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Sustainable leachate treatment by integrating electrolysis with palm-shell activated carbon contactor for environmental protection

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The increasingly concerning issue of water pollution caused by untreated leachate necessitates the implementation of effective wastewater treatment methods. This study addresses the crucial issue of landfill leachate treatment through an innovative and environmentally friendly approach that integrates electrolysis with palm-shell activated carbon contactors. The efficacy of an integrated process for pollutants removal was assessed involving electrolysis with aluminum and iron electrodes, activated carbon contactors with varying bed depths, and the influence of salinity. The findings of the study demonstrated significant advancements in the removal of pollutants from landfill leachate. The utilization of aluminum and iron electrodes in electrolysis has exhibited enhanced efficacy in the removal of several parameters, including ammonia nitrogen, total suspended solids (TSS), chemical oxygen demand (COD) and biochemical oxygen demand (BOD). The pollutants removal efficiency was further improved by implementing up-flow activated carbon treatment, with a bed depth of 15 cm yielding most favorable outcomes. Additionally, the investigation explored the impact of salinity on the efficacy of pollutants removal. Except for BOD, which demonstrated good removal efficiency even at 5% salt, results indicated that the removal effectiveness was maximum when no salt was applied to the samples. The results suggest that this integrated method offers a sustainable and effective solution for landfill leachate treatment, potentially leading to better water quality and environmental preservation. Future study should focus on implementing rigorous laboratory protocols, ensuring accurate dilution factors, refraining from reusing activated carbon, maintaining continuous monitoring throughout treatment operations, and investigating alternative treatment approaches. This study makes a valuable contribution to the ongoing endeavors aimed at tackling the environmental issues related to the treatment of landfill leachate.

Keywords Jeram sanitary landfill leachate, Pollutants removal, Electrodes, Water pollution, BOD and COD

The issue of water scarcity is becoming more urgent worldwide, as there is a limited availability of clean water for both domestic and industrial purposes[1–3] . The existence of detrimental pollutants in water bodies presents significant risks to both the natural ecosystem and human well-being[4–7] . Industries are currently exploring novel approaches to reduce water usage and enhance wastewater treatment processes due to escalating water costs and the implementation of stricter rules on effluent discharge[8,9]. Hamad et al.[10] presented an innovative approach for Methylene Blue (MB) removal on modified adsorbents. Using a new chemical activation approach, they produced good-quality adsorbents. Potable water is still insufficient in many areas, including Malaysia, where river, lake, and other water body pollution has reached critical levels[11–13]. Households widely use water

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treatment solutions to make their water potable at the point of use[14] . This necessitates the implementation of economic and time-efficient methods for treating effluent.

Landfills are a widely employed technique for the disposal of solid waste on a global scale. This practice leads to the production of heavily polluted wastewater, referred to as leachate, as a consequence of waste decomposition[15–18]. There are more than 296 landfills in Malaysia alone,many of them are open dumping sites that present serious threats to the environment and to society[19,20]. Although landfills are generally regarded as a cost-effective and environmentally sustainable means of waste disposal, the generation of leachate continues to be a significant issue[15,21]. Leachate is produced as a result of water seeping into the landfill and acquiring various pollutants, including organic and inorganic substances, heavy metals, and biological waste products, as it passes through the layers of garbage[22–25].

The accelerated expansion of urban areas and industrial sectors has led to a notable escalation in the formation of solid waste, therefore resulting in an amplified production of landfill leachate[15,21,26]. The introduction of untreated leachate into water bodies poses a significant risk to human health due to the presence of toxins, which can potentially result in the transmission of waterborne diseases[27–29]. In addition, it should be noted that untreated leachate contains a significant amount of organic nitrogen, which has been identified as a causative factor in the occurrence of detrimental algal blooms within aquatic ecosystems[30,31]. It is imperative to implement advanced wastewater treatment techniques to treat wastewater prior to directly discharge into rivers and streams.

Energy consumption is a critical factor in assessing the overall sustainability and economic feasibility of electrochemical treatment methods for landfill leachate. Several studies have investigated the energy efficiency of electrolysis in this context. For instance, Zhang et al.[32] analyzed a hybrid electrolysis process for landfill leachate treatment, providing insights into the energy consumption of the electrolysis stage. Additionally, Galvão et al.[33] investigated the effects of current density and electrolysis time on the energy efficiency of electrocoagulation for landfill leachate treatment. They found that optimizing these parameters can significantly reduce energy consumption while maintaining treatment efficiency.

Many researchers studied on the development of new adsorbents. Salama et al.[34] studied on the characterization of magnesium ferrite-activated carbon composites derived from orange peels for enhanced supercapacitor performance. They revealed the potential of activated carbon composites as superior electrode materials for supercapacitors. Badawi et al.[35] derived cobalt ferrite-supported activated carbon from orange peels for real pulp and paper mill wastewater treatment. The composite material exhibited promising potential for multiple applications without a significant loss in its adsorption or functional properties over successive uses. Badawi et al.[36] developed the rice husk waste-based filter for wastewater treatment. Rice husk particles played a crucial role in sustainable pollutants removal. Hassan et al.[37] found an eco-friendly solution for greywater treatment via date palm fiber filter. The findings exhibited significant decreases in turbidity, up to 90%, while TDS and conductivity lowered by up to 15%.

In this study, the integrated system using electrolysis and activated carbon adsorption is adapted. The combined system may offer several advantages for treating landfill leachate compared to single-stage methods. Electrolysis may effectively remove a wide range of pollutants, including organic matter, suspended solids and some heavy metals. Activated carbon adsorption may efficiently eliminate refractory organic compounds, heavy metals, and emerging contaminants that may not be efficiently removed by electrolysis alone. The combination of these two processes may achieve higher overall removal efficiencies and broader pollutant removal capabilities. Electrolysis may pre-treat the leachate, reducing the organic load and improving its biodegradability, thereby enhancing the efficiency of subsequent activated carbon adsorption. Activated carbon may remove residual pollutants that may not be completely removed by electrolysis, further improving the overall treatment efficiency.

