Is Aged Refuse Bioreactor an Effective Leachate Treatment Solution for Small Landfills in Emerging Economies?

Ronei de Almeida, Universidade Federal do Rio de Janeiro, ronei@eq.ufrj.br

Abstract

Leachate is a polluting and complex landfill wastewater. Its treatment is necessary since untreated leachate threatens soil, air, and water resources. Aged refuse bioreactors (ARB) can be a cost-effective solution to treat leachate, as they use low-cost materials and adsorptive/ biological mechanisms to degrade and remove contaminants from landfill wastewater. The bioreactors are constructed from concrete or plastic and contain a mixture of aged refuse (> ten years), used as support media for microorganisms, which degrades the pollutants. In this sense, the following question emerges: Is ARB an effective leachate treatment solution for small landfill sites in developing countries? In the current study, the author reviewed recent studies on ARB for landfill leachate treatment to elucidate this issue. This exploratory work intends to provide insights into low-cost treatment options to support researchers, landfill owners, and policymakers. Overall, organic matter removal is >80%, and ammonia nitrogen can be 100% eliminated after ARB treatment. However, ARB is insufficient to meet water disposal requirements, and further treatment is needed. Future studies on low-cost combined systems for leachate management incorporating ARB are recommended. This endeavor seeks to delineate future research avenues and contribute to addressing leachate management challenges in landfills in emerging economies.

Keywords: Aged refuse bioreactors, Developing countries, Landfill leachate, Wastewater treatment

1. Introduction

Landfill leachate contains a wide range of macro and micro-pollutants of varying concentrations. Hence, its treatment remains a major socio-environmental problem in the waste management system (Kjeldsen et al., 2002). Overall, the leachate treatment chain is designed with several treatment steps aiming to meet landfill wastewater disposal requirements. Despite the low biodegradability of landfill leachate, especially those generated in mature landfills (> ten years), biological treatments are still needed for carbon and nitrogen removal (de Almeida et al., 2023; Gripa et al., 2023).

The Aged refuse bioreactor (ARB) presents a cost-effective biological approach and a promising technology for effectively removing diverse pollutants from landfill wastewater. It has proven to be a successful technique for treating various types of wastewater, including sanitary effluents, fishpond and sugar mill wastewaters, coking wastewater, and livestock waste (Anijiofor et al., 2018; Gutiérrez-Hernández et al., 2021; Zhao et al., 2007). The reactor system utilizes stabilized material or aged refuse derived from municipal solid waste in landfills for over eight years. The aged refuse material is a sustainable and low-cost medium within bioreactors, offering an environmentally friendly waste management solution (Nájera-Aguilar et al., 2021).

Previous work reviewed the utilization of ARB for landfill management (Hassan & Xie, 2014). However, the literature lacks an up-to-date study on this topic; since then, much attention has been given to the applicability of ARB technology. In this sense, this study reviews the recent literature to elucidate the question: Is ARB an effective leachate treatment solution for small landfill sites?

2. Literature Review

The aged refuse bioreactor (ARB) resembles a trickling filter. This system fosters the growth of bacteria attached to surfaces while enabling the downward flow of wastewater due to gravitational forces. Support materials such as crushed rocks, slag, pumice, and plastics are utilized in trickling filters. Conversely, in the case of ARBs, aged refuse serves as the medium. In contrast to trickling filters, ARBs produce reduced amounts of sludge and eliminate the necessity for an additional sedimentation unit to manage sludge removal (Hassan & Xie, 2014).

The treatment mechanisms involve two main processes: adsorption onto aged refuse and biodegradation. The aged refuse serves as a supporting medium for the growth of microorganisms. As a result, microbial activity thrives, removing pollutants from the introduced wastewater. Interestingly, adsorption rather than biodegradation was identified as the primary mechanism in the anaerobic condition (Su et al., 2017).

