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EVALUATION OF THE REMEDIATION POTENTIAL OF ETHANOLIC LEAF EXTRACTS OF *CHROMOLAENA ODORATA*, *AZADIRACHTA INDICA*, AND *PERSEA AMERICANA* ON THE PHYSICOCHEMICAL QUALITY OF LANDFILL LEACHATE

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ABSTRACT

Landfill leachate is a highly contaminated wastewater generated during the decomposition of municipal solid waste and is characterized by elevated concentrations of organic matter, dissolved salts, nutrients, and other physicochemical pollutants that pose serious environmental and public health concerns. This study evaluated the effectiveness of ethanol leaf extracts of *Persea americana*, *Chromolaena odorata*, and *Azadirachta indica*, applied individually and in different combinations, for the remediation of the physicochemical properties of landfill leachate. Fresh leaves of the three plant species were collected, washed, air-dried, pulverized, and extracted using ethanol following standard extraction procedures. The extracts were applied individually, as binary combinations, and as a ternary combination at concentrations of 1, 2, and 3 mg/mL. Treated leachate samples were analyzed for selected physicochemical parameters, including electrical conductivity (EC), total dissolved solids (TDS), turbidity, total hardness, biochemical oxygen demand (BOD), chemical oxygen demand (COD), chloride, sulphate, nitrate, nitrite, calcium, magnesium, phosphate, and potassium using standard analytical methods. Data were subjected to analysis of variance (ANOVA), and treatment means were separated using the Least Significant Difference (LSD) test at a 5% level. The results showed that all plant extracts significantly ($p < 0.05$) improved the physicochemical quality of the landfill leachate compared with the untreated control. Increasing extract concentration from 1 to 3 mg/mL resulted in progressive reductions in EC, TDS, turbidity, total hardness, BOD, and COD, indicating a concentration-dependent remediation effect. Among the single-plant treatments, *Persea americana* consistently exhibited the highest remediation efficiency, whereas *Chromolaena odorata* showed comparatively lower performance at the lowest concentration but improved markedly as the dosage increased. Binary combinations generally outperformed individual extracts, while the ternary combination of *Persea americana* + *Chromolaena odorata* + *Azadirachta indica* produced the greatest overall improvement in leachate quality. The findings demonstrate that ethanol leaf extracts of *Persea americana*, *Chromolaena odorata*, and *Azadirachta indica*, particularly when applied in combination, are effective natural remediation agents for improving the physicochemical quality of landfill leachate.

KEYWORDS: Landfill leachate; Physicochemical properties; Ethanol leaf extracts;; Wastewater remediation; Phytoremediation.

INTRODUCTION

The rapid increase in municipal solid waste (MSW) generation resulting from population growth, urbanization, industrialization, and changing consumption patterns has become one of the most pressing environmental challenges worldwide. Landfilling remains the predominant method of solid waste disposal because of its relatively low operational cost, simplicity, and capacity to accommodate large volumes of waste (United Nations Environment Programme [UNEP], 2024; World Bank, 2023).