This study aims to mitigate the presence of pollutants by employing electrolysis and by utilizing cost-effective activated carbon contactors made from palm-shell-activated carbon. The primary objective is to evaluate the effects of electrolysis and activated carbon contactors on the elimination of different contaminants from the landfill leachate, as well as the influence of salinity on the effectiveness of pollutants removal. Various bed depths of the up-flow fixed bed activated carbon contactor were utilized, e.g. 5 cm, 10 cm and 15 cm. The activated carbon contactor was applied in the process of landfill leachate treatment to eliminate odor, color and taste, as well as a range of organic and inorganic contaminants.

Materials and methods

Preparation and collection of sample

The first crucial step in this investigation was collecting samples from the Jeram Sanitary Landfill in Kuala Selangor, Malaysia. The process was facilitated by trained technicians. Special precautions were taken during the collection of the leachate samples due to their higher concentration of contaminants compared to regular wastewater. Then, the leachate samples were promptly transferred to the laboratory to mitigate any alterations in parameters and features that may arise from extended storage.

Treatment process

The study consisted of six distinct phases, incorporating two primary treatment methods: electrolysis and activated carbon contactor treatment. These stages are outlined in the following paragraphs. In the initial phase, the raw leachate sample's parameters were assessed to establish a baseline reference before starting the electrolysis process. The electrolysis procedure was further divided into two sub-stages. In one sub-stage, conductors made entirely of aluminum were used, while the other employed a combination of iron and aluminum. After completing the electrolysis, the parameters of both sets of samples were evaluated in the following stages to determine which conductor was most effective in facilitating the electrolysis process. Following the analysis, the samples were treated using an up-flow fixed bed activated carbon contactor. Figure 1 illustrates the process flow chart.

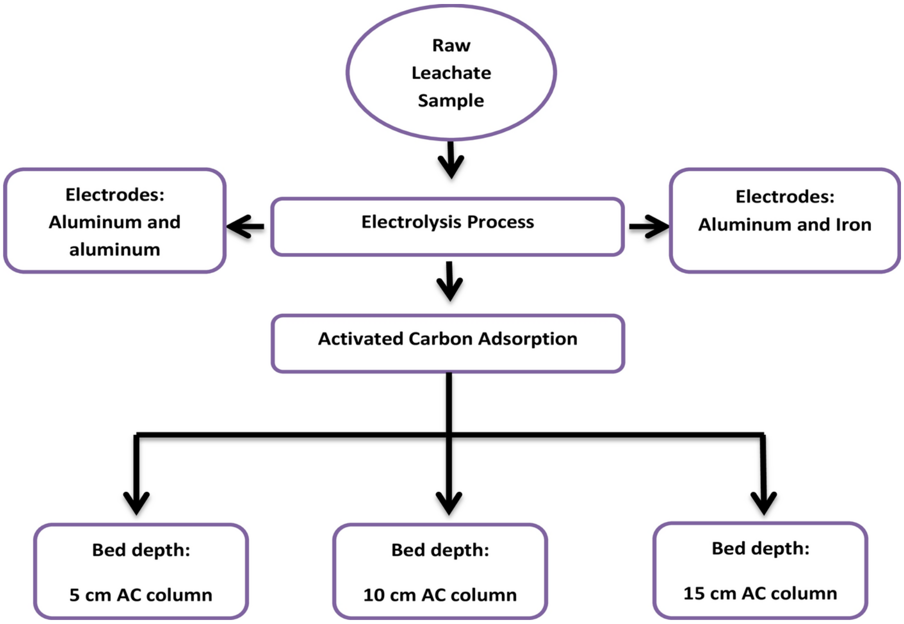

Fig. 1. Flow chart of the treatment process.

Fig. 2. Electrolysis process.

Electrolysis

The electrode material utilized in the study consisted of two variations: aluminum-only (Al-Al) and a combination of aluminum and iron (Al–Fe). The experimental setup was designed to maintain specific conditions, including an optimal voltage of 24 V and a hydraulic retention time of 40 min. Various percentages of salts are applied in the reactor, e.g. 0, 1, 2, 3, 4, and 5% of the landfill leachate to find the effect of salinity on a few pollutants removal. The table salt was used which is available in market.

Figure 2 depicts the electrolysis procedure carried out employing various conductors. The protocol for the electrolysis procedure entailed the initial step of preparing a 3-L sample. Subsequently, both the anode and cathode were installed, and connected to the electrolysis DC power supply. Finally, the sample was subjected to cooling and filtration.

Activated carbon contactor

The activated carbon was utilized in the process of wastewater treatment to eliminate odor, color, and taste, as well as a range of inorganic and organic contaminants. The experimental setup for the up-flow fixed bed activated carbon contactor is depicted in Fig. 3.

The method employed in this study involved the utilization of an up-flow fixed bed activated carbon contactor. The experimental procedure consisted of partitioning the sample into three distinct portions, each of which was subjected to treatment in an up-flow fixed bed activated carbon contactor. The contactor beds were varied in terms of their depths (specifically 5 cm, 10 cm and 15 cm), while the column diameter remained constant (e.g. 10 cm) throughout the experiment. This methodology facilitated the evaluation of the influence of bed depth on