The biochemical environment of the aged refuse bioreactor (i.e., anaerobic and aerobic), temperature, and hydraulic load rate are identified as the main parameters influencing ARB performance in treating landfill wastewater. Among them, temperature plays a pivotal role in treatment performance. In a study conducted by Tong et al. (2015), the effectiveness of carbon and nitrogen removal in ARB was assessed at varying temperatures of 35, 45, and 55ºC. Notably, the highest treatment performance and the swiftest carbon mineralization were observed at the elevated temperature of 55ºC, indicating the significance of thermophilic conditions. Also, volatilization significantly impacted ammonia nitrogen removal under aerobic conditions, resulting in >60% nitrogen in organic forms (Tong et al., 2015). In another study, similar results were obtained, and when the temperature increased from 15 to 30ºC, ammonia nitrogen was removed entirely (Zhang et al., 2016). Due to this, ARB seems a promising solution for landfills in tropical climate regions such as Brazil.

3. Materials and Methods

The research process was conducted using the Scopus database. Scopus was selected because of its well-established citation indexing methods and to guarantee that the publications assessed in the present study were peer-reviewed before publication. A search using keywords and search queries (aged refuse bioreactor OR aged refuse biofilter AND landfill leachate) returned 50 documents (07/03/2023).

The screening was undertaken using the eligibility and exclusion criteria. The eligibility criteria comprised selecting documents categorized as research articles published from 2018 to 2022. Excluding articles published in languages other than English and Portuguese was part of the exclusion criteria. It found 25 documents in total, which were reviewed in detail.

4. Results and Discussion

The pollution parameters monitored in ARB treatability tests include biochemical oxygen demand (BOD), COD, Absorbance at 254 nm (UV_{254}) – linked to recalcitrant organics present in leachate samples (de Almeida et al., 2019), color, ammonia nitrogen, and total nitrogen. COD and UV_{254} – indicators for organic matter and ammonia nitrogen are typical polluting parameters evaluated in recent studies (**Table 1**).

Overall, COD removal efficiency is greater than 80% (Bautista, 2018; Chen et al., 2020; Mu et al., 2022; Hugo A. Nájera-Aguilar et al., 2019), while the UV_{254} removal ranges from 5 to 70% (Chen & Li, 2020; Wen et al., 2021). Ammonia and total nitrogen were effectively removed using ARB, especially semi-aerobic ones. Values of removal efficiency ranged from 50 to 100% (Lu, 2021; Zhang et al., 2016).

Other parameters not presented in Table 1, such as color and heavy metals, were assessed in recent studies. Nájera-Aguilar et al. (2019) reported color and BOD removals of 86.1 and 87.9%. In another work, the removal of cadmium, lead, and copper was 89, 82, and 91%, respectively (Erabee & Ethaib, 2018).

The findings from the table indicate that the performance of different treatment configurations varies based on factors such as operating conditions, treatment duration, and the specific removal parameters targeted. Hydraulic load rates, anaerobic/ semi-aerobic/ aerobic conditions, and the combination of treatment methods all contribute to the overall effectiveness of leachate treatment using aged refuse bioreactors (Sun et al., 2014, 2017; Wen et al., 2021).

Table 1. Studies from the past five years on ARB for landfill leachate management.

Treatment Configuration	Conditions	Removal Efficiency (%)			Reference
		COD	UV_{254}	$N\text{-}NH_3$	
Ozonation + ARB	Semi-aerobic, 178 days of operation, flowrate of 2 L d^{-1}	>80	>70	>90	(Mu et al., 2022)
ARB	Semi-aerobic, 30 days of operation, flowrate of 1 L h^{-1}	>70	>70	>80	(Wen et al., 2021)
ARB + 3D-EF	Anaerobic, ten weeks, hydraulic loading ratio of 15 L m^{-3} d^{-1}	52	n.d	54	(Lu, 2021)
ARB	Semi-aerobic, 300 days of operation, flowrate of 2 L d^{-1}	85 – 95	37 – 62	>90	(Wang et al., 2020)
Two-stage ARB	Anaerobic, >30 weeks of operation, hydraulic load rate of 10 to 50 L m^{-3} d^{-1}	85	n.d	97.4	(Nájera-Aguilar et al., 2019)
ARB + ozonation	Semi-aerobic, HRT of 12 h, flowrate of 60 – 70 mL min^{-1}	>50	5 – 20	n.d	(Chen et al., 2019)
ARB	Anaerobic, one year of operation, hydraulic load rate of 18 L m^{-3} d^{-1},	80	n.d	n.d	(Bautista, 2018)
ARB	Anaerobic, two treatment cycles, hydraulic load rate of 55 L m^{-3} d^{-1}	75 – 95	n.d	n.d	(Erabee & Ethaib, 2018)
Air stripping + two-stage ARB	Anaerobic, monitoring time not identified, hydraulic load rate of 0.10 L kg^{-1} aged refuse d^{-1}	29 – 80	n.d	n.d	(Ding et al., 2018)

