EREM 82/1

Journal of Environmental Research,
Engineering and Management
Vol. 82 / No. 1 / 2026
pp. 129–144
10.5755/j01.erem.82.1.41570

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Received 2025/05

Accepted after revisions 2026/01

https://doi.org/10.5755/j01.erem.82.1.41570

Assessment and Selection of Aerobic Biological Treatment Technology for Closed Landfill Leachate

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The post-closure phase of landfills poses ongoing challenges due to the continual production of leachate. Leachate is a complex liquid mixture of toxic pollutants that are characterized by the presence of complex inorganic and organic contaminants that can potentially impact human health and the natural environment. There is need for the selection and application of appropriate treatment technologies to minimize potential contamination risks in soil, surface water, groundwater and the environment at large. A commonly applied treatment technology for landfill leachate is the aerobic biological treatment. This study conducted a comprehensive review of the most suitable aerobic biological treatment technologies for leachate from closed landfill sites. A Multi-criteria analysis (MCA) was employed to evaluate five aerobic biological leachate treatment technologies for closed landfill. The MCA used a structured approach that considers 16 criteria, grouped into environmental, technical, economical, and social categories to help breakdown the contribution of each category to the leachate treatment technologies and to select the most suitable treatment technology. The results of the MCA showed that Sequencing batch reactor (SBR) outperformed other treatment technologies, with an overall index score ranging from 6.84 to 8.25 out of a maximum of 10.00. The next ranked treatment technology was membrane bioreactor (MBR), with an overall index score ranging from 5.35 to 6.55. The lowest ranked treatment technology was activated sludge (AS), with an overall index score ranging from 4.18 to 5.34. A sensitivity analysis was conducted to evaluate the influence of variation in weighting factors under 7 scenarios and the results of the best performing treatment technology remain unchanged. Although, rotating biological contactors (RBC) had second best performance in 3 scenarios due to the reduction of the priority group weight for environmental category. In real world, emphasis is placed on the environmental performance of treatment technology due to the stringent environmental regulations that is applicable to a closed landfill leachate. This study is beneficial for selecting optimal treatment technology that improves treatment efficiency, supports long term leachate management and ensures regulatory compliance at closed landfills. Hence, MCA is a good decision-making tool that can assist waste management experts for selection of optimal treatment technology for long-term leachate management in closed landfills.

Keywords: Multi-criteria analysis, leachate, waste management, closed landfill, aerobic biological treatment.

Introduction

The continual increase in industrialization, global population and affluent lifestyle has resulted in an increase in the amount of waste generated (Renou et al, 2008; Nanda and Berruti, 2021). According to a recent study conducted by Kaza et al. (2018), it is projected that the global waste would rise to 3.4 billion tonnes by 2050, which is equivalent to twice the population growth rate over the same period. In Canada, the primary means of municipal waste disposal is via landfill (Nanda and Berruti, 2021). Globally, 95% of the municipal waste collected is disposed in the landfills (Gao et al., 2015). The landfills receive waste from different businesses, residences and construction sites. Canada currently has over 3000 municipal solid waste (MSW) landfill sites, with close to 50% already closed (ECCC, 2022). Apart from the use of land space for landfill sites, there are other social, economical and environmental concerns associated with the post closure phase of these landfill sites. One of such issues is the continual production of leachate in the landfill.

Leachate is toxic liquid generated from the mixture of infiltrating water percolating through the waste and transferring pollutants from the waste to the water through a series of microbial, physical and chemical processes (Christensen and Kjeldsen, 1989). The composition of the leachate is made up of heavy metals, toxic materials, inorganic materials, organic materials, ammonia, pathogens, minerals, emerging contaminants and humic materials (Eggen et al., 2010; Chavez et al., 2019). This makes leachate a great concern that needs to be properly managed due to the potential risk of pollution of the soil, surface water bodies and the groundwater quality. This can lead to a potential violation of drinking water quality standards, as reported in many literatures (Mor et al., 2018; Maiti et al., 2016; Hepburn et al., 2019).

Leachate characteristics change over time due to the ongoing degradation of landfilled waste. Zhao et al., (2019) classified leachate into recent, intermediate and old, based on its age and variation of the pH, organic content, chemical oxygen demand (COD), biochemical oxygen demand (BOD), heavy metals and biodegradability. In comparison to wastewater, leachate have elevated levels of COD, BOD, total nitrogen (TN), ammonia nitrogen (NH^{+}_{3}-N) and total phosphorus (TP). In addition, there is a stringent requirement to remove or reduce the levels before discharging to the environment (Bayhan and Ozbek, 2015; Kamuriddin et al., 2017). To address the threat posed to the environment, there are environmental regulations in place to ensure continual monitoring and treatment of leachate long after the landfill is closed. One of such regulations is the Ontario Regulation 232/98 (Ontario Regulation, 2011)

There are different treatment and pre-treatment technologies applied to leachate to mitigate the environmental risk and ensure compliance with regulations before discharging leachate to the environment. These are biological processes, physicochemical processes or a combination of more than one process (Igwegbe et al., 2024; Mojiri et al., 2021). Physicochemical treatments are highly effective in removing refractory compounds from leachate and are mostly used to serve as a secondary treatment or in combination with other treatment technologies. The commonly used physicochemical processes are chemical precipitation, coagulation, flocculation, air stripping, chemical oxidation, membrane separation and advanced oxidation (Kurniawan et al., 2006).