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Despite these advantages, landfill systems generate substantial quantities of leachate, a highly contaminated liquid formed when precipitation percolates through waste deposits and mobilizes soluble organic and inorganic constituents produced during waste decomposition (Kjeldsen et al., 2002; Renou et al., 2008). If inadequately managed, landfill leachate constitutes a major source of environmental pollution, threatening soil quality, surface water, groundwater resources, aquatic ecosystems, and human health because of its complex chemical composition and high pollutant load (Christensen et al., 2001; Naveen et al., 2017; Parida et al., 2023). The composition of landfill leachate is highly variable and is influenced by factors such as landfill age, waste composition, climatic conditions, moisture content, operational practices, and the extent of biological degradation (Kjeldsen et al., 2002; Renou et al., 2008). Young landfill leachates are typically characterized by high concentrations of biodegradable organic matter and elevated biochemical oxygen demand (BOD) and chemical oxygen demand (COD), whereas mature leachates generally contain lower concentrations of biodegradable organic compounds but higher levels of ammoniacal nitrogen, dissolved salts, humic substances, heavy metals, and other recalcitrant contaminants (Kjeldsen et al., 2002; Renou et al., 2008; Aziz et al., 2023). Consequently, landfill leachate quality is commonly evaluated using physicochemical parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, biochemical oxygen demand (BOD), chemical oxygen demand (COD), nutrients, hardness, and major inorganic ions (Mor et al., 2006; Christensen et al., 2001; Parida et al., 2023). These parameters provide essential information on the pollution status of leachate and the effectiveness of treatment processes. Untreated landfill leachate poses serious environmental and public health risks due to its high concentrations of organic pollutants, nutrients, dissolved salts, and potentially toxic substances. Elevated BOD and COD can deplete dissolved oxygen in receiving water bodies, while excessive nutrient concentrations contribute to eutrophication and deterioration of aquatic ecosystems. Furthermore, the migration of leachate through soil profiles may contaminate groundwater, which serves as an important source of domestic and agricultural water in many developing countries. Long-term exposure to contaminated water has been associated with gastrointestinal disorders, kidney and liver dysfunction, neurological impairment, endocrine disruption, and increased cancer risk resulting from prolonged exposure to hazardous organic and inorganic contaminants (Fu & Wang, 2011; World Health Organization [WHO], 2022; Tchounwou et al., 2012; Jaishankar et al., 2014; Briffa et al., 2020). These concerns underscore the need for efficient, sustainable, and environmentally friendly technologies for landfill leachate treatment. Numerous physicochemical and biological technologies have been developed for landfill leachate remediation, including coagulation-flocculation, adsorption, membrane filtration, reverse osmosis, ion exchange, electrochemical oxidation, advanced oxidation processes, biological treatment, constructed wetlands, and hybrid treatment systems (Renou et al., 2008; Crini & Lichtfouse, 2019; Aziz et al., 2023). Although these technologies can achieve high pollutant removal efficiencies, their widespread application is often constrained by high capital and operational costs, intensive energy requirements, continuous chemical consumption, specialized technical expertise, and the generation of secondary sludge requiring further treatment and disposal (Barakat, 2011; Crini & Lichtfouse, 2019). These limitations have stimulated increasing interest in the development of affordable, sustainable, and environmentally benign alternatives for wastewater remediation. Among emerging green technologies, plant-derived materials have gained considerable attention as natural remediation agents because they are renewable, biodegradable, inexpensive, and readily available. Numerous studies have demonstrated that plant materials contain diverse phytochemicals, including phenolics, flavonoids, tannins, saponins, alkaloids, proteins, and polysaccharides, which may contribute to the removal of contaminants from wastewater through mechanisms such as adsorption, coagulation, flocculation, ion exchange, and complexation, depending on their chemical composition and the nature of the pollutants present (Demirbas, 2008; Vijayaraghavan & Yun, 2008; Ali et al., 2021; Ghosh et al., 2022; Crini & Lichtfouse, 2019). Compared with conventional chemical coagulants, plant-derived materials are biodegradable, generate less hazardous sludge, and are considered more environmentally compatible, making them attractive candidates for sustainable wastewater treatment. *Chromolaena odorata*, *Azadirachta indica*, and *Persea americana* are widely distributed tropical plant species known to possess diverse phytochemical constituents with documented antimicrobial, antioxidant, adsorptive, and coagulating properties. Previous studies have demonstrated the effectiveness of plant-derived materials in improving water quality; however, comparative information on the remediation potential of ethanolic leaf extracts of these three indigenous species for landfill leachate treatment remains limited. In addition, little is known about the potential enhancement in remediation efficiency when these extracts are applied in binary or ternary combinations. Addressing these knowledge gaps is important for identifying sustainable, low-cost alternatives for landfill leachate management.

Therefore, this study evaluated the remediation potential of ethanolic leaf extracts of *Chromolaena odorata*, *Azadirachta indica*, and

Persea americana, applied individually and in binary and ternary combinations, for improving the physicochemical quality of landfill leachate. The findings of this study are expected to contribute to the growing body of knowledge on plant-based wastewater remediation and provide scientific evidence supporting the development of environmentally friendly and sustainable technologies for landfill leachate treatment.

MATERIALS AND METHODS

Study Area

The study was conducted using landfill leachate collected from the Lemna Dumpsite located in Calabar Municipality, Cross River State, Nigeria. The dumpsite serves as one of the principal municipal solid waste disposal facilities within the metropolis and receives mixed municipal wastes generated from residential, commercial, and institutional sources. Continuous waste deposition and inadequate containment measures have resulted in persistent leachate generation, posing potential risks to surrounding soil and water resources. The geographical coordinates of the sampling site are approximately 4°56.922′ N and 8°20.974′ E. Laboratory analyses were carried out at the Ministry of Science and Technology Laboratory, Uyo, Akwa Ibom State, Nigeria.

