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Landfill Leachate Treatment Techniques

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ISSN 2364-6934 ISSN 2364-8198 (electronic)
Springer Water
ISBN 978-3-031-63156-6 ISBN 978-3-031-63157-3 (eBook)
https://doi.org/10.1007/978-3-031-63157-3

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Municipal solid waste landfills generate highly polluted landfill leachate, containing heavy metals, organic compounds, and hazardous chemicals. Landfill leachate is the liquid from water percolating through a waste stockpile, and its composition varies depending on the waste and civilization. Treatment of landfill leachate is crucial to prevent environmental pollution and ecotoxicity, but it is complex and costly due to high pollution loading and variable volume.

Waste management in general, and municipal solid waste in particular, is one of the significant challenges facing our societies. With ever-increasing and diversified consumption worldwide, waste production is steadily increasing in quantity, creating enormous risks for the environment and human health. The mechanisms involved in leachate production at landfill sites are biological and physicochemical. The liquid residues of these wastes, following their fermentation and bio-physical-chemical evolution, are a source of juices that penetrate the layer of waste and are enriched with soluble elements of the waste. Rain falling on the landfill and percolating through the thickness of the waste will increase the quantity of leachate. Reducing pollution from these discharges using various discharge treatment techniques offers several advantages: To mitigate the potential harm caused by contaminating the ecological system through overflowing or seepage, as well as the contamination of the groundwater reservoir, it is essential to take preventive measures and implement sustainable practices to safeguard the environment from adverse effects. To enhance the decomposition process of organic substances within the waste accumulation, consequently leading to a rise in the generation of biogas, a concerted effort can be made through various means, such as optimizing environmental conditions, adjusting microbial populations, and implementing efficient waste management practices. To reduce the pollutants in leachates, one can implement strategies to enhance the degradation process of organic matter present in waste materials, thus decreasing the concentration of harmful substances seeping into the environment. The book's contents are comprised of a variety of chapters containing case studies that delve into topics such as leachate collection methods employed at landfill sites, the evaluation of pollution levels resulting from leachate, the environmental consequences associated with such pollution, and lastly, methods for treating pollution to maintain control over it. These case studies demonstrate the least expensive and most commonly utilized biological and physicochemical treatment approaches that effectively diminish pollution levels. Storing leachate in anaerobic conditions within landfill sites has shown its ability to decrease pollution, especially in regions with abundant sunshine. Furthermore, certain countries with elevated temperatures have used stored leachates to water solid waste that has undergone composting treatments. Identifying techniques specifically tailored to address the treatment of these discharges is essential, taking into account the initial conditions and the specific requirements of the surrounding environment. This responsibility is fundamental to our ongoing, urgent efforts to enhance waste management practices. Numerous measures are available to alleviate the negative impacts caused by pollution, although many of these solutions, such as evaporation, reverse osmosis, or mechanization, come with substantial costs. The book encompasses a diverse array of chapters featuring case studies on leachate collection procedures at landfill sites, evaluation of pollution levels stemming from leachate, environmental repercussions, and methods for pollution control. The case studies showcase the most cost-effective and commonly employed biological and physicochemical treatment methods that successfully reduce pollution levels. Storing leachate in anaerobic conditions within landfill sites has effectively decreased pollution levels, particularly in regions with ample sunlight. Additionally, in certain nations with high temperatures, stored leachates are utilized to water solid waste treated through composting. In conjunction with anaerobic or aerobic biological treatment techniques, the book extensively covers physicochemical treatment approaches such as coagulation-flocculation, flotation, and chemical oxidation, providing in-depth real-life case studies. These techniques yield treated water that can be reused for irrigation purposes. Selecting the appropriate leachate treatment method is a multifaceted decision-making process that necessitates consideration of various factors, including waste quality, environmental impacts, costs, and feasibility of implementation. As a comprehensive resource, this book is designed to aid in selecting a treatment technology that offers the lowest capital and operational expenses, guiding individuals through this critical decision-making process and providing the necessary support. Effective treatment methods for landfill leachate include combining biological, chemical, and physicochemical processes to meet treatment standards and minimize environmental and health impacts. Therefore, suitable and efficient treatment for leachate is essential. Recent technologies for leachate treatment removal are highlighted.

Physicochemical methods like coagulation-flocculation, adsorption, and membrane filtration are effective for well-aged leachate while biological methods like membrane bioreactors and activated sludge processes work best for young leachate.

Combining treatment methods shows promise in removing metals and optimizing removal efficiency, but further research is needed to enhance the effectiveness of these techniques.

This book will provide a comprehensive reference for up-to-date knowledge about leachate treatment. Consequently, individuals pursuing a master's or doctoral degree, along with academics, researchers, and students, will be able to comprehend the latest advancements in Landfill Leachate Treatment Techniques, thereby bolstering their investigations. Additionally, this publication will serve as a source of inspiration, guiding readers on practical approaches to address environmental pollution issues resulting from the contamination of freshwater and agricultural soils by leachate, utilizing a diverse array of technologies.