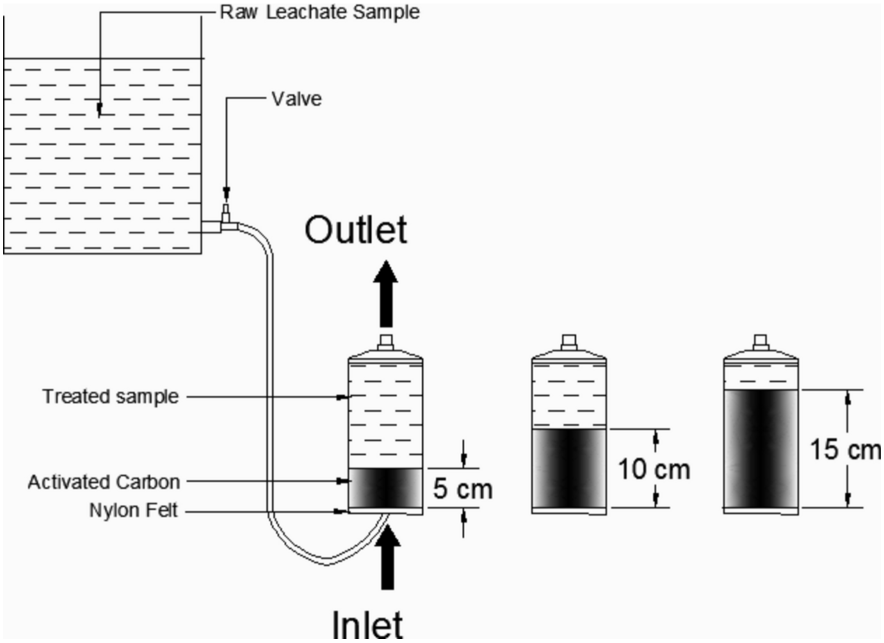

Fig. 3. Up flow AC contactor.

treatment efficacy. To find the impact of activated carbon bed depths on removal efficiency, 3 bed depths were selected based on other studies. For example, Sulaymon and Abood[38] applied four different bed depths of 0.03, 0.05, 0.08 and 0.11 m to estimate the critical bed depth in adsorption process through a fixed-bed of activated carbon at influent furfural concentration in wastewater of 0.2 kg/m^3 with constant flow rate of 16.66×10^{-5} m^3/min and adsorbent particle size of 0.5–1.5 mm.

Wastewater quality parameters

The study involved the analysis of various wastewater quality parameters in order to assess the efficacy of the treatment method. The parameters that were considered in this study encompassed pH, BOD, COD, TSS, total dissolved solids (TDS), ammonia nitrogen, turbidity, total nitrate, dissolved oxygen (DO), conductivity, and salinity. The oven dry method is applied in the laboratory for determining the TDS and TSS, while a digital pocket tester is also used to obtain TDS in leachate samples. The processes for analyzing these parameters were implemented in accordance with standard methods (APHA).

Results and discussion

Overview

This chapter thoroughly examines the findings derived from the investigation into treating landfill leachate using an integrated electrolysis methodology and a contactor containing palm-shell-activated carbon. The results incorporate data from the initial leachate sample, the electrolysis treatment procedure utilizing several electrode configurations, and the subsequent up-flow activated carbon treatment. Furthermore, the chapter examines salinity's impact on pollutant removal's effectiveness.

Data of untreated/raw leachate

The analysis of raw leachate from the Jeram Sanitary Landfill revealed alarming concentrations of pollutants, highlighting the critical need for treatment before discharge into aquatic environments. The measured values of key parameters in the untreated leachate exceeded the permissible discharge limits set by the Malaysian Environmental Quality Regulations of 2009. These significant discrepancies underscore the urgent necessity of implementing effective landfill leachate treatment methods to safeguard the environment. Table 1 presents the statistics for the raw leachate sample alongside the permitted discharge conditions for leachate in Malaysia.

Electrolysis

The research featured the utilization of electrolysis as the initial stage of treatment, wherein the selection of electrode materials had a pivotal role in determining the effectiveness of the treatment. The primary objective of this study was to investigate the impact of different configurations on the removals of TS, TDS, TSS, DO, ammonia nitrogen, nitrate, pH, zinc, sulfide, copper, electrical conductivity, salinity, turbidity, BOD and COD.

Effect on BOD and COD removal

The electrolysis technique exhibited notable efficacy in reducing the concentrations of BOD, and COD. Both electrode configurations demonstrated substantial enhancements in the reduction of these parameters. The reductions in BOD with both the Al-Al and Al–Fe electrode configurations were observed, decreasing from

Parameters	Units	Untreated leachate	Malaysia standards (Environmental Quality Regulations, 2009)
BOD_5 at 20 °C	mg/L	5250	20
COD	mg/L	10,133.3	400
TSS	mg/L	986.7	50
Ammonia Nitrogen	mg/L	110	5
Zinc	mg/L	14	2
Sulfide	mg/L	4	0.5
Copper	mg/L	1	0.2
pH	–	7.9	6–9

Table 1. Untreated leachate properties and discharge standard.

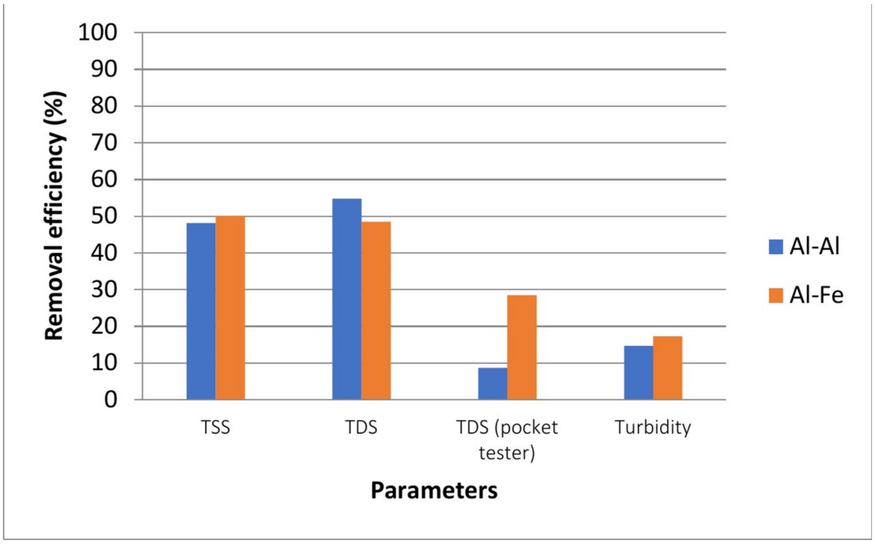

Fig. 4. Removal efficiency of TSS, TDS and turbidity by electrolysis.

