut shell. AC was modified by heating at 600 °C.	Erabee *et al.* (2018)
Ammonia			3.18		
Zn			0.02		
Mn			0.06		
Cu			0.07		
S^{2-}			0.02		
COD	AC	Langmuir	272.75	AC was derived from walnut shell.	Mahdavi *et al.* (2018)
Colour	AC	Langmuir	555.55	AC was derived from sugarcane bagasse.	Azmi *et al.* (2015)
COD			126.58		
Ammonia			14.61		
Colour		Freundlich	0.67		
COD			0.20 (10^{-2})		
Ammonia			3.0 (10^{-7})		
Pb	AC	Pseudo-second order	0.03	AC was derived from sugarcane bagasse.	Salas-Enríquez *et al.* (2019)
Cu			0.01		
Ni			0.01		
Zn			0.01		
Colour	Biochar	Langmuir	83.33	Biochar was derived from fallen mature fruits at 600 °C.	Shehzad *et al.* (2016)
COD	Biochar		35.71		
Ammonia			500.00		
COD	Biochar	Pseudo-second order	490	Biochar was derived from coconut shell at high temperature, and it is activated via microwave heating.	Lam *et al.* (2020)
COD	Biochar	Freundlich	5.80	Biochar was derived from Miscanthus at 450.	Kwarciak-Kozłowska *et al.* (2019)
FA	Magnetic graphene oxide	Langmuir	82.16	–	Zhang *et al.* (2016)
HA			106.50		
Pb			45.50		
Bisphenol A	Bentonite modified by hexadecyl trimethyl ammonium bromide (HTAB)	Pseudo-second order	10.44	The HTAB-bentonite was synthesized by cation exchange with HTAB solution (20 mmol/L) over stirring.	Li *et al.* (2015)
Ni	Red mud	Langmuir	11.06	Batch experiments were done with neutral pH, adsorbent dosage of 10 g/L and shaking speed of 75 rmp.	Ayala & Fernández (2019)
Zn			12.04		
Cd			12.57		
Ni		Freundlich	2.08		
Zn			4.40		
Cd			3.79		

(*continued*)

Table 5 | continued

Pollutants in landfill leachate	Adsorbent	Adsorption isotherm	Adsorption capacity (mg/g)	Remarks	References
Ammonia	Zeolites (Clinoptilolite)	Langmuir	17.45	–	Pauzan *et al.* (2020)
Bisphenol A	High silica Y-type zeolite powder	Pseudo-second order	141.0	Batch experiments were done in temperature room for 4 h at pH = 7.	Chen *et al.* (2015)
Colour	Zeolites	Langmuir	0.01	Activated zeolites were produced by heating to 250 °C.	Aziz *et al.* (2020)
COD			3.0 (10^{-4})		
Ammonia			8.9 (10^{-3})		
Colour	Zeolites	Langmuir	42.55	–	Bashir *et al.* (2017)
COD			0.22		
Ammonia			0.31		
Pb	MS@GG	Pseudo-second order	253.80	MS modified with PDA and then coated with glutathione/graphene oxide (GG)	Feng *et al.* (2019)
HA	Aminated Magnetic Nanoadsorbent	Langmuir	181.82	Amino-functionalized Fe_3O_4@SiO_2 nanoparticles were produced by surface functionalization of Fe_3O_4@SiO_2 nanoparticles using (3-aminopropyl) trimethoxysilane (APTMS) as the silylation agent. Batch experiments were done at neutral pH and shaken speed 150 rmp.	Wang *et al.* (2015a, 2015b) >
Pb	Fe_3O_4@Mesoporous Silica-Graphene Oxide Composites	Langmuir	333.33	–	Wang *et al.* (2013)
Cd			166.67		