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Chapter 1
Municipal Solid Waste Landfill Leachate Treatment: A Review

Anshu Gupta, Akanksha Verma, and Paulraj Rajamani

Abstract One of the main problems posed by municipal solid waste landfills is the generation of leachate and the main issue related to landfill leachate is its treatment, especially in developing countries. Landfill leachate is highly polluted discharge containing high loads of heavy metals, organic compounds, ammonia (NH_3-N), chemical oxygen demand (COD), toxic chemicals, pathogens, and various other hazardous chemicals. It must be treated and appropriately disposed in order to avoid the environmental pollution and ecotoxicity caused by its disposal. The type of method selected for treatment depends upon the quality as well as quantity of leachate. The composition as well as quantity of leachate depends upon several factors like type of landfill, age of landfill, seasonal variations, degree of compaction, climatic conditions, precipitation, mode of operation etc. Therefore, the development of an efficient method for treatment of landfill leachate is very crucial. For the treatment process of landfill leachate, several methods including physicochemical, biological, chemical, and physical methods have been used. However, these methods are very complex and costly as they require various processes. Also, due to high pollution loading, complex chemical composition, and seasonally variable volume of leachate the treatment process become very difficult. Therefore, it becomes necessary to implement a combination of different methods including biological, chemical, and physicochemical processes for the effective treatment of leachate. The main objective behind treatment of landfill leachate is to make leachate meet the treatment standards so that it poses least impact on the environment as well as human health after its disposal.

Keywords Municipal solid waste · Landfill leachate · Leachate treatment · Ecotoxicity · Treatment standards

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S. Souabi and A. Anouzla (eds.), *Landfill Leachate Treatment Techniques*, Springer Water, https://doi.org/10.1007/978-3-031-63157-3_1

1.1 Introduction

Among the several methods of managing solid waste, landfilling is the most widely used and preferable method [34]. It is preferred due to several factors including technical feasibility, ease of operation, requirement of minimum supervisions and technology, as well as low operation expenditure [45]. The infiltrating water which passes through the solid waste landfill and transfers the contaminants from solid phase to liquid phase results in the formation of landfill leachate. Due to the heterogenous nature of the waste and because of the different compaction densities that will be encountered, water will be able to percolate through and appear as leachate at the base of the site [18]. The physical appearance of leachate is yellow or blackish colored and the smell is acidic and offensive when it emerges from a typical landfill. The quality of landfill leachate is affected by various factors, such as the waste type, operational conditions, climate, hydrogeology, and age of landfill [24]. The composition of landfill leachates varies greatly depending on the age of the landfill [1, 60]. The content of pollutants in leachate is usually high in the early years of operation and gradually decrease with the time [60]. In large parts of Asia, landfill characteristics are influenced by the monsoon climate, which includes the characteristic differences between the rainy season and dry seasons. Leachate in dry season is concentrated because of the evaporation whereas in the rainy season, large amount of leachate is produced with low concentration of pollutants [89, 93]. For the proper and efficient operation of leachate treatment, evaluation of seasonal variation plays an important role [59, 85].

1.2 Properties/Characteristics of Landfill Leachate

Landfill leachate is characterized by conventional parameters comprising of chemical oxygen demand (COD), total organic carbon (TOC), biochemical oxygen demand (BOD), suspended solids, pH, ammonia (NH_4^+-N) and heavy metal concentrations. The ratios of BOD_5/COD and COD/TOC are typical indicators for the biodegradability of organic compounds and the oxidized state of organic carbon [24]. The strength of leachate of one landfill differs from that of another. It is due to the variation in the composition of solid waste. A developing country experiences a higher organic content in the composition of MSW compared to a developed country [73].

Several factors affect the rate and characteristics of leachate from a landfill and exhibit considerable differences. These factors include variations in refuse composition and moisture content, degree of compaction, particle size, hydrology of site, the age of landfill as well as seasonal factors such as temperature, precipitation, and moisture content [23, 42, 56]. As the landfill age increases from young to old, the chemical oxygen demand (COD) (organic/inorganic) in the leachate declines whereas the ammonia nitrogen concentration starts rising. High ammonia concentration in the old landfill leachate is due to the hydrolysis and fermentation of nitrogen-containing fractions of biodegradable refuse substrates [1]. Gupta and Rajamani [33] found the leachate Pollution Index (LPI) values for all the three landfill sites in Delhi indicate that the leachates produced from these sites are highly polluted, hazardous and should be treated before disposing them to the environment. The individual values of the pollutants should meet the standards set by the authorities for these pollutants. Concentration of Chromium, Pb, BOD_5 and COD in the leachate samples was found beyond the permissible limits set by as per the Gazette of India, for leachate disposal in all the leachate samples [31].