Biological treatment methods involve the use microorganisms to degrade organic matter in leachate while chemical and physical treatment methods are processes used to reduce suspended solids (SS) or oxidize organic matter in landfill leachate (Teng et al., 2021). Some studies have also attempted leachate recirculation with waste to stimulate microbial activities and enhance decomposition (Benson et al., 2007). For a closed landfill leachate management, consideration is given to cost as well as effectiveness of treatment technology in reducing COD, ammonia and nutrients. Due to its simplicity and low cost, biological treatment technologies are commonly used for leachate treatment and it is reported to be effective in the removal of organic compounds, nitrogen and ammonia content that are present in closed landfill leachate (Kurniawan et al., 2010). This treatment can be achieved under anaerobic or aerobic conditions. Aerobic conditions have been reported to attain a higher treatment efficiency within a shorter retention time and produce lower sludge quantity when compared to anaerobic processes (Show et al., 2019, Miao et al., 2019). In a closed landfill, most of the organic matter would have become recalcitrant over time, reducing the applicability of anaerobic treatment technologies for closed landfill leachate.

Aerobic biological treatment technologies are the most widely used approach for closed landfill leachate management due to ability to degrade complex organic contaminants and effectiveness in removing nitrogen (Li et al., 2021). The commonly used aerobic processes are sequencing batch reactors (SBR), activated sludge (AS), trickling filters (TF), rotating biological contactors (RBC) and membrane bioreactors (MBR) (Ilmasari et al., 2022). These processes allow for the degradation of pollutants via microorganism activities in the presence of oxygen, leading to the removal of degradable organic material and ammonia. There is a need for detailed analysis, evaluation and comparison of each aerobic biological treatment process for the selection of the most suitable treatment technology. Consideration should be given to the environmental, economical, technical and social impacts of each process, alongside the ability to comply with the applicable regulation. A popular tool that is widely used in the analysis, comparison and selection of best alternatives out of multiple alternatives is MCA. The MCA divides complex and large problems into smaller parts so that each part can be evaluated and the contribution of each part to a whole part is integrated into selecting the best choice. This has been applied to selection of best treatment method in sanitary wastewater treatment (Omran et al., 2021) and petroleum refinery wastewater treatment (Livingstone and Abbassi, 2018).

Hence, the objective of this paper is to review the different aerobic biological treatment technologies for leachate generated in a closed municipal landfill and select the best treatment strategy using MCA. This study strengthens environmental theory by presenting a well-structured and transparent framework for conducting MCA of different aerobic biological treatment technologies, while assessing the environmental, economical, social and technical categories affecting leachate management. The results of this study will provide guidance to waste management experts towards selection of treatment technologies that are socially acceptable, economical and environmental friendly.

Methods

Review of aerobic biological treatment technologies

A comprehensive review of the aerobic biological treatment technologies reported in literature for leachate management was conducted to identify key performance parameters for comparative evaluation. Based on the review, six key parameters were selected for inclusion in the evaluation of the aerobic biological treatment technologies. The parameters are treatment time (HRT), SS, COD, BOD, TN and NH^{+}_{3}-N. *Fig. 1* shows a breakdown of the five aerobic biological treatment technologies considered in this study.

Peer reviewed studies on the application of aerobic biological treatment technologies for leachate management were systematically examined and screened based on data availability in relation to the six selected parameters. The studies were selected if they reported treatment efficiency for at least one of the six selected parameters. For each aerobic biological treatment technology, average values of the selected parameters were calculated using performance data reported under optimal operating conditions across several studies (Aghamohammadi et al., 2007; Yong et al., 2018; Saleem et al., 2018; Aluko and Sridhar, 2013; Castillo et al., 2007). The standard deviation and arithmetic mean for each parameter were determined to estimate the overall effectiveness of each treatment method for subsequent analysis.