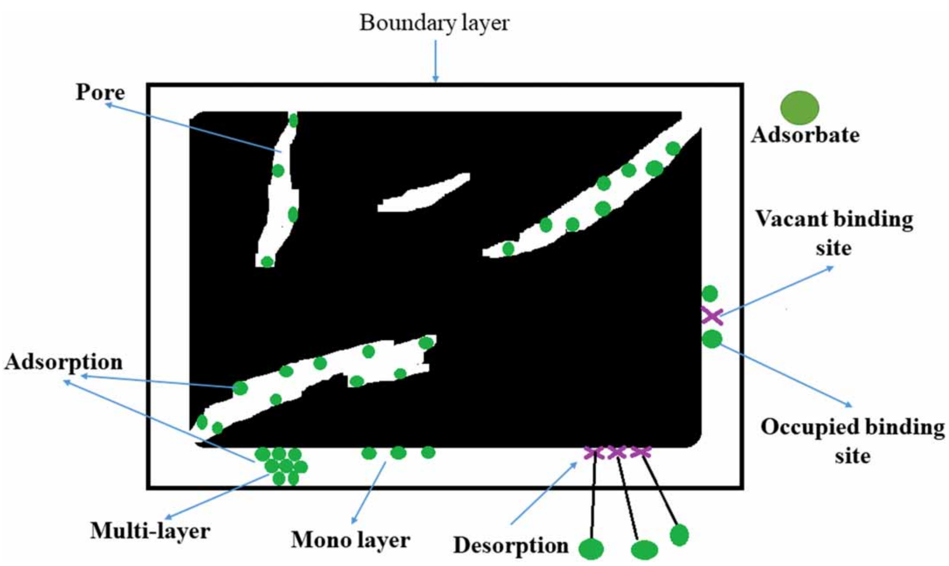


Figure 2 | Basic model of adsorption (Source: Bello & Raman 2019).

Adsorbed hydroxyl radicals at metal oxide (MO_x) electrodes (except for BDD and Pt) may form chemisorbed active oxygen.

$$MO_X + (^{\bullet}OH)_{ads} \rightarrow MO_{X+1} + H^+ + e^- \quad (5)$$

Meanwhile, the hydroxyl radicals will react to one another to form molecular oxygen to complete the electrolysis of the water molecules.

$$MO_X(^{\bullet}OH)_{ads} \rightarrow M + O_2 + H^+ + e^- \quad (6)$$

Organic pollutants (R) in landfill leachate can be oxidised via the mechanisms illustrated in Equation (7) by reacting to the physiosorbed hydroxyl radicals $MO_x(\cdot OH)$ formed by Equation (6).

$$MO_X + (^{\bullet}OH)_{ads} + R \rightarrow MO_X + CO_2 + H_2O + \text{inorganicions} \quad (7)$$

When electricity is applied to wastewater, oxygen gas derived from the breakup of water molecules and chlorine gas is produced in a chloride ion solution (Equations (8) and (9)). Hypochlorous acid (HOCl) and hypochlorite ion (OCl^-) are vital ions responsible for the indirect oxidation of ammonium to nitrogen gas (Equations (10) and (11)) (Ghimire *et al.* 2020). EO has been deemed effective for ammonium elimination (Mandal *et al.* 2017).

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad E^0 = -0.83V \quad (8)$$

$$2Cl^- \rightarrow Cl_2 + 2e^- \quad E^0 = -1.36V \quad (9)$$

$$2NH_4^+ + 3HOCl \rightarrow N_2 + 3H_2O + 5H + 3Cl^- \quad (10)$$

$$2NH_4^+ + 2OCl^- \rightarrow N_2 + 2HCl + 2H_2O + 2H^+ \quad (11)$$

In an EO procedure, the formation of metal oxide on an anode relies on the pH of the electrolyte and metal ion. Yasri & Gunasekaran (2017) indicated that a metallic hydroxide film might form on an anode in an alkaline media for transition metals (Equations (12) and (13)).

$$M^{n+}_{(aq)} + OH^-_{(aq)} \rightarrow M(OH)_{n(ads)} \quad (12)$$

$$M(OH)_{n(aq)} \rightarrow M_2O_{n(s)} + 2nH^+_{(aq)} + ne^- \quad (13)$$

EO, BDD, Ti/Pt, Ti/PbO_2, Ti/SnO_2, Ti/Pt/SnO_2–Sb_2O_4, Ti/RuO_2–IrO_2 and graphite have been commonly applied as electrodes for the treatment of landfill leachate (Ukundimana *et al.* 2018). Among the benefits of EO, the breakdown of high molecular organic compounds, the absence of sludge and the complete mineralisation of organics are its most significant advantages (Mandal *et al.* 2017).