1.3 Environmental Issues Posed by Landfill Leachate

Landfill leachate has been generally found toxic, presenting potential threats to the surrounding environment and ecosystems [10]. The toxicity is generally determined based on its physicochemical properties, with ammonia, chemical oxygen demand (COD) and heavy metals being identified as the major contributors. Wdowczyk and Szymanska-Pulikowska [93] have reported that the toxic nature of the leachate may have resulted from the occurrence of high concentrations of ammonical nitrogen (AN), copper, and chromium. Gupta and Paulraj [33] have also reported a very high concentration of ammonical nitrogen in the landfill leachate samples. In the previous studies [31] have reported that the toxicity of landfill leachate was dependent on the concentration of heavy metals (Pb, Cu), conductivity and organic matter (COD and BOD_5). Gupta and Paulraj [32] have reported that landfill leachate collected in three seasons (summer, winter, and monsoon) caused toxicity in *Vicia faba* seedlings by inhibiting growth, antioxidant enzyme activities as well as a reduction in chlorophyll content. The Transmission Electron Microscopy (TEM) images of cells of *Vicia faba* root tips which were highly stressed by the contaminated leachate, provide new evidence for the presence of autophagic vacuoles in the cells [34]. Gupta et al. [35] have further found that their results evidently indicate the ability of landfill leachate to interrupt mitochondrial redox homeostasis, which might be a likely source for the immunotoxic consequences leading to plausible patho-physiological conditions in humans susceptible to such environmental exposures. If exposed for long term, it promotes an increase and accumulation of chromosomal aberrations affecting the cellular mechanisms, leading to a loss of cellular control, neoplasia, and cellular apoptosis [51]. Gupta et al. [34] have stated that that if leachate is released into the environment without treatment, it can lead to contamination of the aquatic environment in the vicinity of the landfill even at diluted concentrations. Their study also states that the long-term exposure to toxic agents that are present in leachate has a strong impact both on the environmental health and on the organisms living in the ecosystem posing a risk to the organisms exposed. Several methods are included to lessen the harmful health effects of wastewater on the surrounding biota, such as restricting inappropriate disposal of industrial and urban effluents and carrying out proper treatment of industrial and municipal solid waste before dumping it into the water body [91, 92]. Gupta and Rajamani [32] suggested that the most important

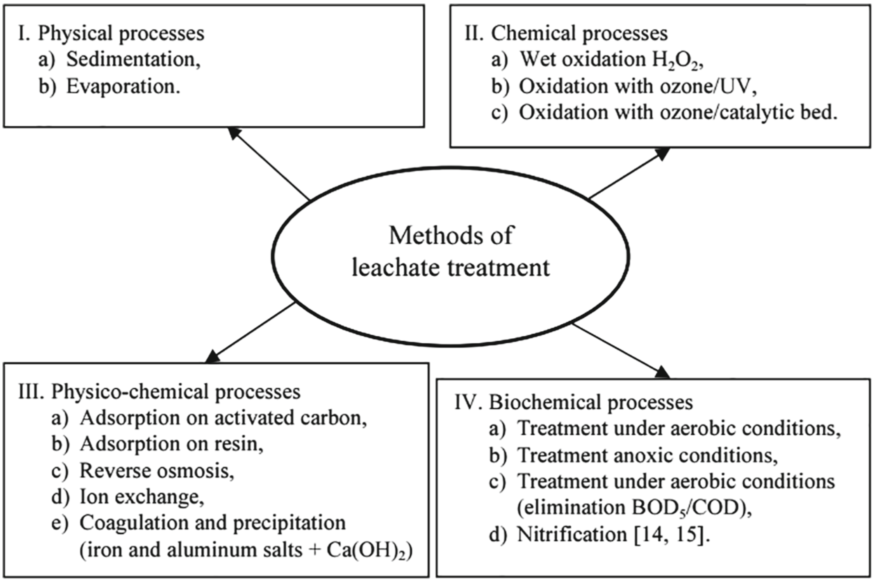

Fig. 1.1 Commonly used Leachate treatment methods for Landfill Leachate. *Source* Jelonek and Neczaj [41]

aspect for the treatment of landfill leachate is controlling its concentration which varies with respect to different seasons so that the proper management of landfills is ensured. Following the findings of these earlier studies, efforts are being made to address the issue of leachate treatment to reduce the impact on the environment and human health caused by percolation into groundwater and the contamination of surface water [7, 9, 48, 80].

1.4 Treatment of Landfill Leachate

The treatment methods for landfill leachate can be categorized as, biological, physical–chemical, and chemical methods, biochemical processes (Fig. 1.1). Besides this, conventional methods that include recirculation of landfill leachate and transfer of leachate to sewage treatment plants are also practiced.

1.5 Conventional Treatment Methods for Landfill Leachate

Recirculation and transfer of leachate to sewage plants are the traditional techniques for landfill leachate treatment.