Fig. 1. *Overview of aerobic biological treatment technologies*

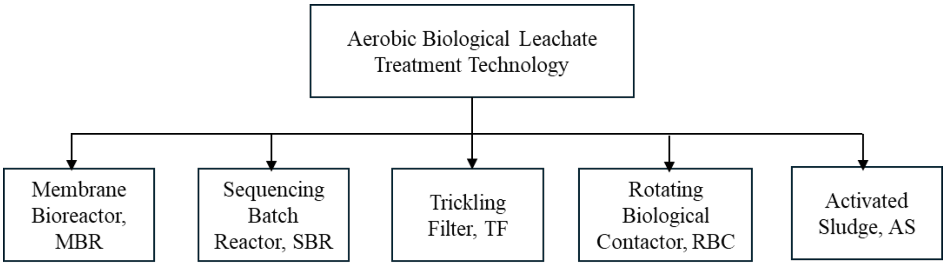
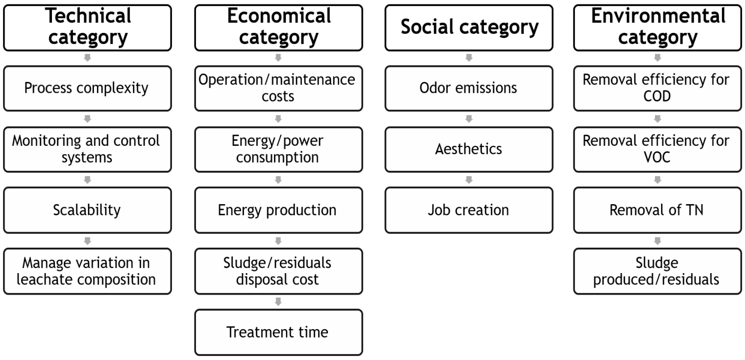


Fig. 2. *Overview of criteria considered in each category in the MCA*



Multi-criteria analysis

For the MCA, sixteen criteria were identified and classified into four categories: environmental, technical, economical, and social. The criteria selected under the environmental category were removal efficiencies for BOD/COD, volatile organic compounds (VOC), TN, and sludge production. For economical category, energy/power related cost, operational/maintenance cost, sludge or byproducts disposal cost and time were selected. For technical category, process complexity, monitoring and control systems, scalability and ability to manage leachate variation in volume and quality were considered. The social category included odor emission, aesthetics and job creation opportunities for each treatment technology. *Fig. 2* shows an overview of the criteria considered in each category in the MCA. The criteria were selected based on their relevance to leachate treatment performance in aerobic biological treatment and data availability in literature. The criteria in each category were selected to capture core parameters for comprehensive MCA of the performance of aerobic biological treatment technologies. It is important to note that in the presence of certain additional datasets that are representative of a site-specific feature, additional parameters may be incorporated to further improve the results, but this study focused on critical parameters based on past studies and industry standards.

Table 1. *Criteria considered in the MCA and determination of ranking indices*

Categories	Criteria	Objective
Economical	Operational/maintenance costs	Minimization
	Energy/power consumption	Minimization
	Energy production	Maximization
	Sludge/residue disposal cost	Minimization
	Treatment time	Minimization
Environmental	Removal efficiency for BOD/COD	Maximization
	Removal of VOC	Maximization
	Removal of TN	Maximization
	Sludge produced/residuals	Minimization
Technical	Process complexity	Minimization
	Monitoring and control systems	Minimization
	Scalability	Maximization
	Manage variation in leachate composition	Maximization
Social	Odor emission	Minimization
	Aesthetics	Maximization
	Job creation	Maximization

In each treatment technology, a ranking index was calculated based on the data and values outlined in the review section for each treatment technology. The approach used to derive the ranking indices is based on the performance and is summarized in *Table 1*. The evaluation of the various aerobic biological treatment technologies for landfill leachate was rated on a scale of 1, 4, 7 and 10, corresponding to their respective levels of performance. This non-linear scale captures significant differences in treatment performance and allows for clearer differentiation between moderately acceptable and highly favorable options. It is commonly used in MCA frameworks and employs four anchor points: 1 (very poor), 4 (poor), 7 (good), and 10 (excellent), ensuring clear separation between performance levels for each criterion. This minimizes overlap in performance ranking and ensures that performance levels in different criteria are captured. A detailed explanation of how scores were assigned for each criterion is presented in *Table 2*.

In the environmental category, equal weightings of 25% were assigned to the removal efficiencies BOD/COD, VOCs, TN and sludge production. Similarly, within the economical category, energy/power related cost, operational/maintenance cost, sludge or byproducts disposal cost and time were each weighted 20%. For the technical category, process complexity, monitoring and control systems, scalability and ability to manage leachate variation in volume and quality were each weighted 25%, while in the social category, criteria such as odor emission, aesthetics and job creation opportunities were weighted 40%, 30% and 30%, respectively.