The Fenton process has been commonly employed for the oxidation of different organics from wastewater, as it exhibits a high oxidation potential of 2.72 V (Nakhate *et al.* 2018). Fe(II) ions are oxidised into Fe(III) in the presence of excess H_2O_2 (Equation (14)). This reaction mechanism displays the activation of H_2O_2 in the presence of Fe(II) ions to form hydroxyl radicals that can oxidise organic compounds (Gautam *et al.* 2019). This classic Fenton reaction may be assisted by electric currents (i.e. the electro-Fenton process) or UV irradiation (i.e. the photo-Fenton process), thereby considerably enhancing its efficacy (Seibert *et al.* 2019). Singa *et al.* (2018) argued that compared with other AOPs, the Fenton process includes benefits such as an easy implementation operation, high efficiency and the lack of an energy requirement for H_2O_2 activation.

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + {}^{\bullet}OH \quad (14)$$

Ozone is a powerful oxidant, with a redox potential of 2.07 V in an alkaline solution. Consequently, O_3 can oxidise organic and inorganic substances. Gautam *et al.* (2019) claimed that the key drawbacks of landfill leachate treatment through ozonation include the following. (1) Leachate is a complex wastewater with high organic compounds; hence, high amounts of ozone are required. (2) Ozone mass transfer from a gas to a liquid is low. The ozonation of pollutants may be performed by two techniques, namely, direct and indirect ozonation (Wang & Chen 2020).

A direct O_3 molecule reaction with contaminants involves oxidation–reduction reactions (e.g. reactions between O_3 and HO_2/or $O_2^{-\bullet}$; Equations (15) and (16); Wang & Chen 2020).

$$O_3 + HO_2^- \rightarrow O_3^{-\bullet} + HO_2^{\bullet} \quad (15)$$

$$O_3 + O_2^{-\bullet} \rightarrow O_3^{-\bullet} + O_2 \quad (16)$$

An indirect reaction by •OH is revealed in the following equation (Nilsson 2018):

$$3O_3 + OH^- \rightarrow 2OH^{\bullet} + 4O_2 \quad (17)$$

UV treatment has been generally used to degrade aquatic organic compounds and kill microbes. During the absorption of UV light, electrons are transferred to oxygen molecules that convert O_2 and contaminant molecules into radicals (Equations (18) and (19)).

$$P \rightarrow P^{\bullet} \quad (18)$$

$$P^{\bullet} + O_2 \rightarrow P^{+\bullet} + 2O^{-\bullet} \quad (19)$$

UV treatment may result in the homolytic cleavage of the chemical bonds of contaminants, thereby causing the formation of two radicals (Mishra *et al.* 2017).

Approximately 99.9% of diethyl phthalate (DEP; organic pollutant) is removed from landfill leachate through the ozone/hydrogen peroxide process (O_3/H_2O_2) at an initial concentration of 20 mg/L DEP and 120 min of ozonation (Mohan *et al.* 2019).

Membrane technology

The use of different membrane technology to treat wastewater has gained considerable attention (Dabaghian *et al.* 2019). Membrane separation involves the selective filtration of influent through different-sized pores (Warsinger *et al.* 2016). Microfiltration (MF), dynamic membranes (DMs), nanofiltration (NF), ultrafiltration (UF) and reverse osmosis (RO) are the main membrane processes employed in landfill leachate treatment (Dabaghian *et al.* 2019). The advantages of using membranes include low overall energy requirements, simplicity and high efficiency (Siyal *et al.* 2019).

DMs may provide a new approach by exploiting fouling as a means for solid–liquid separation. A DM is specified as a self-forming and regenerative fouling surface formed by the removal of colloids, suspended solids and microbial cell particles through a coarse underlying support material (Saleem *et al.* 2018b; 2019). For this purpose, cheap materials, such as filter cloths, have been applied as underlying support to develop DMs (Saleem *et al.* 2019).

MF and UF are categorised as low-pressure (<2 bar) processes. Separation by MF is primarily performed by sieving. However, this process is generally limited to the elimination of organic colloids, suspended solids or particles and bacteria owing to fairly large pore sizes (approximately 0.1–1.0 μm). UF membranes likewise operate mainly via sieving but contain a broader separation range compared with MF and rely on pore sizes between 0.01 and 0.1 μm to remove pathogens, particles and colloids (Warsinger *et al.* 2016).