Landfill leachate recirculation: Due to ease and very less operational cost, landfill leachate recirculation has been extensively employed in previous decades. The key influencing factors in the effectiveness of recirculation are frequency of recirculation and volume. However, it may lead to accumulation of refractory substances in the leachate due to multiple cycles of recirculation. It affects the stability of the landfill system resulting in rise in difficulty of successive landfill leachate treatment [22].

Transfer of landfill leachate to sewage plants: Discharge of landfill leachate to wastewater treatment plants (WWTPs) is also a convenient and inexpensive method for landfill leachate disposal. However, the effectiveness of downstream treatment processes is significantly affected and the overall treatment efficiency is reduced due to the addition of leachate containing high concentrations of Dissolved organic matter (DOM) [26].

Furthermore, recalcitrant organic compounds have been found resistant to biological degradation, allowing them to pass through WWTPs. In addition, effective pretreatment should be employed to remove UV-quenched substances as the non-degraded organic compounds, especially persistent UV-absorbing DOM, can significantly interfere with UV disinfection in WWTPs [99]. This will reduce the negative effect of landfill leachate on UV disinfection.

1.6 Integrated Treatment Technologies in Leachate Treatment

In order to fulfil and satisfy the strict discharge limit standards set up by the authorities, it is very crucial to develop and find a new alternative in leachate treatment. It is therefore common to integrate various treatment technologies either conventional or advanced processes. Figure 1.2 explains the diverse leachate treatment techniques that might be applied as an integrated treatment technologies in leachate treatment.

1.7 Natural Attenuation

Constructed wetlands (CWs): According to Verma et al. [90], the amalgamation of different physical, chemical and biological processes occurring in nature, which can efficiently reduce concentration, toxicity, and/or mobility of contaminants can be defined as natural attenuation. CWs are mainly of two types, free surface water system and subsurface flow system, depending on the nature of wastewater flow. The treatment of wastewater in CWs involves a combination of biological and biochemical processes [94]. The wetlands provide suitable setting for speedy natural attenuation of organic contaminants. It happens due to the presence of large diversity of microorganisms, nutrients in the discharging groundwater, and a wide range of

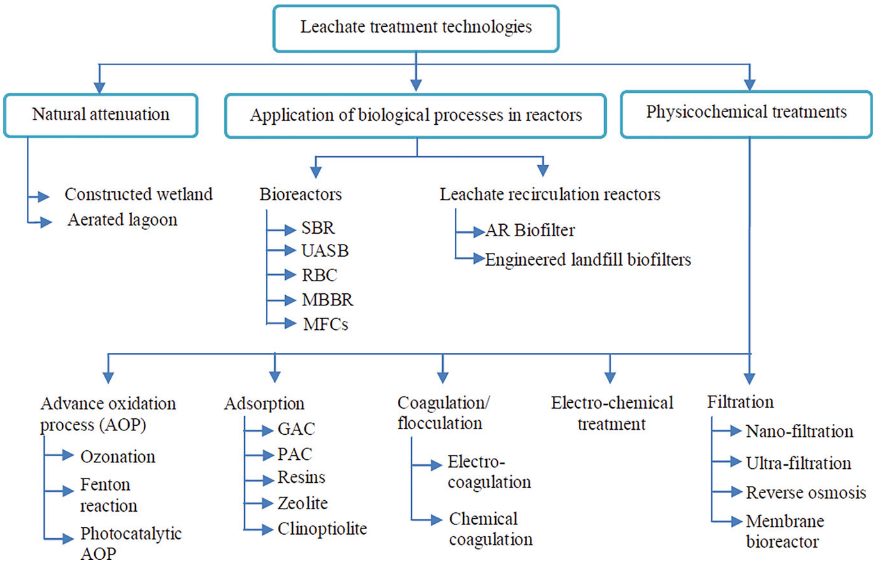

Fig. 1.2 Classification of Leachate treatment Technologies. *Source* Mukherjee et al. [66]

redox conditions in the surrounding groundwater or surface water interfaces [57, 87]. Microbial communities present in CWs can break down the complex organic compounds in wastewaters. The rate of attenuation of organic contaminants increases with age as the microbial population increases in a CW [20].

Phytoremediation: It is an attractive technology for landfill remediation and according to Kim and Owens [49], it can stabilize soil while simultaneously remediating landfill leachate. Plants planted in CWs influence the redox potential by supplying oxygen to the soil in the root rhizospheric zone. In this zone, enhanced nitrification by nitrifying bacteria takes place, thereby reducing the NH_4-N concentration in the landfill leachate [15]. CWs show high BOD_5, TN, and FCs removal efficiency of 91%, 96%, and more than 99%, respectively [17, 61, 76, 94]. Examples of leachate treatment in CWs and the achieved efficiency is tabulated in Table 1.1.