Table 2. *Criteria scoring matrix showing the assigned performance scores*

Criteria	1	4	7	10
Operational / Maintenance costs	Very high and unsustainable	High and burdensome	Manageable for most budgets	Low and cost-efficient
Energy / Power consumption	Extremely energy-intensive	High energy usage	Moderate energy needs	Minimal energy demand
Energy production	No energy recovery	Very limited recovery potential	Some energy recovered	Significant and consistent energy production
Sludge / Residue disposal cost	Excessive and difficult to manage	High with logistical concerns	Moderate and manageable	Minimal sludge, low-cost disposal
Treatment time	Very slow processing	Time-consuming	Reasonable turnaround	Fast and efficient
BOD/COD removal	Ineffective reduction of organic load	Limited effectiveness, inconsistent	Generally effective	Highly effective and reliable performance
VOC removal	Cannot address VOCs effectively	Minimal effect on VOCs	Capable of removing most VOCs	Very strong VOC reduction and control
TN removal	Poor or no nitrogen control	Limited nitrogen handling	Adequate nitrogen mitigation	Excellent nitrogen stabilization/removal
Sludge produced / Residuals	High volume, hard to manage	Significant sludge generation	Some sludge, manageable	Very low or negligible residuals
Process complexity	Highly complex, requires specialists	Complicated with multiple steps	Reasonably easy to operate	Simple, user-friendly, minimal oversight
Monitoring and control systems	Requires constant manual oversight	Minimal automation, often unreliable	Partial automation, consistent feedback	Fully automated and integrated monitoring
Scalability	Not adaptable to larger/smaller scales	Scaling requires significant changes	Moderate adaptability	Easily scalable across site sizes
Manage variation in leachate composition	Fails under variable conditions	Sensitive to changes in composition	Can handle moderate variation	Consistently performs under diverse conditions
Odor emission	Strong and unpleasant odors	Noticeable odor issues	Minor and manageable odors	Odor-free or minimal emissions
Aesthetics	Visually unappealing/ intrusive	Noticeable but acceptable	Neutral and relatively discreet	Visually unobtrusive, well-integrated
Job creation	No notable employment impact	Creates a few temporary jobs	Generates consistent roles	Supports long-term job creation and training

The weighting factors and qualitative performance scores were assigned by the authors based on prior experience and knowledge. The overall index score (OIS) for each technology was calculated using a modified multi-criteria evaluation approach adapted from Jóźwiakowski et al. (2015) and Plakas et al. (2016), as outlined in *Equation 1*. The best-performing technology was identified using *Equation 2*.

$$OIS = \sum_{j=1}^{M} \sum_{i=1}^{N} r_{ij} * f_i * c_j \qquad (1)$$

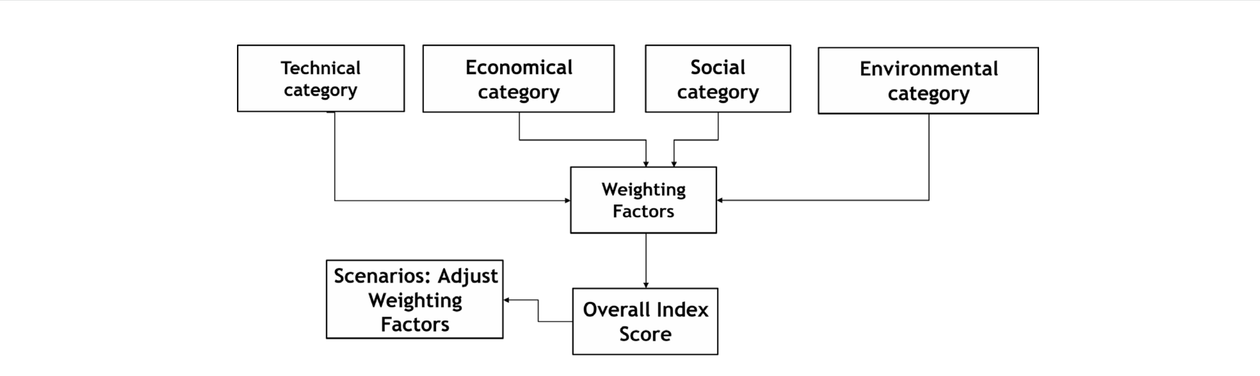
where OIS – overall index score; M – number of categories; N – number of criteria within each category; r – ranking indices for each criteria; c – category weight; f – criteria weighting factor.

$$BTS = MAX(OIS)_n \qquad (2)$$

where BTS – best treatment technology; n – treatment technology (1,2,3,4,5); MAX – maximum.

To enhance the robustness of the analysis, the MCA was performed under seven different scenarios, each varying the priority group weighting for each category. The ranking indices determined in the review sections remained constant across all scenarios. The seven weighting scenarios allowed for the computation of seven OISs for each treatment technology, using *Equation 1*. These OIS values were then directly compared, with the highest OIS indicating the most suitable treatment strategy, as determined by *Equation 2*. The process used to conduct the MCA is shown in *Fig. 3*.

Fig. 3. *Overview of the MCA calculation with the weighting scenarios*



Results and Discussion

Aerobic biological treatment technologies

The performance of aerobic biological treatment technologies for landfill leachate is evaluated and compared considering evidence reported in the literature and the outcomes generated by the decision support tool. Treatment efficiency, operational demands, and practical applicability are examined to highlight the relative advantages, limitations, and trade-offs associated with each alternative under varying conditions. The detailed results of this evaluation are presented in the following subsections.

Activated sludge (AS)

The AS technology is one of the primitives and most commonly used aerobic biological treatment technologies. In this method, a high concentration of diverse aerobic microorganisms populations are used to break down the organic contaminants in the leachate (Ilmasari et al., 2022). The mixture of the activated sludge and the leachate in an aeration tank is referred to as a mixed liquor (Scholz, 2016). The mixed liquor has microbial population that can breakdown organic pollutants in leachate treatment. In this treatment, leachates are mixed in the aeration tank, where microorganisms in the mixed liquor degrade the organic pollutants and break down into carbon dioxide, water and new biomass (Kamaruddin et al., 2017). This is followed by a stage where the sludge settles in a settling tank, and the treated liquid is discharged as effluent. To help maintain an optimal microbial population, a portion of the sludge is reused and sent back into the aeration tank, while the excess sludge material is sent to a sludge treatment plant (Wiszniowski et al., 2006).