Collection of Landfill Leachate

Landfill leachate samples were collected from active seepage points within the Lemna Dumpsite using sterile high-density polyethylene containers previously rinsed with distilled water. Immediately after collection, the initial pH of the leachate was determined using a calibrated digital pH meter. The samples were tightly sealed, properly labelled, and transported in insulated ice chests to the laboratory for analysis. Upon arrival, the samples were stored at 4°C and analysed within 24 h to minimise physicochemical and microbial alterations before treatment.

Collection and Preparation of Plant Materials

Fresh leaves of *Persea americana*, *Chromolaena odorata*, and *Azadirachta indica* were collected from the Botanical Garden of the University of Calabar, Calabar, Nigeria. The plant materials were washed thoroughly with distilled water to remove adhering soil particles and other contaminants before being air-dried at room temperature (25–30°C) for ten days until a constant weight was attained. The dried leaves were pulverised into a fine powder using a laboratory grinder and stored in airtight containers until extraction.

Preparation of Ethanolic Leaf Extracts

Ethanolic extracts were prepared using the Soxhlet extraction method. Briefly, 100 g of powdered leaf material from each plant species was wrapped in a Whatman filter paper thimble and transferred into the Soxhlet extractor. Two hundred millilitres of analytical-grade ethanol were added to a 250 mL round-bottom flask connected to the extraction apparatus. Extraction was carried out under reflux for approximately 6–8 h until the solvent in the siphon tube became colourless, indicating exhaustive extraction.

Following extraction, the solvent was concentrated using a water bath maintained at 40–50°C. The concentrated extracts were further dried in a desiccator to remove residual solvent and stored in sterile amber bottles at 4°C until use. For the treatment experiment, stock solutions were prepared by dissolving appropriate quantities of the crude extracts in distilled water to obtain final concentrations of 1, 2, and 3 mg/mL, respectively.

Experimental Design

The experiment was arranged as a 4 × 7 factorial in a Completely Randomised Design (CRD). The first factor consisted of four extract concentrations (0, 1, 2 and 3 mg/mL), while the second factor comprised seven extract treatments, namely:

- *Persea americana*
- *Chromolaena odorata*
- *Azadirachta indica*
- *Persea americana* + *Chromolaena odorata*
- *Persea americana* + *Azadirachta indica*
- *Chromolaena odorata* + *Azadirachta indica*
- *Persea americana* + *Chromolaena odorata* + *Azadirachta indica*

Each treatment combination was replicated three times, giving a total of 84 experimental units.

Treatment of Leachate Samples

One hundred millilitres of landfill leachate were dispensed into sterile sample bottles for each treatment. Appropriate volumes of the prepared plant extract solutions were added to achieve final concentrations of 1, 2, and 3 mg/mL, while untreated leachate served as the control. Each treated sample was thoroughly mixed to ensure uniform distribution of the extract before being subjected to a coagulation–flocculation process using the Jar Test procedure. Samples were rapidly mixed at 250 rpm for 2 min to facilitate dispersion of the extracts, followed by slow mixing at 40 rpm for 20 min to promote floc formation. The mixtures were subsequently allowed to settle for 30 min.

Following sedimentation, the treated samples were maintained under laboratory conditions for 42 days to allow sufficient interaction between the plant extracts and dissolved contaminants. At the end of the treatment period, approximately 80 mL of the clarified supernatant was carefully withdrawn using a sterile pipette and used for physicochemical analyses. The Jar Test procedure was performed according to George et al. (2018).

Physicochemical Analysis

Physicochemical analyses were conducted according to the Standard Methods for the Examination of Water and Wastewater (APHA, 2017). All reagents used were of analytical grade, while distilled water was used throughout the analyses. All determinations were carried out in triplicate, and the results were expressed as mean ± standard deviation.

The following parameters were determined:

- pH using a calibrated digital pH meter;
- Electrical conductivity (EC) using a conductivity meter;
- Total dissolved solids (TDS) using the gravimetric method;
- Turbidity using a nephelometric turbidimeter;
- Chloride using the argentometric titration method;
- Sulphate using the turbidimetric method;
- Nitrate using ultraviolet spectrophotometry;
- Nitrite using the colourimetric method;
- Total hardness using the EDTA titrimetric method;
- Calcium using EDTA titration with murexide indicator;
- Magnesium by difference between total hardness and calcium hardness;
- Phosphate using the ascorbic acid method;
- Potassium using flame photometry;
- Chemical oxygen demand (COD) using the dichromate reflux method; and
- Biochemical oxygen demand (BOD_5) using the five-day incubation method (APHA, 2017; Agbor et al., 2026).