5250 to 4260 mg/L and 3450 mg/L, respectively. The Al–Fe configuration achieved a BOD removal efficiency of 34.29%, while the Al-Al configuration showed a lower removal efficiency of 18.86%. Similar trends were observed for COD, where the Al–Fe configuration demonstrated a superior removal efficiency of 31.58%, compared to 19.28% for the Al-Al configuration. The results of this study indicate that the electrolysis process significantly improved the leachate's water quality, with the Al–Fe combination outperforming the Al-Al configuration. The superior removal efficiency of the Al–Fe electrode configuration compared to the Al-Al configuration in electrolysis may be attributed to the synergistic effects of aluminum and iron ions. Both aluminum and iron ions may react with hydroxide ions generated at the cathode to form metal hydroxides. These hydroxides may act as coagulants and flocculants, destabilizing colloidal particles and promoting their aggregation.

Effect on TSS, TDS and turbidity removal

The electrolysis procedure significantly influenced the reduction of TSS, TDS, and turbidity. Both electrode designs yielded promising results. According to the data presented in Fig. 4, TSS levels decreased, with the Al–Fe treatment achieving a slightly higher removal efficiency of 50.17% compared to the Al-Al treatment.

The outcomes for TDS were acquired using two distinct approaches, namely the conventional method (Oven dry method) and the digital pocket tester. These methods revealed disparities in the recorded values. The TDS values for the same leachate samples are compared in Fig. 4, while the oven dry method is more reliable as reported. Significant removal of TDS was achieved with both methods. However, Al-Al had a greater removal effectiveness of 54.80% compared to the Al–Fe configuration achieving the best removal effectiveness of 17.32%.

Effect on ammonia nitrogen and nitrate removal

The investigation evaluated the efficacy of ammonia nitrogen and nitrate removal after the process of electrolysis. Both experimental setups exhibited a reduction in ammonia nitrogen concentrations. The Al–Fe configuration demonstrated a superior removal effectiveness of 63.6%, while the Al-Al configuration achieved a 50% removal efficiency. Conversely, nitrate removal was more effective with the Al-Al configuration, achieving 50% removal compared to 28% with the Al–Fe configuration.

Effect on pH, zinc, sulfide, copper, electrical conductivity and salinity removal

The initial measurement of the untreated leachate's pH was 7.94, which is close to neutrality. Subsequent to the electrolysis process, the pH levels increased to 8.27 for the (Al-Al) configuration and 8.44 for the (Al–Fe) configuration, indicating a notable transition towards alkaline conditions. The electrolysis process increases the concentration of hydroxide ions over time in the leachate samples, which increases the pH value. Electrolysis increases pH levels because of the formation of hydroxide ions at the cathode, which is the negative terminal of a DC battery. Electrons enter the leachate at the cathode during electrolysis, starting a reduction reaction that yields hydroxide ions and hydrogen gas. The pH rises as a result of the hydroxide ions making the solution basic. The findings of this study are supported by other studies. Ciblak et al.[39] studied on pH and redox potential for water treatment and found that the pH values of the mixed sulfate and chloride electrolytes increased steadily as a result of electrolysis.

According to the data presented in Fig. 5, both zinc and sulfide concentrations decreased during the process of electrolysis. The highest effectiveness in removing zinc was achieved when Al–Fe electrodes showing a recorded removal efficiency of 92.14%. For sulfide, the maximum removal efficiency of 57.50% was observed using Al-Al electrodes. The concentration of copper was effectively reduced from an initial value of 1 mg/L to 0 mg/L, by the utilization Al-Al electrodes. Conversely, no significant change in copper concentration was noted when a combination of Al and Fe electrodes was employed. Additionally, the conductivity exhibited a notable increase to 87.3 µS/cm when utilizing aluminum electrodes, whereas the salinity readings for both electrolysis procedures had an upward trend. The relationship between electrical conductivity and salinity was underscored, with particular emphasis on the impact of dissolved ions in water on conductivity. The findings demonstrate electrolysis's significant influence on leachate features, showcasing noteworthy alterations in pH levels, metal composition, and electrical properties. pH, electrical conductivity and salinity were increased after electrolysis treatment.

Up-flow activated carbon treatment

The subsequent phase of the treatment procedure entailed the implementation of up-flow activated carbon contactor treatment after the electrolysis process, incorporating modifications in the depth of the activated carbon bed. This section examines the influence of bed depth on the efficacy of removing critical factors.

Effect on BOD and COD removal

The combination of electrolysis with activated carbon contactor treatment significantly improved the removal efficacy for BOD and COD. The removal efficiencies of activated carbon were found to increase when the bed depths were increased. At a bed depth of 15 cm, the best removal efficiency was reported as shown in Fig. 6. The BOD removal efficiency was found to be 81.71%, while the COD removal efficiency was determined to be 84.21% when the bed depth was set at 15 cm.

Effect on TSS, TDS and turbidity removal

Similar to BOD and COD, the efficacy of removing TSS, TDS, and turbidity also improved with increased bed depth of activated carbon. At a bed depth of 15 cm, the optimal removal efficiency for these parameters was achieved (Fig. 7).