The activated sludge technology has been commonly used for leachate treatment and has shown to be very effective in reducing organic matter, heavy metals, nutrients, ammonia, phenolic compounds and suspended solids. However, a major drawback for the treatment efficiency of the activated sludge system is its low effectiveness for denitrification (Lebron et al., 2021). Additionally, other challenges associated with the AS technology are the large volume of sludge production, high energy consumption for aeration, associated costs for sludge disposal/management and microorganisms inhibition due to the presence of high ammonium nitrogen in leachate (Luo et al., 2020). Different studies have explored modification to help address these challenges by the addition of adsorbents and application of an electric field (Aghamohammadi et al., 2007; Akkaya et al., 2017). *Table 3* shows a summary of past studies using AS treatment technologies for landfill leachates management.

Sequencing batch reactor (SBR)

The SBR is a variation of the AS technology that has been widely employed for the treatment of leachate. Unlike the AS set up that uses several tanks for the different phases of treatment, SBR combines the entire treatment phases into a one tank (Ilmasari et al., 2022). The SBR technology is made up of 5 phases. These phases are fill, reaction, settling, decantation and the idling phase (Singh et al., 2020). Depending on the operation requirements, the different phases can be modified to accommodate different variations in leachate quality and quantity. SBR has been reported to be effective for treatment of high concentrations of nutrients, inorganic, organic contaminants and suspended solids. Several variations of the SBRs have been used to optimize biological nitrogen removal (Singh et al., 2020). These variations have made SBR a very adaptable treatment technology, which makes it a good alternative for treatment of landfill leachate, where there is seasonal variation in quantity and quality (Renou et al., 2008).

The effectiveness of SBR is influenced by the organic matter source, cycle duration, organic loading rate, pH and temperature. A study conducted by Selvam et al., (2019) showed that optimal SBR performance was observed in an OLR range of 0.75–1.5 g COD/L.d. The removal efficiencies for BOD and COD were 96% and 92%, respectively. Rapid nitrification and ammonia removal rates were achieved at lower temperatures. In addition, it was concluded that supplementing the treatment system with organic matter source increased total nitrogen removal efficiency to 90%. A major drawback with the SBR system is the need for sludge settling, as the quality of the effluent of the treated water can be compromised by sludge bulking if there is disturbance to the system (Laitinen et al., 2006). *Table 4* shows a summary of past studies using SBR treatment technologies for landfill leachates management.

Table 3. *Summary of past studies using AS for leachate management*

			Removal efficiency (%)				
Reference	Description	Time (days)	BOD	COD	SS	TN	NH_3
Aghamohammadi et al., (2007)	Lab scale AS reactor at room temp.	0.92 – 2.22	-	46	-	-	78
Fang et al., (2020)	AS system for Di-n-butyl phthalate removal in leachate	3.6	-	54	-	41	-
Akkaya et al., (2017)	Lab scale batch AS reactor	-	-	82	-	-	22
Campos et al., (2020)	Pilot units for conventional AS and Fixed filed AS	0.48	82	87	-	-	-
Boonnorat et al., (2021)	Two-stage acclimatized AS system	1	94	91	-	-	100
Mean (%)		1.7	88	72	-	41	67
Standard deviation (%)		1.2	6.0	18.4	-	-	32.8

- data not available

Table 4. *Summary of past studies using SBR for leachate management*

		Removal efficiency (%)				
Reference	Description	BOD	COD	SS	TN	NH_3
Yong et al., (2018)	Intermediate leachate treatment in a SBR	-	49.49–54.95	53.64–54.55	-	92.36–97.07
Wei et al., (2012)	Leachate treatment with aerobic granular SBR	-	82.8–84.4	-	35	44.1–92.3
Grosser et al., (2019)	Leachate treatment in SBR	6–48.5	4–48	-	-	11–42
Xu et al., (2020)	Leachate treatment by heterotrophic Denitrification and Partial Nitrification in SBR	-	55	-	60	-
Morling (2010)	Full scale SBR	98.0–99.6	85.0–96.2	-	67.5–91	94.8–97.3
Remmas et al., (2018)	Full scale twin SBR for treating leachate	41.9	86	-	71	97.6
Mean (%)		56	66	54	61	77
Standard deviation (%)		30.8	23.2	0.5	16.7	27.3

- data not available

Membrane bioreactors (MBR)

The MBR is an aerobic biological treatment technology that combines a membrane filtration unit with an activated sludge based reactor. The aim of this modification is to allow for a more efficient removal of suspended solids in the treated effluent. In contrast with the AS set up, this removes the need for a clarifier tank (Hashisho and El-Fadel, 2016). Microfiltration and ultrafiltration are the most widely used membranes in MBR systems (Lebron et al., 2021). MBR treatment technology has demonstrated high effectiveness in treating leachate, despite variations in leachate characteristics. Past studies have shown that MBR can achieve up to 99% removal efficiency for BOD, COD and ammonia (Coppini et al., 2018; Heang et al., 2020; Ittisupornrat et al., 2021). Additionally, MBRs have shown a strong tendency to remove micropollutants present in leachate through mechanisms such as sorption, degradation and volatilization. The past studies by (Boonnorat et al., 2016) demonstrated that removal efficiency for micropollutants using MBRs ranged between 90–99%.