An aerated lagoon: It is a biological purification technique that uses free culture with an artificial oxygen supply [96]. The variance between an aerated lagoon and activated sludge is that the former does not sustain a fixed concentration of microorganisms [12, 97]. Luo et al. [58] have shown that for the on-site treatment of landfill leachate, aeration tanks are a simple and effective method that also has low-cost, where treatment is performed by biological oxidation. Researchers treated leachate having comparatively low COD (an average of 1740 mg L^{-1}) and high ammonium (an average of 1241 mg L^{-1}) levels using four interconnected aerated lagoons. With a total nitrogen load removal of 80%, the COD removal efficiency averaged 75%. Other studies treated leachate having 5050 mg L^{-1} DOC (dissolved organic carbon) and 1670 mg L^{-1} TN using a two-stage anaerobic/optional lagoon system (i.e., 32 days

Table 1.1 Overview of leachate treatment techniques involving natural processes

Technology	Mechanism and process	Scope	Efficiency (%)	Country	Advantage	Disadvantage	Selected references
Constructed wetlands	Phytoremediation by cattail and in situ microorganisms	BOD_5	91				
		TN	96	Thailand	Low operation and maintenance cost	Buildup of excessive salts in soil due to poor understanding of soil plant system and improper management	[77]
		FC	> 99				
		Total P	98–99				
		Cd	99.70				
	Phytoremediation by reeds and cattail	BOD_5	50				
		COD	59	Slovenia	Low operation and maintenance cost	Slow operation in the initial phase	[17]
		NH_3-N	51				
		Total P	53				
		Fe	84				
		Chloride	35				
	Phytoremediation by cattail (*Typbalatifolia*)	COD	27.30				
		NH_4-N	62.30	Turkey	Low operation and maintenance cost	Low removal in the initial phase, Long stabilization period	[94]
		PO_4-P	52.60				
		Fe (III)	21				
	Phytoremediation by *Phragmitesaustralis* and Salix purpurea	SS	83.70	Slovenia	Leachate reuse as fertilizer for the growth of energy crops	Large amount of elements percolate back into the waste layers after irrigation	[43]
		BOD_5	65.50				
		NH_4-N	41.90				
		Total P	38.40				

(continued)

Table 1.1 (continued)

Technology	Mechanism and process	Scope	Efficiency (%)	Country	Advantage	Disadvantage	Selected references
		Phenols	61.70				
Aerated lagoons	Microbial oxidation, plant uptake	COD	75	United Kingdom	Low operation and maintenance cost	Long hydraulic retention time	[61]
		TN	80		Suitable for the removal of N		

Source Mukherjee et al. [66]

for the anaerobic part and 240 days for the facultative part) and ultimately achieved removal efficiencies of 40% for COD, 64% for BOD, 77% for NH_4^+-N, 63% for NO_3-N, 77% for TN, 42% for P, 44% for SO_4^{2-}, and 44% for Mn [58]. Furthermore, the feasibility of treating phenolic and organic chemicals in an aeration tank was also explored. The tank was found to eliminate approximately 55–64% of the COD and 80–88% of the phenol from leachate [58]. The advantages of using aerated lagoons for leachate treatment include: the achievement of a correct bacteriological yield, limited operating constraints, the possibility of treating concentrated effluents, less sensitivity to hydraulic load variations, the possibility of adapting to seasonal variations in organic load, the storage of sludge for 10–15 years, and good landscape integration [96].

The potential disadvantages of the system are mainly related to the use of electromechanical equipment requiring a specialized agent for maintenance, possible noise pollution, and a relatively high operating cost (high energy consumption) [86].

1.8 Physicochemical Processes

The physical and chemical processes are the processes that help in reducing the suspended solids, colloidal particles, floating material, color, and toxic compounds by either flotation, coagulation-flocculation, adsorption, chemical oxidation or air stripping. Physical/chemical treatments for the landfill leachate are used in addition to the pre-treatment or to treat a specific pollutant (stripping for ammonia) [72]. For the treatment of landfill leachate, the common chemical methods used comprise of coagulation-flocculation, chemical precipitation, and chemical and electrochemical oxidations. Meanwhile, the major physical leachate treatment methods are air-stripping, adsorption and membrane filtration [95].

Electrocoagulation (EC): Another interesting method for the treatment of landfill leachate is by electrocoagulation. EC is an electrochemical method that treats different types of waste water by making use of electrical current without adding chemical coagulants. This method can efficiently remove small particles or colloidal pollutants content in wastewater [19]. It not only effectively removes pollutants from several wastewater such as slaughterhouse wastewater, dairy industry wastewater, vegetable oil refinery, nitrate-bearing wastewater, wastewater containing heavy metals and pesticides and phenolic compound, but it can also efficiently remove fluoride and humic acid content in leachate. The coagulants in situ are generated in EC method when aluminium or iron ions coming from aluminium or iron electrodes are electrically dissolved [11]. EC has become one of the reliable methods for landfill leachate treatment and has also received a substantial attention as it offers lots of advantages. Advantages of EC method include:

- less production of sludge, does not require chemical, easy to operate, low cost and operating in a short time [39].