Meanwhile, NF can eliminate ions that contribute substantially to osmotic pressure; thus, it allows operation pressures that are lower than those used in RO. Pre-treatment is required for heavily contaminated wastewater for NF to be effective (Nqombolo *et al.* 2018).

Among the new procedures for landfill leachate treatment, RO is one of the most promising and effective techniques (Yao 2017). The RO process separates contaminants into two streams, namely, permeate (filtrate) and highly polluted concentrates, which are often recirculated into the waste body (Tałałaj 2019). Pertile *et al.* (2018) removed 43% of COD and 63% of BOD from landfill leachate through MF, with a transmembrane pressure of 0.5–1.4 bar.

Coagulation and flocculation

Fundamentally, coagulation facilitates the destabilisation of fine particles (colloids) from wastewater to form a floc that can be settled simply (Achak *et al.* 2019). Coagulation/flocculation efficacy relies on selected coagulants/flocculants. Coagulants are generally trivalent-metal inorganic salts, such as aluminium sulphate, polyaluminium chloride and ferric chloride (Wei *et al.* 2018). Lippi *et al.* (2018) stated that the main advantage of this treatment is its high effectiveness in removing organic matter, suspended solids and humic acids. However, drawbacks include the cost of chemicals and the management of generated sludge.

Nascimento *et al.* (2016) utilised natural chitosan as a coagulant for landfill leachate treatment. The removal rate for colour and turbidity was 80 and 91.4%, respectively, with a chitosan dosage of 960 mg/L and a pH of 8.5. Nithya & Abirami (2018) removed 85.2% of turbidity from landfill leachate via pine bark as a natural coagulant, with a pH of 7 and a coagulant dosage of 4 g/mL.

Hybrid physical/chemical methods

To improve removal efficiency and decrease energy consumption, several physical/chemical treatment methods have been combined to treat landfill leachate. Xiang *et al.* (2019) posited that hybrid processes, especially AOPs, combined with other treatments may be promising approaches for saving energy. Four integrated systems for combined physical/chemical methods have been identified.

AOPs combined with membranes. The integration of membrane filtration with AOPs may efficiently mitigate membrane-fouling problems, thereby enhancing overall separation performance (Pan *et al.* 2019). Santos *et al.* (2019) removed 94–96% of COD and 96–99% of colour from landfill leachate by combining the Fenton, NF and MF processes. Santos *et al.* (2019) indicated that the concentration of dissolved solids may be high after an AOP–Fenton process owing to the presence of organic matter that has not been completely oxidised and the addition of salts and acid/basic agents. Thus, the use of membranes can resolve this issue.

AOPs combined with coagulation. According to Chen *et al.* (2019), this integrated method can reduce the concentration of organic pollutants and increase the biodegradability of wastewater by altering the molecular structure of residual organics. Gautam *et al.* (2019) identified energy intensiveness, electrode passivation and the formation of chlorinated organics as the main drawbacks of electrocoagulation methods. Integrated photoelectrooxidation and activated carbon can remove 70.3% of COD, 58.3% of ammonia and 58.4% of TN (Klauck *et al.* 2017). Chen *et al.* (2019) eliminated 88.3% of COD, 98.8% of colour and 94.3% of UV254 from landfill leachate by using a combined coagulation–ozonation process.

AOPs combined with adsorption. The integration of AOPs with adsorption has been suggested to improve pollutant removal efficiency, specifically, metals from landfill leachate. Bello & Raman (2019) stated that complex organic contaminant can be degraded by AOPs but complete mineralisation is not mostly practical and some intermediate contaminants are frequently generated. Therefore, combining AOPs and adsorption could remove these intermediates. Integrated H_2O_2-granular activated carbon can reduce 97.3% of COD and increase biodegradable ratio by 116% (Eljaiek-Urzola *et al.* 2018). Eljaiek-Urzola *et al.* (2018) stated that integrating H_2O_2 with activate carbon can improve the decomposition of peroxide in free radicals and enhance performance. Jafari *et al.* (2017) removed 99.8% of tetracycline, as emerging pollutants, from aqueous solution by Heterogeneous Fenton: activated carbon–Fe_3O_4.