Determination of Remediation Efficiency

The remediation efficiency of each treatment was evaluated by calculating the percentage reduction in each physicochemical parameter relative to the untreated control using the following equation:

$$\text{Percentage reduction (\%)} = [(C_0 - C_t) / C_0] \times 100$$

Where: C_0 = initial concentration of the parameter in untreated leachate (control) C_t = concentration of the parameter after treatment.

The calculated values were used to compare the effectiveness of the different plant extracts and their combinations in improving the physicochemical quality of the landfill leachate.

Statistical analysis

Data generated from the study were subjected to two-way analysis of variance (ANOVA) appropriate for a factorial Completely Randomised Design to evaluate the effects of extract type, extract concentration, and their interaction on the physicochemical characteristics of the treated landfill leachate. Where significant differences were observed ($p < 0.05$), treatment means were separated using the Least Significant Difference (LSD) test at the 5% probability level. All statistical analyses were performed using appropriate statistical software, and results were presented as mean ± standard deviation.

RESULTS AND DISCUSSION

Effects of Ethanol Leaf Extracts on the Physical Properties of Landfill Leachate

The effects of ethanol leaf extracts of *Persea americana*, *Chromolaena odorata*, *Azadirachta indica*, and their combinations on the physical properties of landfill leachate are presented in Table 1, while the percentage reductions in selected physicochemical parameters are shown in Table 3.

pH and Temperature

The untreated landfill leachate was strongly acidic, with a pH of 4.08 ± 0.08. Treatment with all plant extracts significantly ($p < 0.05$) increased the pH of the leachate, with the magnitude of increase depending on extract concentration and treatment combination. The highest pH (7.36 ± 0.09) was recorded in the ternary combination (*P. americana* + *C. odorata* + *A. indica*) at 3 mg mL^{-1}, whereas the lowest pH among treated samples (5.20 ± 0.09) was observed in *A. indica* at **1 mg mL⁻¹*. In general, pH increased progressively with increasing extract concentration. Temperature varied only slightly among treatments, ranging from 32.8 to 39.5°C, and no consistent concentration-dependent pattern was observed.

Electrical Conductivity and Total Dissolved Solids

Electrical conductivity (EC) was significantly ($p < 0.05$) reduced following treatment with all plant extracts. The untreated leachate recorded the highest EC (7830 ± 1.67 µS cm^{-1}), whereas the lowest value (810 ± 1.78 µS cm^{-1}) occurred in the ternary extract at 3 mg mL^{-1}. Similarly, total dissolved solids (TDS) decreased significantly from 1843 ± 2.09 mg L^{-1} in the untreated leachate to 263 ± 6.09 mg L^{-1} following treatment with the ternary extract at the highest concentration. The percentage reduction analysis (Table 3) further showed that remediation efficiency increased with extract concentration. The ternary extract produced the greatest reductions in EC (89.7%) and TDS (85.7%) among all treatments.

Total Hardness, Turbidity and Alkalinity

Treatment with the ethanol leaf extracts resulted in significant reductions ($p < 0.05$) in total hardness, turbidity and alkalinity compared with the untreated control (Table 1). Total hardness decreased from 576 ± 2.01 mg L^{-1} in the untreated leachate to 78 ± 1.98 mg L^{-1} following treatment with the ternary extract at 3 mg mL^{-1}. Likewise, turbidity decreased markedly from 884 ± 1.45 NTU to 168 ± 1.25 NTU, while alkalinity declined from 475 ± 3.20 mg L^{-1} to 63.4 ± 1.83 mg L^{-1}. The highest percentage reductions in total hardness (86.5%) and turbidity (81.0%) were also recorded for the ternary extract at 3 mg mL^{-1} (Table 2).

Dissolved Oxygen, Biochemical Oxygen Demand and Chemical Oxygen Demand

Dissolved oxygen (DO) increased significantly following treatment, whereas biochemical oxygen demand (BOD) and chemical oxygen demand (COD) declined significantly ($p < 0.05$) in all treated samples (Table 1). The untreated leachate recorded a DO concentration of 5.8 ± 0.09 mg L^{-1}, which increased to values ranging from 6.0 to 9.6 mg L^{-1} after treatment. Conversely, BOD decreased from 17.3 ± 0.84 mg L^{-1} in the untreated leachate to 4.0 ± 0.05 mg L^{-1} following treatment with *P. americana* + *A. indica* at 3 mg mL^{-1}. Similarly, COD decreased substantially from 2984 ± 3.91 mg L^{-1} in the untreated leachate to 310 ± 1.90 mg L^{-1} following treatment with the ternary extract at 3 mg mL^{-1}. Percentage reduction analysis revealed that the ternary extract achieved the greatest COD reduction (89.6%), whereas the highest BOD reduction (77.0%) was observed in the *P. americana* + *A. indica* treatment at 3 mg mL^{-1} (Table 3).