- EC in leachate/wastewater treatment only needs a simple equipment, easy to work with and the process produces flocs similar to the chemical flocs. The flocs produced are expected to be larger, more stable and contain less bound water. They also stated that the TDS content after EC process is lesser than after the chemical treatment [65].
- Mohammadizaroun and Yusoff [64] found that the EC process requires less maintenance as the electrolytic processes in the EC cells are being controlled electrically and no moving parts even without the supply of electricity (such as rural area), the EC can still be operated using the sufficient energy available from the solar board attached to it.

Advanced Oxidation Process (AOP): In recent years, for the removal of organic materials and degradation of recalcitrant pollutants in wastewater, advanced oxidation processes (AOPs) have been recognised as an alternative method and the most promising procedures [1, 81]. Chemical oxidation process is the main treatment method in AOP techniques. Generally, there are two processes involved in AOP method, the first process is the formation of highly reactive free radical and the second process is the chemical reaction of radicals produced with an organic compound present in water [38]. The AOPs can be divided into two type of oxidation processes: chemical and photochemical oxidation [81]. The example of each type is listed in Table 1.2 [41].

Adsorption: Adsorption process is considered as one of the most effective and promising approaches for removing DOM and NH_4^+-N in landfill leachate. It is recognized as one of the most efficient and extensively used fundamental approach in wastewater treatment processes [25, 50]. For the treatment of landfill leachate, the adsorbents with characteristics like a large surface area, microporous structure, surface reactivity, and thermostability have been applied. Activated carbon (AC) are the most used absorbents. Traditionally activated carbon has been used for leachate treatment due to its large porous surface area, controllable pore structure, thermal

Table 1.2 Examples of photochemical and chemical processes

Advanced oxidation processes-(AOPs)			
	Photochemical processes		Chemical processes
1	UV photolysis	1	Fenton reaction Fe^{2+}/H_2O_2
2	Reaction photo-fenton	2	Oxidation with ozone and hydrogen peroxide
3	Processes using UV/H_2O_2	3	Electrochemical oxidation
4	Processes using UV/O_3	4	Oxidation in supercritical conditions (supercritical water oxidation-SCWO
5	Processes using $UV/H_2O_2/O_3$	5	Wet air oxidation-(WAO)
6	Photocatalytic degradation in aqueous suspension semiconductors		
7	Processes with ultrasound		

Source Jelonek andNeczaj [41]

stability, and low acid/base reactivity [52, 62]. Activated carbon has a superior ability to remove a wide variety of organic and inorganic pollutants dissolved in aqueous and gaseous environments [21, 83]. AC adsorption can improve the biodegradability of old landfill leachate, although the overall COD removal rate is low, with only 40% of organic matter removal achieved with 10 g/L AC, while the BOD_5/COD ratio increased from 0.18 to 0.56 [30]. AC adsorption preferentially removed the chromophoric DOM with hydrophobicity and microbial by-products in fluorescent DOM [26]. The addition of powdered activated carbon (PAC) improved the performance of biological treatment of leachate [46, 47]. Lim et al. [54] used EDTA modified rice husk in a sequencing batch reactor (SBR) and achieved better COD and nitrogen removal efficiency as compared to commercially available PAC. Activated carbons can be prepared from a large variety of carbon containing materials through pyrolysis. Large number of agricultural byproducts have been used to prepare inexpensive and renewable additional source of activated carbons such as sugarcane bagasse, rice straw, soybean hulls, rice hulls, peat moss, nutshells, and other lignocellulosic wastes [5, 44, 74]. Other low-cost adsorbents that have been successfully used for heavy metal (HM) removal are peat and rubber wood ash [36, 78]. These adsorbents may also be used for the treatment of leachate. A basic two stage process consisting of carbonization followed by activation is followed to produce activated carbons. In the first step the carbon content is enriched for the creation of an initial porosity and second activation stage helps in enhancing the pore structure [2, 3]. The combinations of hydrophilic and hydrophobic groups in the adsorbents make an excellent adsorption system which can remove both metallic ions and organic substances [68]. Addition of PAC to activated sludge reactors has shown to enhance the biological treatability of leachate [6]. The main drawbacks of AC adsorption include the requirement for AC regeneration and high levels of adsorbent consumption. Therefore, finding a low-cost and effective adsorbent has attracted much research attention. AC prepared from $ZnCl_2$ treatment of sewage sludge and cabbage has been applied to treat landfill leachate by adsorbing DOM, achieving a COD removal rate of 85.61% under optimal conditions [98]. Zeolite has also been applied for the treatment of landfill leachate as post-treatment with COD removal rates of 30% [69]. Recently, biochar has emerged as a good substitute for AC. Phosphoric acid activated biochar prepared from rice husk has been successfully used for the treatment of landfill leachate, resulting in about 80% removal of COD [58].