Membrane filtration combined with coagulation or adsorption. According to Alimoradi *et al.* (2018), coagulants or adsorbents have been applied sequentially to membranes to eliminate suspended and colloidal substances from wastewater, thereby reducing organic load and hindering membrane fouling. Gkotsis *et al.* (2017) emphasised that the use of coagulants in MBR systems could contribute significantly to reducing transmembrane pressure. Apart from that, Alimoradi *et al.* (2018) stated that coagulation pre-treatment delays the reversible and irreversible fouling by improving sludge filterability and by eliminating soluble microbial products, respectively. Alimoradi *et al.* (2018) removed more than 90% of Al by integrated coagulation-membrane bioreactor. 99.2% of COD, 100% of suspended solids and 97.3% of total organic carbon were removed by combined coagulation and membrane (Boluarte *et al.* 2016). 100% of 4-chlorophenol, 78–100% of oxidation intermediates from wastewater by integrated catalytic oxidation and adsorption (Arsene *et al.* 2013).

Hybrid physical/chemical and biological methods

Biological ways are frequently employed to treat landfill leachate. However, a biological procedure alone is not efficient enough to eliminate the bulk of refractory contaminants in landfill leachate (Wu *et al.* 2010). Therefore, researchers (Mojiri *et al.* 2016b) have suggested integrated biological methods and physical/chemical techniques to improve biodegradability ratios and increase biological performance in treating landfill leachate. Five commonly applied combined treatment methods have been identified.

Integrated adsorption and biological treatment methods

Adsorption can be employed to diminish contaminants and leachate toxicity to provide favourable growth conditions for microbial growth (Er *et al.* 2018). Munz *et al.* (2007) listed the advantages of combination of adsorption, such as activated carbon, and biological methods as: protecting microorganisms from load pick of inhibiting organic and inorganic compounds, improving refractory organics, improving sludge settleability and dewaterability capacity. Besides, the application of the adsorption technique together with the biological method leads to a reduction of the quantity of adsorbent employed for the wastewater treatment process (Yi *et al.* 2018). Sawdust added to an SBR can remove 99% of COD and 95% of ammonia (Mohajeri *et al.* 2018). More than 60% of ampicillin was eliminated by integrating adsorption and biodegradation (Shen *et al.* 2010). Ammonia was removed at more than 70% from landfill leachate by integrated adsorption and biological treatment (Yi *et al.* 2018).

Integrated membrane and biological treatment methods

Generally, the membrane bioreactor is a vital innovation in treating wastewater treatments since it overcomes the disadvantages of the conventional activated sludge process, such as producing excess sludge, requiring secondary clarifiers, and limitations with elimination of recalcitrant (Iorhemen *et al.* 2016). Among anaerobic biological methods, the anaerobic membrane bioreactor (AnMBR) system, which decouples HRT from solid retention time (SRT), is feasible for treating heavy wastewater, such as leachate (Abuabdou *et al.* 2020). Regarding the drawbacks of membrane bioreactors, Abuabdou *et al.* (2020) argued that starting an AnMBR in temperatures below 20 °C may result in the reduction of biomass growth, thereby causing a long SRT for stabilisation. Xu *et al.* (2019) removed more than 90% of sulphonamides and tetracyclines by using a membrane bioreactor. More than 90% of COD was removed from landfill leachate by AnMBR (Zayen *et al.* 2010).

Integrated AOP and biological treatment methods

He *et al.* (2020) expressed that integrating AOP techniques, as a pre-treatment, leads to readily biodegradable intermediates for biological posttreatment. Therefore, it has a positive impact for treating wastewaters, such as landfill leachate. Researchers (He *et al.* 2020; Xia *et al.* 2020) reported that zone oxidation, photocatalyst and EO are promising pre-treatment methods to enhance biodegradability of refractory contaminants. A combined semiaerobic aged refuse biofilter and ozonation process can eliminate 92.1% of colour and 61.4% of UV_{254} from landfill leachate (Chen *et al.* 2019). More than 70% of aromatic pollutants, such as p-aminophenol, by hybrid reactor including ozone pre-treatment and bioreactor (Xia *et al.* 2020). COD concentration was decreased to less than 50 mg/L by combined photocatalytic pre-oxidation reactor with SBR (He *et al.* 2020). Integrated ozonation and membrane bioreactor removed up to 99% of pharmaceuticals, such as Etodolac (Kaya *et al.* 2017). 100% of sulfadiazine, 97% of total organic carbon, 94% of BOD_5 and 97% of COD were eliminated by ozonation and membrane bioreactor (Lastre-Acosta *et al.* 2020).