In MBR, the HRT is a critical parameter that influences the efficiency of the system. In the study by Wichitsathian et al., (2004), the removal efficiency of BOD increased from 94% to 98% by increasing the HRT from 16 to 24 hours. However, a shorter HRT of 8 hours correlated to poor COD removal efficiency of 23% in leachate treatment. Different studies have demonstrated that the leachate BOD/COD ratio can influence the length of HRT. For instance, for leachate with BOD/COD ratio of 0.4 to 0.8, an HRT of 5 to 20 days was recommended and leachate with BOD/COD ratio of 0.2–0.03 required a longer HRT of 24 to 45 days (Alvarez-Vazquez et al., 2004). Despite variations in leachate characteristics, the commonly used HRTs range from 12 hours to 3 days in MBR treatment technology. A common drawback of the MBR is membrane fouling which can be caused by long SRTs. This results in the buildup of dead microbial cells and decrease in microbial activity, thereby reducing the performance of the system (Lin et al., 2012, El-Fadel et al., 2018). *Table 5* shows a summary of past studies using MBR treatment technologies for landfill leachates management.

Trickling filters (TF)

TF is an aerobic biological treatment technology that involves distributing leachate over a bed of media (natural or synthetic) where a microbial biofilm breaks down organic matter as the water trickles through. TF uses a forced or self propelled rotary distributor arm to evenly distribute the leachate over the fixed bed reactor. The rotary arm supports the development of biofilms for the treatment of organics (Ilmasari et al., 2022). The TF has been shown to be a viable option for the leachate treatment in a closed landfill, but it has a major challenge of biomass accumulation under strong organic load. In cases where leachate has a high pollutant load or requires nitrification, a two-stage TF has been used to address high pollutant load in leachate (Torretta et al., 2017;

Table 5. *Summary of past studies using MBR for leachate management*

			Removal efficiency (%)				
Reference	Description	Time (days)	BOD	COD	SS	TN	NH_3
Saleem et al., (2018)	Nylon mesh dynamic MBR	10	98	75	99	-	96
Coppini et al., (2018)	Full scale MBR	10	-	-	-	90	98
Heang et al., (2020)	Two stage MBR	2.5	99	96	100	97	97
Ittisupornrat et al., (2021)	MBR under prolonged SRT	-	99	79	99	-	99
Mean (%)		7.5	99	83	99	94	98
Standard deviation (%)		3.5	0.5	9.1	0.5	3.5	1.1

- data not available

Qasim and Zhu, 2017). Previous studies have shown that TF applied to leachate treatment under increasing temperature resulted in an increase in the ammonia removal efficiency (Matthews et al., 2009). In a study conducted by Mondal and Warith (2008) using a TF filled with chips and tire crumbs, a 76–90% and 81–96% removal efficiency was attained for COD and BOD, respectively. Additionally, the study attained a 15–68% for ammonia removal efficiency. Similarly, a study conducted by Aluko and Sridhar (2013) using sand and gravel media attained a removal rate of 48% for COD, 76% for BOD, 59% for ammonia and 73% for suspended solids in treating leachate. Studies have shown that TF is most efficient when used for treating leachate with ammonia nitrogen concentration below 50 mg/L. TF is limited by nitrification inhibition and filter clogging under high organic loading (Lebron et al., 2021). *Table 6* shows a summary of past studies using TF treatment technologies for landfill leachates management.

Table 6. *Summary of past studies using TF for leachate management*

			Removal efficiency (%)				
Reference	Description	Time (days)	BOD	COD	SS	TN	NH_3
Saleem et al., (2018)	Nylon mesh dynamic MBR	10	98	75	99	-	96
Coppini et al., (2018)	Full scale MBR	10	-	-	-	90	98
Heang et al., (2020)	Two stage MBR	2.5	99	96	100	97	97
Ittisupornrat et al., (2021)	MBR under prolonged SRT	-	99	79	99	-	99
Mean (%)		7.5	99	83	99	94	98
Standard deviation (%)		3.5	0.5	9.1	0.5	3.5	1.1

- data not available

Rotating biological contactors (RBC)

The RBC is an aerobic biological treatment technology that makes use of circular polyethylene or PVC disks, installed on a rotating shaft in a tank. Microorganism on the disk degrades the organic matter in the leachate and optimal microorganism growth is created by constant rotation of the disks between submersion in leachate and exposure to air (Qasim and Zhu, 2017). This technology works by ensuring there is enough contact time between the disc and the leachate, thereby enabling the microbial degradation of pollutant. Biomass accumulation is prevented by the continual alternation between submersion and exposure to air. A clarification process is then applied to remove the excess biomass (Abdelfattah et al., 2020).