Effect on ammonia nitrogen, nitrate, salinity and electrical conductivity removal

The removal efficiencies of ammonia nitrogen, nitrate, salinity, and electrical conductivity exhibited enhancement as the bed depths of activated carbon increased. Notably, a 15 cm bed depth was associated with the maximum removal efficiency for most of these factors (Fig. 8). The activated carbon applied in this study cannot adsorbed the ammonia nitrogen further on increasing the bed depths from 5 to 10 cm. The adsorption capacity of activated

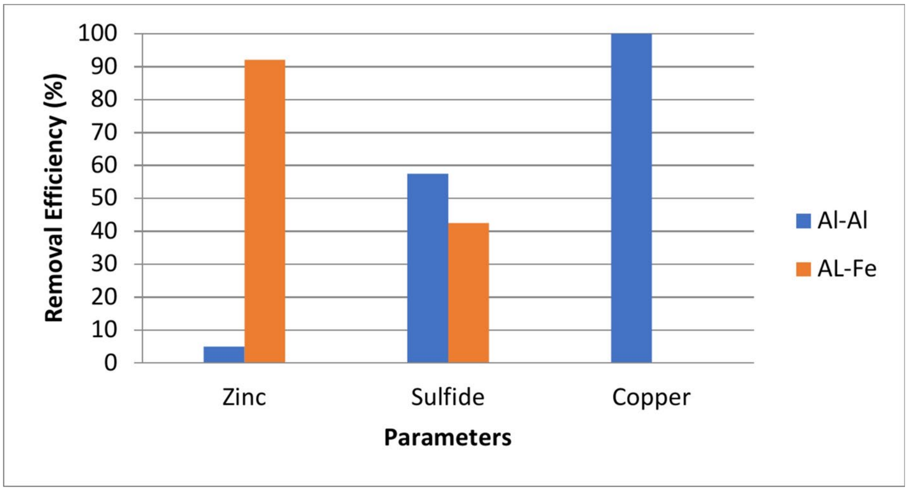

Fig. 5. Removal efficiency of zinc, sulfide and copper by electrolysis.

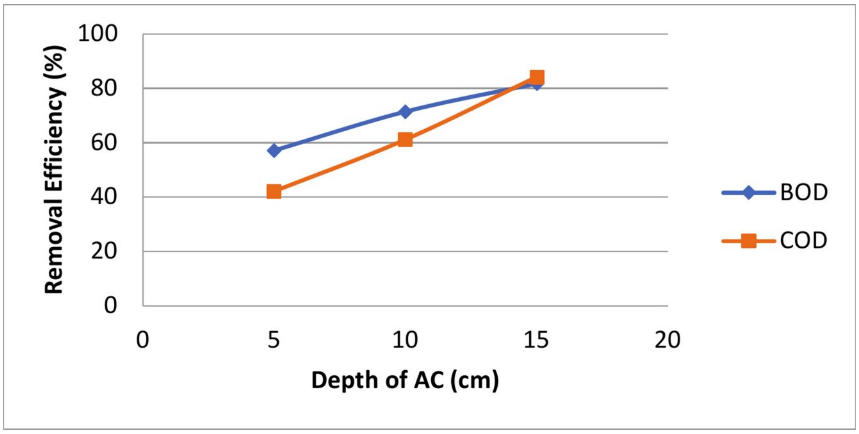

Fig. 6. Removal efficiency of BOD and COD by activated carbon adsorption.

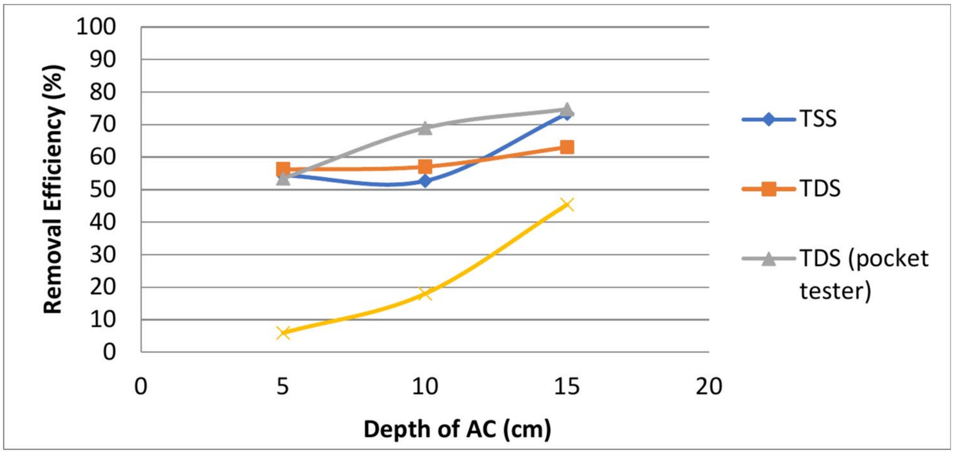

Fig. 7. Removal efficiency of TSS, TDS and turbidity by activated carbon adsorption.

carbon for ammonia nitrogen may be affected by the chemical components in the feedstock, which might be the reason behind the reduction of ammonia nitrogen removal.

Salinity effects on removal efficiency

To comprehend the impact of salinity on the treatment process, various proportions of salt were introduced into the samples, followed by subsequent examinations subsequent to electrolysis and activated carbon treatment.

Effect on BOD and COD removal

The introduction of salt into the samples led to varying outcomes in BOD and COD removal efficiencies, as shown in Fig. 9. The highest removal efficiency for BOD was observed at 0% salt concentration, at 84.21%, which decreased to 36.36% with the addition of 1% salt. Removal efficiency improved again with higher salt concentrations, reaching 92.31% at 5% salt. Conversely, COD removal efficiency decreased with increasing salt concentrations, starting at 81.1% with 0% salt and dropping to 46.27% at 5% salt.