Integrated coagulation and biological treatment methods

Coagulation/flocculation can be applied as pre-treatment and posttreatment with biological treatment methods (Niazi 2018; Güvenç & Güven 2019). Employed coagulation/flocculation as a pre-treatment leads to improvement of the biodegradability and reduces COD, colour and metals in landfill leachate. These advantages can enhance the treatment of landfill leachate with biological methods. The use of the coagulation/flocculation as a posttreatment can remove refractory pollutants, such as metals, COD and organics. Niazi (2018) expressed that biological treatment results the degrading dissolved and colloidal organics which transform to active biomass. The active biomass in reject water produced from the biological method can get more dissolved organics and colloidal solids from the wastewater which is eliminated by coagulation. An integrated coagulation and anaerobic bioreactor process can remove 72% of COD and 70% of total organic carbon (Yadav *et al.* 2016).

Constructed wetlands

Mojiri *et al.* (2016b) suggested that the constructed wetland (CW) system was engineered to increase water quality. A wetland system comprises permeable substrata, such as gravel, which is typically planted with emergent wetland plants, such as *Schoenoplectus*, *Typha*, *Phragmites* and *Cyperus*. Dan *et al.* (2017b) expressed that degradable organic carbon and ammonia can be efficiently removed from landfill leachate by CW systems. Nitrogen pollutants can be removed by adsorption through substrate, absorption through plant roots, volatilisation in ammonia forms, biological degradation and biochemical transformation into N_2 (Gottshall *et al.* 2007; Badejo *et al.* 2018). Zhuang *et al.* (2019) expressed that more than 50% of nitrogen can be eliminated by microbial activities, such as the nitrification/denitrification process, while around 25% of nitrogen may be absorbed by plant roots. Up to 89% of ammonia removal using a CW was reported by Mannarino *et al.* (2006).

The majority of phenolic compounds are removed by microbial activities and adsorption through substrate (Rossmann *et al.* 2012). Dan *et al.* (2017a) removed 88–100% of phenols, 18–100% of 4-tert-butylphenol and 9–99% of bisphenol A by using a vertical flow-constructed wetland. Apart from organic contaminants, heavy metals can be removed by CW systems.

According to Dan *et al.* (2017b), various mechanisms, such as the adsorption of soil or substrates as well as particulates and soluble organics, the precipitation of insoluble salts and the uptake of aquatic plants and microorganisms, may affect metal removal via CW systems. Ujang *et al.* (2005) removed up to 92.2% of Zn, 96.8% of Ni, 99.5% of Cu, 87.5% of Cr and 98.1% of Pb by using a CW which contained *E. sexangulare* and media.

CONCLUSIONS

Landfill leachate often possesses significant pollution potential with high concentrations of organic and inorganic contaminants. Primary landfill leachate treatment techniques consist of physical, chemical and biological methods. Owing to high concentrations of contaminants in landfill leachate and its low biodegradability, integrated treatment methods and co-treatment with wastewater are strongly recommended. Membrane filtration and integrated biological methods (nitrification/denitrification/anammox) have demonstrated high performance in removing nitrogen and ammonia from landfill leachate. Moreover, coagulation/flocculation methods have exhibited high efficiency in removing suspended solids and turbidity, with a removal rate of more than 90%. Bioremediation has demonstrated varied removal efficiency for COD, ranging from 17.5 to 60% depending on bacteria or algae species, thereby failing to show high performance in reducing COD. Finally, physical/chemical treatments have exhibited high performance in removing heavy metals.

ACKNOWLEDGEMENT

We would like to thank the Japan Society for the Promotion of Science for their support and fellowship. This work was supported by JSPS KAKENHI, grant number JP17F17375.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 16 September 2020; accepted in revised form 11 November 2020. Available online 1 December 2020