Table 1: Physical properties of leachate samples from Lemna Landfill treated with ethanol plant extracts

Plant extract	Conc./ratio	pH	Temp (^{0}C)	EC (µs/cm)	Total Hardness	Turbidity (NTU)	Alkalinity (mg/L)	TDS (mg/L)	BOD (mg/L)	DO (mg/L)	COD (mg/L)
	Control	$4.08^{f}\pm0.08$	39.5±0.10	$7830^{a}\pm1.67$	$576^{a}\pm2.01$	$884^{a}\pm1.45$	$1843^{a}\pm2.09$	$475^{a}\pm3.20$	$17.3^{a}\pm0.84$	$19.6^{a}\pm0.43$	$2984^{a}\pm3.91$
Persea americana	1	$5.46^{d}\pm0.07$	36.4±0.09	$1284^{c}\pm4.09$	$263^{b}\pm2.67$	$644^{b}\pm2.09$	$642^{c}\pm1.21$	$166^{b}\pm5.09$	$6.1^{c}\pm0.21$	$7.5^{d}\pm0.09$	$815^{b}\pm2.09$
	2	$6.08^{c}\pm0.12$	37.2±0.10	$1273^{c}\pm1.08$	$148^{d}\pm3.08$	$632^{b}\pm1.78$	$607^{d}\pm2.04$	$74^{d}\pm3.23$	$7.30^{c}\pm014$	$8.6^{c}\pm0.12$	$810^{b}\pm1.67$
	3	$6.88^{a}\pm0.17$	34.5±0.12	$1107^{e}\pm2.28$	$94^{e}\pm2.73$	$248^{g}\pm2.78$	$532^{e}\pm3.84$	$72^{d}\pm2.09$	$5.80^{c}\pm0.06$	$7.0^{d}\pm0.08$	$743^{c}\pm4.23$
Chromolaena odorata	1	$5.36^{d}\pm0.06$	35.6±0.08	$2484^{b}\pm2.78$	$184^{c}\pm1.89$	$386^{c}\pm1.53$	$704^{b}\pm3.08$	128c±2.78	$8.10^{b}\pm0.67$	$9.4^{b}\pm0.07$	$836^{b}\pm5.07$
	2	$6.39^{b}\pm0.08$	36.2±0.21	$984^{g}\pm1.23$	$143^{d}\pm1.67$	$384^{c}\pm3.06$	$602^{d}\pm6.03$	$83^{d}\pm2.91$	$7.2^{c}\pm0.23$	$8.4^{c}\pm0.11$	$825^{b}\pm2.68$
	3	$6.53^{a}\pm0.13$	35.6±0.18	$926^{g}\pm7.12$	$88^{e}\pm0.87$	$204^{h}\pm1.43$	$494^{e}\pm3.89$	$60.2^{d}\pm0.67$	$6.1^{c}\pm0.16$	$7.3^{d}\pm0.09$	$640^{d}\pm2.08$
Azadirachta indica	1	$5.20^{e}\pm0.09$	37.3±0.12	$1864^{d}\pm3.40$	$194^{c}\pm1.34$	$226^{g}\pm1.78$	$609^{d}\pm3.09$	$148^{b}\pm1.56$	$8.2^{b}\pm0.13$	$9.3^{b}\pm0.10$	$743^{c}\pm4.67$
	2	$6.60^{a}\pm0.11$	32.8±0.08	$1043^{f}\pm4.02$	$128^{d}\pm1.23$	$201^{h}\pm2.54$	$486^{e}\pm2.91$	$73^{d}\pm2.01$	$5.2^{c}\pm0.08$	$6.3^{d}\pm0.07$	$609^{e}\pm3.92$
	3	$6.78^{a}\pm0.08$	37.0±0.18	$962^{g}\pm2.83$	$124^{d}\pm1.09$	$196^{h}\pm1.23$	$384^{f}\pm2.02$	$56.6^{d}\pm1.01$	$4.2^{c}\pm0.07$	$5.4^{e}\pm0.04$	$548^{f}\pm2.45$