Effect on TSS, TDS and turbidity removal

The inclusion of salt also yielded diverse impacts on the efficacy of TSS, TDS, and turbidity reduction. The parameters exhibited the best removal effectiveness at a salt concentration of 0%, with a subsequent decrease in efficiency reported upon the addition of 1% salt. However, there was a subsequent increase in salt levels to 3% and 5% (Fig. 10).

Effect on ammonia nitrogen, nitrate, electrical conductivity and salinity removal

The removal effectiveness of nitrate was higher at a salt concentration of 0%, as depicted in Fig. 11 and it was highest at a salt concentration of 5%. The other measures, particularly ammonia nitrogen, electrical conductivity and salinity, exhibited higher removal efficiencies while the salt concentration was at 0% but showed a decrease trend mostly in efficiency as the salt percentage grew.

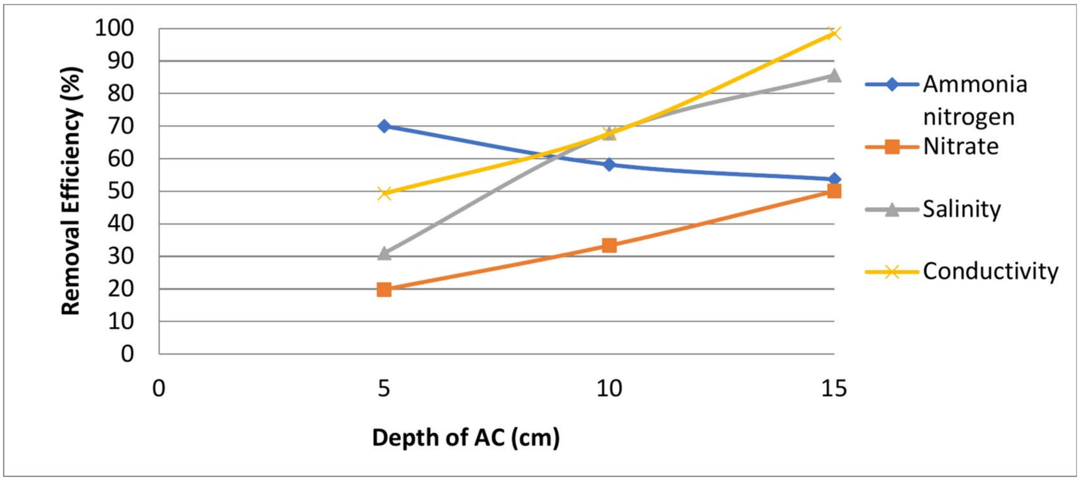

Fig. 8. Removal efficiency of ammonia nitrogen, nitrate, salinity and electrical conductivity by activated carbon adsorption.

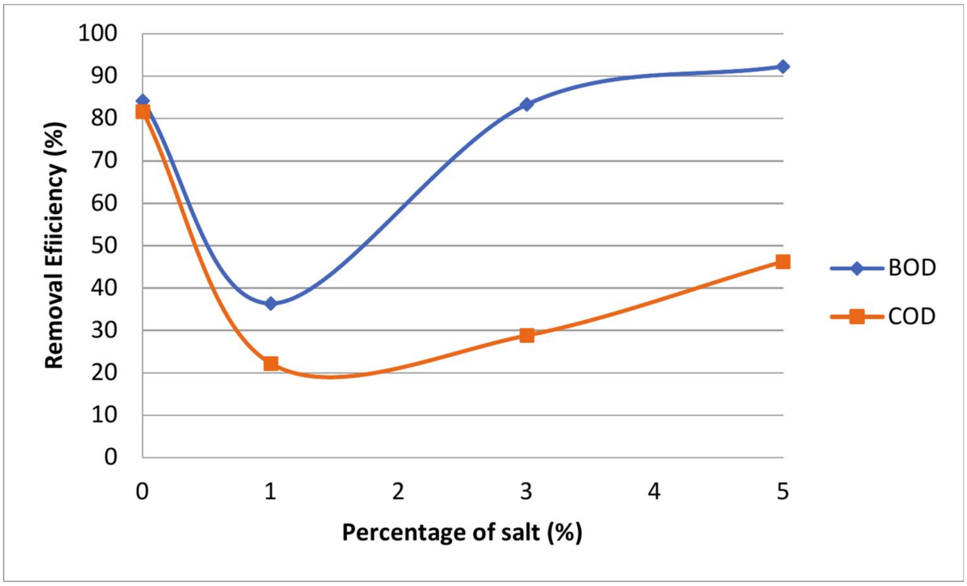

Fig. 9. Removal efficiency of BOD and COD by electrolysis and activated carbon adsorption.

In general, the initial decrease and subsequent increase in removal efficiency with increasing salt concentration in electrolysis may be attributed to complex electrochemical reactions and mass transfer phenomena. An increase in salt concentration may enhance the conductivity in the solution, leading to improved current flow and increased generation of reactive species, such as hydroxyl radicals and metal ions. These species can effectively oxidize organic pollutants and coagulate suspended solids, resulting in higher removal efficiencies in electrolysis. However, at higher salt concentrations, several factors may counteract these positive effects. Salt concentration is important in electrolysis because it affects the electrolyte's efficiency of electrolyzed oxidizing water and the amount of chlorine produced, and enhances the electrical conductivity[40]. The salt concentration and the solvent used affect the electrolyte's performance. The ideal salt concentration has a high number of free ions, which ensures high ionic conductivity[41].