1.9 Biological Treatment

Due to its simplicity, dependability, and excellent cost-effectiveness, biological treatment is frequently employed for leachates containing significant amounts of organic compounds but retaining high BOD concentrations [27]. Biological treatments can be classified as aerobic or anaerobic, depending on the oxygen present. Organic substances are biodegraded by bacteria under aerobic conditions, producing carbon dioxide (CO_2) and sludge, whereas under anaerobic conditions, biogas (a mixture composed mainly of CO_2 and CH_4) is produced. Biodegradation is extremely successful at eliminating organic and nitrogenous materials from juvenile leachate with a high BOD/COD ratio (> 0.5) [63]. The significant presence of refractory chemicals, primarily humic and fulvic acids, limits the effectiveness of such processes over time. Biological treatment of landfill leachate is broadly used due to its low economic costs and environmental impacts. However, a considerable number of refractory species remain in the effluent. In addition, organics, inorganic salts and metals have been found to pose inhibitory effects on activated sludge [30]. Therefore, the effectiveness of biological treatment largely depends on the type and composition of landfill leachate. Consequently, biological treatments are usually selected to treat young landfill leachate with high biodegradability.

Aerobic treatment: During aerobic treatment, the nitrification of ammonia nitrogen is carried out and organic contaminants that are only partially biodegradable are removed. Some aerobic biological processes including aerated lagoons, aerobic activated sludge, sequential batch reactors, rotating biological contactors, bacterial filters, moving bed biofilm reactors, fluidized bed biofilm reactors, membrane bioreactors (MBR), engineered wetlands, fungal treatments, and phytoremediation have all been successfully used to treat landfill leachate [88]. Aerobic biological treatments use microorganisms naturally present in the natural environment to degrade the pollutants. For example, in inactivated sludge-type treatment plants, the oxygen supply might be artificial (turbine or microbubble diffusion) or natural (wind or cascade system) in small lagoon facilities [67, 75]. Although aerobic techniques have successfully eliminated ammonia and organic pollutants, several disadvantages of these techniques have forced us to concentrate on other technologies [13, 84]. Among these drawbacks are [40, 40]:

- The need for a long aeration period
- A high energy demand and extra sludge generation
- Microbial suppression due to a high ammonia nitrogen content.

Fluidized bed biofilm reactor (FBBR): Due to its benefits—high biomass concentration, high removal performance, high shock tolerance, a stable ecosystem, good heterotrophic denitrification impact, and low energy consumption—the aerobic fluidized bed biofilm reactor (AFBBR) has gained much popularity in recent years. The amount of industrial wastewater produced has increased dramatically [14]. The primary goal of AFBBR technology, which has a density similar to wastewater, is to achieve homogeneous fluidization of the suspended media through aeration. This can enhance the amount of time that the biofilm on the suspension medium's surface touches the wastewater. The system ultimately accomplishes effective wastewater treatment [71]. FBBRs (fixed bed biofilm reactors) are a commonly used technology for BOD and ammonia removal in wastewater treatment. Compared to activated sludge, FBBRs are less sensitive to volatile flows, interrupted aeration, or grease leakages, making them a good choice for industrial applications, such as in the food and beverage, dairy, and chemical industries. FBBRs consist of two main components: plastic film holders and air diffusers. Different film-support designs are selected depending on the BOD and ammonia loading [53, 55, 70]. However, in most cases, a vertical flow channel design will provide sufficient surface area and reduce the risk of clogging. The submerged biofilm on the film's surface requires oxygen for BOD and ammonium removal. The aeration diffusers provide oxygen. The first microorganisms settle after about 2 weeks on the film's surface. To continue the growth of the biofilm, the microorganisms digest the organic waste (BOD) and consume the oxygen supplied by the aeration diffusers. Only after all the BOD has been removed can the oxidation of ammonium NH_4^+ to nitrite NO_3^- begin. In the first step, microorganisms facilitate the oxidation of NH_4^+ to NO_2^- (nitrite), H+ acid, water, and ATP. Then, in the second step, nitrite is further oxidized to NO_3^- nitrate and more ATP [12, 29, 96].

An advantage of such a system is that the broad flow rate range of the aeration diffusers allows flexible operation [96]. This is very important when less BOD and ammonia are present. Reducing the oxygen supply will reduce energy costs but the same effluent results will be maintained. When more BOD and ammonia are present, increasing the oxygen supply will result in more significant removal of BOD and ammonia, so no further upgrading is required. If too much biofilm is produced, the filler material can become clogged, substantially increasing the oxygen supply will cause a scouring effect and clean the blocked channels. Per our instructions, the scouring process can also be automated by programming a VFD for specific intervals. Additionally, the oxygen input can be minimized for energy saving by monitoring the DO, BOD, and ammonia levels [29].