RBC treatment technology is highly effective for the removal of nitrogen in small scale applications. A past study conducted by Cortez et al., (2011) showed that a single stage RBC treatment system that used polymethylmethacrylate disks resulted in a 95% reduction in nitrate-nitrogen levels from leachate. Similarly, a study conducted by Cema et al., (2007) attained a 0.56, 0.76, and 0.93 kg N/m^3/day removal rates for ammonia, nitrite and total inorganic nitrogen, respectively. A major drawback with the RBC systems is the high tendency for biomass accumulation that can result in clogging. Also, removal efficiency may be limited in high nitrite level concentrations (Ilmasari et al., 2022). *Table 7* shows a summary of past studies using RBC treatment technologies for landfill leachates management.

Table 7. *Summary of past studies using RBC for leachate management*

			Removal efficiency (%)				
Reference	Description	Time (days)	BOD	COD	SS	TN	NH_3
Castillo et al., (2007)	RBC using 4 stage acetate disc	1	-	52	-	-	-
Cortez et al., (2011)	RBC using 1 stage poly methylmethacrylate disc	0.42	-	-	-	95	-
Kulikowska et al., (2010)	Two-stage RBC	1	-	-	-	-	99
Mean (%)		0.80	-	52	-	95	99
Standard deviation (%)		0.27	-	-	-	-	-

- data not available

Multi-criteria analysis

MCA was used to evaluate five aerobic biological treatment technologies for leachate generated in a closed landfill. A ranking system was applied to evaluate various treatment technologies, using different criteria categorized under environmental, technical, social and economical categories. These ranking indices for the criteria were determined based on the performance of each treatment technology for leachate treatment in different studies in literature. A summary of the average values of the performances of each treatment technology based on past studies in literature is shown in *Table 8*. Average performance values were calculated using available data in literature only. Missing datasets in literature were excluded from the calculation and denoted by “-“. However, it is important to note that the values for the ranking indices are approximate due to variations in different study methodologies and the limited number of data points available in literature. Expert knowledge was used for ranking, where quantitative data were missing, to compare treatment technology performance and to ensure a fair and informed comparison.

Table 8. *Average value of the performance of each treatment technology*

		Removal efficiency (%)				
	Time (days)	BOD	COD	SS	TN	NH_3
SBR	10.2	56.0	65.6	54.1	61.3	76.6
MBR	7.5	98.7	83.3	99.3	93.5	97.5
TF	14.0	84.2	65.5	76.7	-	59.5
RBC	0.71	-	52	-	97	99
AS	1.7	88.0	72.0	-	41.0	66.7

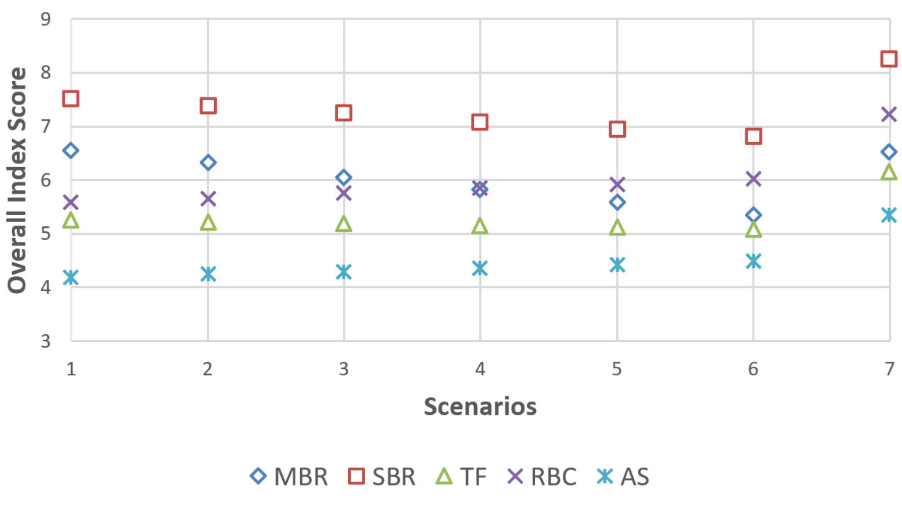
- data not available

An OIS was calculated for each MCA, under different weighting scenarios for each leachate treatment technology. The seven weighting scenarios are shown in *Table 9* and the calculated OIS from the MCA is presented in *Fig. 4*. Under all weighting scenarios, SBR achieved the highest overall index score, ranging from 6.84 to 8.25. MBR ranked second with a score ranging from 5.35 to 6.55. Lowest ranked treatment technology was AS, with a OIS ranging from 4.18 to 5.34. The highest ranked treatment technologies are due to the high performance across all the 4 categories (environmental, social, economical and technical). The lowest-ranked methods treatment technology was AS. The lowest ranked treatment technology was due to the low ranking performances in all the criteria in the categories.