Summary and discussion of results

The comprehensive results of the investigation are presented in Table 2. The combination of electrolysis and the utilization of a palm-shell activated carbon contactor has demonstrated significant efficacy in mitigating the quantities of crucial contaminants present in landfill leachate throughout the treatment process. The maximum COD removal efficiency is 31.6% by electrolysis (Al–Fe) only, whereas the minimum is 15.8% (Al-Al). The activated carbon adsorption efficiency ranges from 15.4 to 76.9% for bed depths of 5–15 cm. Therefore, the overall COD removal efficiency is 84.2% by electrolysis (Al–Fe) and adsorption (15 cm) techniques. Table SM1

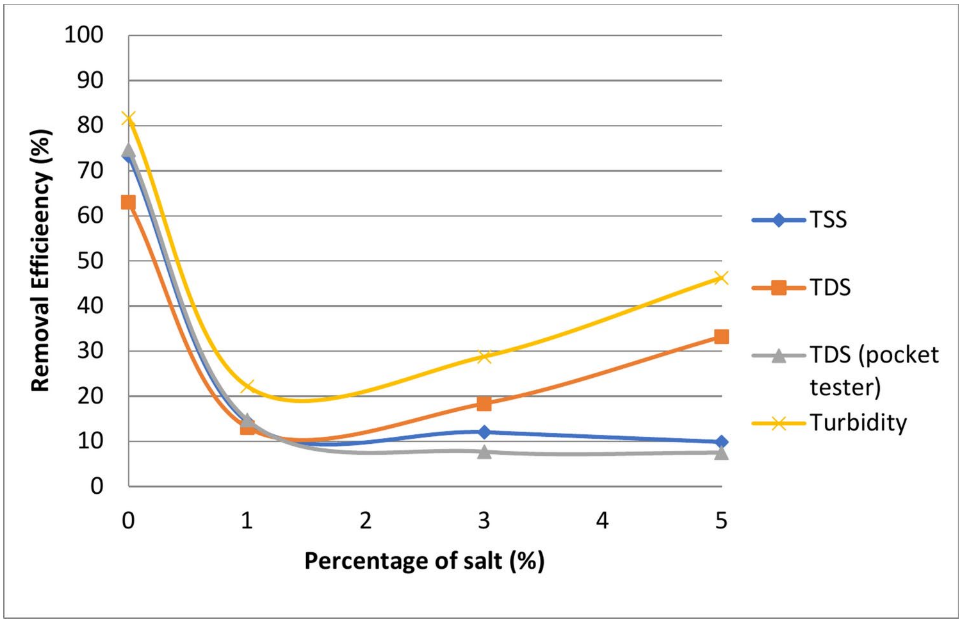

Fig. 10. Removal efficiency of TSS, TDS and turbidity by electrolysis and activated carbon adsorption.

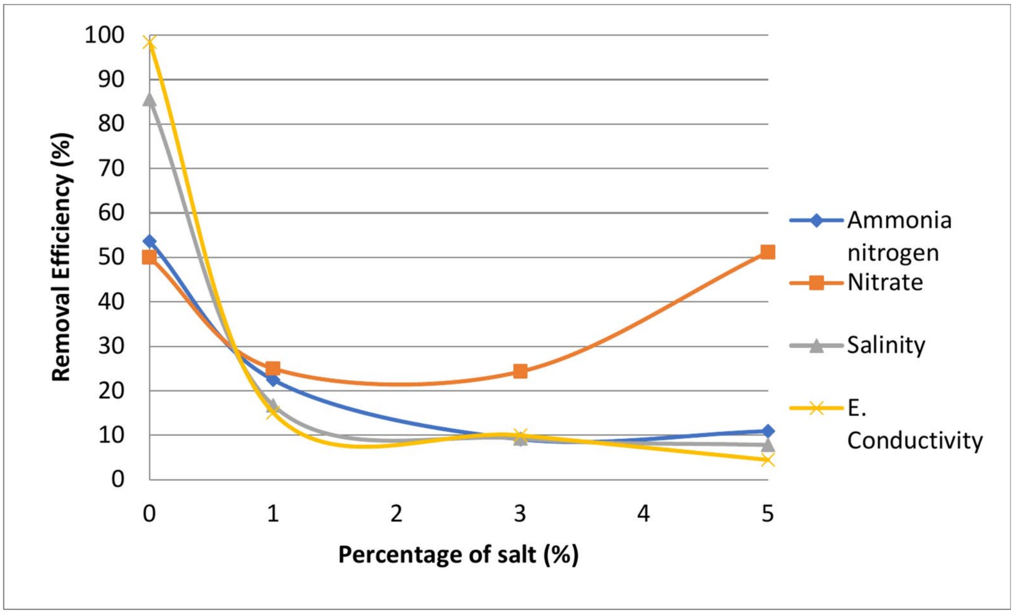

Fig. 11. Removal efficiency of ammonia nitrogen, nitrate, electrical conductivity and salinity by electrolysis and activated carbon adsorption.

shows the standard deviation of 2 treated samples by electrolysis only and of 3 treated samples by activated carbon after electrolysis (Supplementary Materials).

Ammonia nitrogen comprises of nitrogen in the form of unionized ammonia (NH_3) and ionized ammonium (NH_4^+)[42,43]. In the electrolysis process, the ammonia nitrogen is reduced from 110 to 50 ppm using Al-Al electrode (40 ppm using Al–Fe electrode), probably due to the degradation of NH_4^+ to nitrogen. The BOD and COD is removed by electrolysis as 34.3 and 31.6% (using Al–Fe electrode), respectively, probably due to the degradation of most of the organic matter in leachate to carbon dioxide. The findings of this study are supported by other studies[44].