3D-EF = three-dimensional electrode eletro-Fenton, ARB = aged refuse bioreactor, BOD = biochemical oxygen demand, COD = chemical oxygen demand, HRT = hydraulic retention time. N-NH3 = ammonia nitrogen. n.d = not determined.

Regarding treatment combinations, it is observed that advanced oxidation processes are preferred due to the necessity of eliminating recalcitrant organics after ARB treatment. Fenton and ozonation were investigated in integrated systems (Chen et al., 2019; Chen & Li, 2020; Lu, 2021). In a recent study, the ARB + three-dimensional electrode electro-Fenton (3D-EF) system was developed at a laboratory scale. The optimum operating conditions were 15 L m^{-3} d^{-1} hydraulic loading rate for ARB, Fe^{2+} concentration 1.0 mM, initial pH 3.0, and current density 30 mA cm^{-2} for 3D-EF. COD, ammonia nitrogen, and color removal ratios were 96.2%, 94.3%, and 93.6%, respectively. The ARB mechanism effectively targeted a significant portion of the organic matter. At the same time, the 3D-EF system's contribution encompassed the removal of recalcitrant substances and the refining the final effluent via post-treatment polishing. Leachate ecotoxicity was reduced after undergoing the hybrid treatment (Lu, 2021).

Moreover, a recent investigation has demonstrated the potential efficacy of ARB in the on-site removal of antibiotics and antibiotic-resistant genes (ARGs) from leachate. The collective removal performance of antibiotics reached approximately 76.75%, with notably high removal rates observed for sulfanilamide and macrolide compounds, exceeding 80% elimination efficiency. Notably, within the scope of targeted ARGs, crucial genes responsible for tetracycline and macrolide resistance (tetM, tetQ, and ermB) were successfully eliminated from landfill leachate (Su et al., 2017).

5. Conclusions

ARB aligns with the principle of "waste control by waste", demonstrating its practicability on a full scale. Overall, organic matter removal is above 80%, and ammonia nitrogen can be wholly eliminated after ARB treatment. The reviewed literature shows that ARB technology is advantageous for smaller and medium-sized landfills due to its cost-efficiency, environmental compatibility, and straightforward operation. Nevertheless, its viability necessitates rigorous evaluation encompassing technical and economic considerations at laboratory and pilot scales before implementation. Moreover, ARB is insufficient to meet water disposal requirements, and further treatment is needed. Advanced oxidation treatments such as Fenton and ozonation are the most investigated techniques to complement ARB treatment. However, chemicals and energy demand may make these processes unfeasible in some sites. Therefore, future studies on low-cost combined systems for leachate management incorporating ARB are recommended. This endeavor seeks to delineate future research avenues and contribute to addressing leachate management challenges in landfills from emerging economies. As a possibility, a nature-based solution, including constructed wetlands, might be a promising approach in future investigations.

References

Anijiofor, S. C., Nik Daud, N. N., Idrus, S., & Che Man, H. (2018). Recycling of fishpond wastewater by adsorption of pollutants using aged refuse as an alternative low-cost adsorbent. *Sustainable Environment Research*, *28*(6), 315–321. https://doi.org/10.1016/j.serj.2018.05.005

Bautista, J. A. (2018). Biorreactor empacado con materiales estabilizados (beme), como pretratamiento para lixiviados de rellenos sanitarios. *Revista Mexicana de Ingeniería Química*, *17*(2), 561–571. https://doi.org/10.24275/uam/izt/dcbi/revmexingquim/2018v17n2/Bautista