1.10 Combination of Methods

Activated sludge process has been reported to remove up to 52.5% of COD from landfill leachate with a BOD_5/COD ratio of 0.17 [79]. However, the disadvantage of activated sludge process is that it may produce large amounts of sewage sludge. Because of their ineffectiveness in the degradation of bio-refractory organics, standalone biological treatments generally fail to meet discharge standards. To overcome this limitation, biological treatments are often coupled with physicochemical processes. In a recent study, electrocoagulation-biofiltration hybrid techniques have been used to treat landfill leachate, with the electrocoagulation process achieving 37 $\pm$ 2% COD removal, mainly in the form of insoluble COD and HA, followed by 42 $\pm$ 7% COD removal in the subsequent biofiltration process [28]. The integration of the air-stripping, MBR and nanofiltration (NF) processes can provide highly efficient landfill leachate treatment, resulting in an overall reduction in COD, ammonia, color and toxicity of approximately 88, 95, 100 and 100%, respectively [8]. Recently, MBR technology has emerged as a promising method for the treatment of landfill leachate, utilizing a combination of membrane separation and biodegradation processes. MBR has many advantages in the treatment of landfill leachate, such as high effluent quality acquisition, high process stability, low environmental impacts, increased retention of mixed liquor suspended solids biomass and low sludge production. Depending on the landfill age and operational conditions, MBR has been adapted to treat landfill leachate, resulting in a wide variation in COD removal efficiencies, ranging from 23 to 90% [4]. Compared with conventional activated sludge processes, MBR has a higher loading rate and higher COD removal efficiency at a shorter hydraulic retention time.

The choice of one treatment technique over another is strongly linked to the composition of the leachate, its age, and the purification performance required by the standards in force [37, 82].

Biological processes are based on the activity of microorganisms contained in the leachate and the activity of external microorganisms, depending on the type of process used. They are generally very effective for the treatment of young leachates with a BOD/COD ratio exceeding a value of 0.5. The treatment results in reductions in NH_3, NH_4^+, iron, and biodegradable organic matter (Table 1.3). On the other hand, this treatment produces a large quantity of sludge which subsequently requires another treatment (Table 1.3). Physicochemical processes are more effective for the treatment of aged or stabilized leachates. Indeed, over time, the leachates are enriched with compounds refractory to biodegradation, which inhibits the activity of microorganisms and limits the effectiveness of biological processes. This treatment is known for its formation of sludge and the use of chemicals during treatment, depending on the type of treatment used. However, it does separate pollutants in suspension and colloidal particles [77, 82].

Table 1.3 Comparison of conventional treatment methods

Process	Features	Benefits	Disadvantages
Biological	Use of bacterial culture	Inexpensive Removes NH_3, NH_4^+, iron and biodegradable organic matter	Substantial production of sludge Ineffective in the presence of toxic and non-biodegradable pollutants
Physical (activated carbon filteration, membrane filteration)	Non-degrading	Separation of particulate or dissolved pollutants	High investment and energy costs Generation of concentrates
Physical–chemical	Fixation of pollutants by coagulation and separation of the flocs formed	Separation of suspended pollutants and colloidal particles	Use of chemicals Sludge formation
Chemical	Use of an oxidant Cl_2, ClO_2, O_3	Chemical oxidation of pollutants-little or no waste Increased biodegradability	Partial oxidation (formation of intermediates) Oxidant management

Source Bouaouda et al. [16]

1.11 Conclusion

As the population is growing, the quantity of solid waste generated is also increasing. It is further leading to continuous upsurge in the quantity of leachate generated from landfills. As the leachate is highly contaminated and polluted, it is pertinent that it must be treated before being discharged into the natural environment. Conventional as well as natural treatment methods are carried out for leachate treatment. Along with these, various techniques can be used for this purpose, such as biological, physical–chemical, and membrane methods. Most physical–chemical treatments are used as pre-treatments or post-treatments to complement conventional treatment processes or remove specific contaminants. These treatments effectively remove organic compounds that are difficult to decontaminate biologically. The type of method or technique selected to treat the leachate depends upon several factors including type of landfill, age of landfill, seasonal variations, degree of compaction, climatic conditions, precipitation, mode of operation, type of waste, moisture content, etc. As young leachate is biodegradable; in contrast, biological processes lose their effectiveness with leachate aging as the aged leachates are characterized by high concentrations of ammonia nitrogen that inhibit their activity. For leachate treatment, the contemporary trend encompasses an amalgamation of biological, chemical, and physicochemical processes in multiple-stage treatment systems. Preferred methods depend on various technical considerations, which should be adequately evaluated because one method cannot generally be used for common applications. A number of research works have been carried out in order to come out with a treatment system that can improve performance and is cost effective. For developing sustainable treatment technologies for the treatment of landfill leachate, the main criteria are treatment efficiency, meet the treatment standards, reduced cost and minimising negative environmental consequences.

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