It is important to note that the energy consumption of electrolysis may vary widely depending on factors, e.g. leachate composition, electrode material, current density and treatment time (HRT). To accurately assess the energy efficiency of a specific electrolysis process, a detailed energy balance analysis is necessary. This analysis should consider the energy input for electricity, pumping, and any auxiliary equipment, as well as the energy

Parameters	Unit	Experimental results					
		Untreated/raw leachate	Electrolysis (Al-Al)	Electrolysis (Al–Fe)	Activated carbon (5 cm)	Activated carbon (10 cm)	Activated carbon (15 cm)
pH	–	7.94	8.27	8.44	8.60	8.51	8.42
TDS-P	ppm	36,800.00	33,600.00	26,300.00	17,133.33	11,433.33	9300.00
Salinity	ppm	27,800.00	42,400.00	32,400.00	19,166.67	8966.67	4000.00
Conductivity	μS/cm	66.20	87.30	64.40	33.57	21.40	1.02
Ammonia nitrogen	mg/L	110.00	50.00	40.00	33.00	46.00	51.00
COD	mg/L	10,133.33	8533.33	6933.33	5866.67	3733.33	1600.00
TSS	mg/L	986.67	511.67	491.67	450.00	467.00	263.00
TDS-C	mg/L	27,316.67	12,347.00	14,070.00	11,968.00	11,737.00	10,098.00
Nitrate	mg/L	96.00	48.00	71.00	77.00	64.00	48.00
Turbidity	NTU	456.00	383.00	377.00	429.00	374.00	249.00
BOD	mg/L	5250.00	4260.00	3450.00	2250.00	1500.00	960.00

Table 2. Summary of experimental results using electrolysis and adsorption techniques. *TDS-P* TDS measured by the digital pocket tester, *TDS-C* TDS measured by conventional method (Oven dry method). The standard deviation for each characteristic of each data in the leachate samples may be assumed as ± 5%.

output in the form of treated effluent. The sustainability of electrochemical treatment methods for landfill leachate in landfills may be improved by carefully considering energy efficiency and implementing energy-saving strategies. The energy cost of the Fe/Gr electrode is 35.9 and 2.1 times lower than that of Ti/PbO_2 for the removal of COD and NH_4^+, respectively[32]. The energy consumption of bio-treatment landfill leachate using a novel reactive electrochemical membrane (REM) technology was 3.6 kWh/m[345].

The findings depicted in Fig. SM1 indicate that the Al–Fe electrode design exhibited the highest level of efficiency in the process of electrolysis (Supplementary Materials). It implies that the turbidity removal rate is lower compared to other parameters, which is challenging to remove in higher percentages by electrolysis. The subsequent up-flow activated carbon treatment, specifically utilizing a 15 cm bed depth, exhibited enhanced efficacy in removing pollutants, as depicted in Fig. SM2 (Supplementary Materials). The impact of salinity on the removal efficiency of various factors was observed to be variable. These results underscore the viability of adopting a sustainable methodology for treating landfill leachate. The integrated process, as demonstrated, presents notable enhancements in terms of water quality and environmental safeguarding. Additional investigation is required to enhance the therapy procedure and effectively tackle the impacts of diverse parameters and circumstances.

The integrated system using electrolysis and activated carbon adsorption may be adapted to various landfill leachate compositions and scaled up for large-scale applications in industries. Pilot-scale testing may optimize the system for specific leachate characteristics. Flexible reactor designs, advanced process control, and integration with other treatment technologies may enhance the system's performance. For scaling up, modular designs, parallel operation, economies of scale, and optimized energy management are crucial. Thorough leachate characterization, optimized reactor design, advanced process control, and effective sludge management are key factors to be considered for successful implementation of this integrated system in landfill leachate treatment.

In further study, it is suggested to perform the physical and chemical characterization of the activated carbon and of the electrodes to verify the mechanisms involved in the landfill leachate treatment. It is recommended to find the optimal activated carbon bed depth in further study to treat landfill leachate. Further study may evaluate the electrode degradation rate, especially in the presence of high-salinity leachate, and its potential impact on the longevity and cost-effectiveness of the system. The physical or chemical characterization should be carried out for the activated carbon and electrodes used in the system. The removal of total organic carbon and refractory organic matter can be studied further to check whether they are particularly resistant to treatment or not.

Conclusions

This study aimed to evaluate the effectiveness of an up-flow fixed bed activated carbon contactor in removing various pollutants from landfill leachate. The results indicate that the removal effectiveness of COD and BOD was 31.58% and 34.29%, respectively, when iron and aluminum electrodes were used. Additionally, using the same electrode design, TSS demonstrated the best removal effectiveness of 50.17%. When aluminum and iron electrodes were used, ammonia nitrogen, zinc, and conductivity showed the most promising results, with removal efficiencies of 63.64% for ammonia nitrogen, 92.14% for zinc, and 2.72% for electrical conductivity. After the electrolysis process, salinity rose; however, the rise was less pronounced when iron and aluminum electrodes were used. With aluminum electrodes alone, nitrate, sulfide, and copper all had higher removal efficiencies: 50% for nitrate, 57.50% for sulfide, and 100% for copper. Apart from ammonia nitrogen, which showed a decline in removal effectiveness with increasing bed depth, a bed depth of 15 cm regularly produced the best results for most parameters. At a bed depth of 15 cm, the removal efficiencies of BOD and COD were 81.71% and 84.21%, respectively. The electrical conductivity demonstrated a noteworthy elimination efficiency of 98.46%. However, at a 15 cm bed depth, the ammonia nitrogen removal efficiency dropped to 54.64%.

The impact of salinity is also examined in relation to the efficacy of pollution mitigation. Except for BOD, which demonstrated good removal efficiency even at 5% salt, results indicated that the removal effectiveness was maximum when no salt (0%) was applied to the samples. The variations in salt percentages that have been noticed can be ascribed to mistakes made during experiments, such reusing activated carbon and improperly storing the samples. All the experiments should be repeated at least three times to confirm the findings of this study using the same source or different sources of landfill leachate samples in any countries. Finally, it may be concluded that the efficiency of different contaminants' elimination remains apparent, even though the treatment process's overall efficacy may be weakened in some situations. It is also obvious that concentrations of some parameters are increased due to electrolysis treatment in leachate, e.g. pH.

Data availability

Further information/data may be supplied upon request. For access to the data and materials, please contact A. Ahsan at ashikcivil@yahoo.com.

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Declarations

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The authors declare no competing interests.

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