Chen, W., He, C., Gu, Z., Wang, F., & Li, Q. (2020). Molecular-level insights into the transformation mechanism for refractory organics in landfill leachate when using a combined semi-aerobic aged refuse biofilter and chemical oxidation process. *Science of The Total Environment*, *741*, 140502. https://doi.org/10.1016/j.scitotenv.2020.140502

Chen, W., & Li, Q. (2020). Elimination of UV-quenching substances from MBR- and SAARB-treated mature landfill leachates in an ozonation process: A comparative study. *Chemosphere*, *242*, 125256. https://doi.org/10.1016/j.chemosphere.2019.125256

Chen, W., Zhang, A., Jiang, G., & Li, Q. (2019). Transformation and degradation mechanism of landfill leachates in a combined process of SAARB and ozonation. *Waste Management*, *85*, 283–294. https://doi.org/10.1016/j.wasman.2018.12.038

de Almeida, R., Moraes Costa, A., de Almeida Oroski, F., & Carbonelli Campos, J. (2019). Evaluation of coagulation–flocculation and nanofiltration processes in landfill leachate treatment. *Journal of Environmental Science and Health - Part A Toxic/Hazardous Substances and Environmental Engineering*, *54*(11), 1091–1098. https://doi.org/10.1080/10934529.2019.1631093

de Almeida, R., Porto, R. F., Quintaes, B. R., Bila, D. M., Lavagnolo, M. C., & Campos, J. C. (2023). A review on membrane concentrate management from landfill leachate treatment plants: The relevance of resource recovery to close the leachate treatment loop. *Waste Management & Research : The Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, *41*(2), 264–284. https://doi.org/10.1177/0734242X221116212

Ding, W., Zeng, X., Hu, X., Deng, Y., Hossain, M. N., & Chen, L. (2018). Characterization of Dissolved Organic Matter in Mature Leachate during Ammonia Stripping and Two-Stage Aged-Refuse Bioreactor Treatment. *Journal of Environmental Engineering*, *144*(1), 1–7. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001291

Gripa, E., Dario, S., Daflon, A., Almeida, R. De, Valéria, F., & Campos, J. C. (2023). Landfill Leachate Treatment by High-presssure Membranes and Advanced Oxidation Techniques with a focus on Ecotoxicity and By-products Management: A Review. *Process Safety*

and Environmental Protection. https://doi.org/10.1016/j.psep.2023.03.074

Gutiérrez-Hernández, R. F., Nájera-Aguilar, H. A., Araiza-Aguilar, J. A., Martínez-Salinas, R. I., García-Lara, C. M., González-Vázquez, U., & Cruz-Salomón, A. (2021). Novel Treatment of Sugar Mill Wastewater in a Coupled System of Aged Refuse Filled Bioreactors (ARFB): Full-Scale. *Processes*, *9*(3), 516. https://doi.org/10.3390/pr9030516

Hassan, M., & Xie, B. (2014). Use of aged refuse-based bioreactor/biofilter for landfill leachate treatment. *Applied Microbiology and Biotechnology*, *98*(15), 6543–6553. https://doi.org/10.1007/s00253-014-5813-5

Erabee, I., & Ethaib, S. (2018). Treatment of Contaminated Landfill Leachate using Aged Refuse Biofilter Medium. *Oriental Journal of Chemistry*, *34*(3), 1441–1450. https://doi.org/10.13005/ojc/340334

Kjeldsen, P., Barlaz, M. A., Rooker, A. P., Baun, A., Ledin, A., & Christensen, T. H. (2002). Present and Long-Term Composition of MSW Landfill Leachate: A Review. *Critical Reviews in Environmental Science and Technology*, *32*(4), 297–336. https://doi.org/10.1080/10643380290813462

Lu, M. (2021). Advanced treatment of aged landfill leachate through the combination of aged-refuse bioreactor and three-dimensional electrode electro-Fenton process. *Environmental Technology*, *42*(11), 1669–1678. https://doi.org/10.1080/09593330.2019.1677781