Table 9. *Weighting scenarios variation for each factor*

Scenario	Environmental category	Economical category	Technical category	Social category
1	0.20	0.60	0.10	0.10
2	0.30	0.50	0.10	0.10
3	0.40	0.40	0.10	0.10
4	0.50	0.30	0.10	0.10
5	0.60	0.20	0.10	0.10
6	0.70	0.10	0.10	0.10
7	0.80	0.00	0.10	0.10

Fig. 4. *MCA results under the seven weighting scenarios*



The highest ranking achieved for the SBR treatment technology can be attributed to its strong performance in both the environmental and economical categories that had the higher weighting in this MCA. SBR yielded consistently high scores in the high priority criteria under the environmental and economical categories, which resulted in the highest OIS relative to the other treatment technologies. For instance, the high OIS of SBR can be attributed to its strong performance across different criteria such as the treatment efficiency and operational flexibility while the lower OIS of certain treatment technologies such as TF or RBC can be attributed to higher operational burdens or limitations in handling variable leachate loads. In comparison, other treatment technologies such as MBR and RBC performed well in certain criteria in technical category but did not perform as well as the SBR in the highest weighted categories SBR consistently had a strong performance in the categories that had the highest weighting factors. The environmental and economical categories had highest weighting factors due to their significance in leachate management in a closed landfill site. While other treatment technologies performed competitively in some other categories, their strengths were concentrated in criteria with lower weighting factors such as social category, which had a smaller influence on OIS. This shows that the final ranking of each treatment technology reflects not only the individual performance of the highest weighted factors but the overall performance in all the categories.

The performance of RBC in this MCA was ranked second best performance in the last three scenarios due to the reduction in the weighting factor for environmental category. For leachate treatment, it is important to note that emphasis will be given to the environmental performance due to the strict environmental regulation that applies to closed landfills and leachate is a highly contaminated liquid that is strictly regulated. Hence, there is need for a good performance in the environmental category for a treatment technology to be applicable in real world.

Five additional weighting scenarios were used to reflect the relative importance of the four categories. In leachate management, environmental category criteria are considered critical criteria due to the stringent regulatory requirements and the impacts pollution could cause to the environment and human health. The economical category criteria are also crucial to leachate management in closed landfill sites because budget limitation is a common constraint. The technical category criteria are critical because they can affect the cost and the efficiency of the treatment technology. The social category criteria are of utmost importance as closed landfill sites are sometimes converted to other beneficial uses such as office space, residential buildings or parks. *Table 10* shows the order of the results of the performances of the five scenarios when consideration is given solely to one category. Results remained unchanged and SBR ranked highest and AS ranked lowest.

Table 10. *Preferred technology in each factor considered in the MCA*

Ratio of weighting factors	Preferred treatment strategy	Treatment technologies ordered from highest to lowest OIS
1:1:1:1	SBR	SBR, MBR, RBC, TF, AS
1:0:0:0	SBR	SBR, RBC, TF, MBR, AS
0:1:0:0	SBR	SBR, MBR, TF, RBC, AS
0:0:1:0	SBR	SBR, MBR, TF, RBC, AS
0:0:0:1	SBR	SBR, MBR, RBC, AS, TF

The MCA approach considers the totality of environmental, technical, social and economical category criteria. This resulted in SBR being the highest ranked treatment technology for leachate treatment in a closed landfill site.

Conclusions

Leachate generation continues in a landfill long after the landfill has attained its maximum waste capacity. This is of great environmental, social, economical and health concern due to the volume and toxicity of leachate produced. Aerobic biological treatment is a widely applied treatment technology for leachate management due to the ability to degrade the organic contaminants that are present in leachate. Selection of appropriate leachate treatment technologies is crucial to mitigate the adverse impacts, with consideration given to the environmental, technical, social, economical category criteria and compliance with applicable regulations. MCA is a robust and adaptable tool for selecting leachate treatment technologies post-closure of municipal landfills.

In this study, five aerobic biological treatment technologies were reviewed: MBR, SBR, TF, RBC and AS. Each technology was reviewed with respect to HRT and removal efficiency for COD, BOD, SS, TN and NH^+_3-N. For the MCA, 16 criteria were identified and grouped into environmental, technical, social and economical categories for each treatment technology. A ranking index that was assigned to each criterion was used to calculate an overall index score for the evaluation of the five aerobic biological treatment technologies. The result of the MCA shows that the best treatment strategy for leachate management in a closed municipal landfill is SBR across all 4 factors. The next ranked best on performance in the MCA is the MBR. The lowest ranked aerobic treatment technology is AS. Sensitivity analysis shows that the result remains unchanged when different weighting scenarios are considered. The performance of the MCA remained unaffected when individual categories were considered to evaluate the influence of each category on the results of the MCA. Hence, MCA can address the complexity of selecting the best aerobic treatment technology for leachate in a closed landfill sites by considering different criteria that are essential to attain a result that balances environmental, social, technical and economical aspects.

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