Mu, S., Chen, X., Song, B., Wu, C., & Li, Q. (2022). Enhanced performance and mechanism of the combined process of ozonation and a semiaerobic aged refuse biofilter for mature landfill leachate treatment. *Chemosphere*, *308*(P3), 136432. https://doi.org/10.1016/j.chemosphere.2022.136432

Nájera-Aguilar, H. A., Mayorga-Santis, R., Gutiérrez-Hernández, R. F., Araiza-Aguilar, J. A., Martínez-Salinas, R. I., García-Lara, C. M., & Rojas-Valencia, M. N. (2021). Aged Refuse Filled Bioreactor Using Like a Biological Treatment for Sugar Mill Wastewater. *Sugar Tech*, *23*(1), 201–208. https://doi.org/10.1007/s12355-020-00881-4

Nájera-Aguilar, Hugo A., Gutiérrez-Hernández, R. F., Bautista-Ramírez, J., Martínez-Salinas, R. I., Escobar-Castillejos, D., Borraz-Garzón, R., Rojas-Valencia, M. N., & Giácoman-Vallejos, G. (2019). Treatment of low biodegradability leachates in a serial system of aged refuse-filled bioreactors. *Sustainability (Switzerland)*, *11*(11), 1–16. https://doi.org/10.3390/su11113193

Su, Y., Wang, J., Huang, Z., & Xie, B. (2017). On-site removal of antibiotics and antibiotic resistance genes from leachate by aged refuse bioreactor: Effects of microbial community and operational parameters. *Chemosphere*, *178*, 486–495. https://doi.org/10.1016/j.chemosphere.2017.03.063

Sun, X., Sun, Y., Zhao, Y., & Wang, Y.-N. (2014). Leachate recirculation between alternating aged refuse bioreactors and its effect on refuse decomposition. *Environmental*

Technology, *35*(7), 799–807. https://doi.org/10.1080/09593330.2013.852625

Sun, X., Zhang, H., Cheng, Z., & Wang, S. (2017). Effect of low aeration rate on simultaneous nitrification and denitrification in an intermittent aeration aged refuse bioreactor treating leachate. *Waste Management*, *63*, 410–416. https://doi.org/10.1016/j.wasman.2016.12.042

Tong, H., Yin, K., Giannis, A., Ge, L., & Wang, J.-Y. (2015). Influence of temperature on carbon and nitrogen dynamics during in situ aeration of aged waste in simulated landfill bioreactors. *Bioresource Technology*, *192*, 149–156. https://doi.org/10.1016/j.biortech.2015.05.049

Wang, F., Huang, Y., Zhou, X., He, C., & Li, Q. (2020). Molecular-level transformation characteristics of refractory organics in landfill leachate during ozonation treatment. *Science of the Total Environment*, *749*. https://doi.org/10.1016/j.scitotenv.2020.141558

Wen, L., Álvarez, C., Zhang, Z., Poojary, M. M., Lund, M. N., Sun, D.-W., & Tiwari, B. K. (2021). Optimisation and characterisation of protein extraction from coffee silverskin assisted by ultrasound or microwave techniques. *Biomass Conversion and Biorefinery*, *11*(5), 1575–1585. https://doi.org/10.1007/s13399-020-00712-2

Wen, P., Huang, Y., Qiu, Z., & Li, Q. (2021). Microbial response during treatment of different types of landfill leachate in a semi-aerobic aged refuse biofilter. *Chemosphere*, *262*, 127822. https://doi.org/10.1016/j.chemosphere.2020.127822

Zhang, J., Lv, C., Tong, J., Liu, J., Liu, J., Yu, D., Wang, Y., Chen, M., & Wei, Y. (2016). Optimization and microbial community analysis of anaerobic co-digestion of food waste and sewage sludge based on microwave pretreatment. *Bioresource Technology*, *200*, 253–261. https://doi.org/10.1016/j.biortech.2015.10.037

Zhao, Y., Lou, Z., Guo, Y., & Xu, D. (2007). Treatment of sewage using an aged-refuse-based bioreactor. *Journal of Environmental Management*, *82*(1), 32–38. https://doi.org/10.1016/j.jenvman.2005.11.015