PA+ CO	1 (1:1)	$6.02^{c}\pm0.06$	35.1±0.11	$986^{g}\pm3.78$	$148^{d}\pm2.91$	$268^{f}\pm0.98$	$652^{c}\pm1.08$	$112^{c}\pm1.67$	$5.8^{c}\pm0.09$	$7.0^{d}\pm0.05$	$618^{e}\pm2.03$
	2 (1:1)	$6.84^{a}\pm0.04$	36.8±0.15	$984^{g}\pm2.89$	$130^{d}\pm2.43$	$243^{g}\pm1.32$	$404^{f}\pm1.49$	$83.4^{d}\pm1.03$	$5.3^{c}\pm0.08$	$6.5^{d}\pm0.06$	$534^{f}\pm1.23$
	3 (1:1)	$6.92^{a}\pm0.05$	37.3±0.12	$864^{h}\pm3.07$	$89^{e}\pm1.21$	$183^{h}\pm1.56$	$302^{g}\pm2.89$	$52.1^{d}\pm2.09$	$4.9^{c}\pm0.07$	$6.0^{d}\pm0.10$	$494^{g}\pm2.78$
PA + AI	1 (1:1)	$6.58^{a}\pm0.08$	39.3±0.11	$974^{g}\pm2.89$	$124^{d}\pm2.01$	$321^{d}\pm1.89$	$494^{e}\pm2.90$	$134^{c}\pm1.92$	$6.8^{c}\pm0.10$	$8.2^{c}\pm0.08$	$508^{g}\pm2.04$
	2 (1:1)	$6.67^{a}\pm0.04$	35.2±0.08	$983^{g}\pm2.10$	$117^{d}\pm1.45$	$228^{g}\pm2.01$	$483^{e}\pm1.78$	$87.8^{d}\pm1.09$	$4.3^{c}\pm0.08$	$7.0^{d}\pm0.04$	$491^{g}\pm1.20$
	3 (1:1)	$7.01^{a}\pm0.07$	36.2±0.09	$820^{h}\pm1.20$	$94^{e}\pm1.10$	$194^{h}\pm2.34$	$294^{g}\pm1.24$	$62.4^{d}\pm0.98$	$4.0^{c}\pm0.05$	$6.3^{d}\pm0.04$	$412^{h}\pm2.56$
CO + AI	1 (1:1)	$6.84^{a}\pm0.06$	34.5±0.08	$948^{g}\pm2.78$	$134^{d}\pm0.89$	$304^{e}\pm2.39$	$546^{e}\pm3.07$	$156.8^{b}\pm0.89$	$5.7^{c}\pm0.23$	$7.0^{d}\pm0.11$	$531^{f}\pm1.89$
	2 (1:1)	$6.88^{a}\pm0.03$	36.4±0.06	$824^{h}\pm2.19$	$104^{e}\pm2.09$	236g±2.08	$309^{g}\pm2.09$	$98.6^{d}\pm0.27$	$4.8^{c}\pm0.17$	$6.8^{d}\pm0.13$	$409^{h}\pm0.89$
	3 (1:1)	$6.94^{a}\pm0.07$	37.9±0.04	$816^{h}\pm1.78$	$82^{e}\pm0.87$	$207^{h}\pm1.57$	$254^{h}\pm2.23$	$54.2^{d}\pm0.56$	$5.3^{c}\pm0.14$	$6.2^{d}\pm0.21$	$392^{h}\pm1.90$
PA+CO+AI	1 (1:1:1)	$6.34^{b}\pm0.09$	36.5±0.80	$848^{h}\pm1.20$	$128^{d}\pm0.89$	$243^{g}\pm2.03$	$469^{e}\pm2.67$	$118.4^{c}\pm0.48$	$6.2^{c}\pm0.12$	$7.5^{d}\pm0.20$	$489^{g}\pm1.78$
	2(1:1:1)	$7.21^{a}\pm0.10$	36.2±0.23	$836^{h}\pm1.34$	$94^{e}\pm0.68$	$205^{h}\pm1.89$	$311^{g}\pm4.09$	$94.2^{d}\pm2.31$	$5.1^{c}\pm0.23$	$6.3^{d}\pm0.08$	$324^{i}\pm3.20$
	3(1:1:1)	$7.36^{a}\pm0.09$	37.0±0.11	$810^{h}\pm1.78$	$78^{e}\pm1.98$	$168^{i}\pm1.25$	$263^{h}\pm6.09$	$63.4^{d}\pm1.83$	$4.3^{c}\pm0.12$	$6.0^{d}\pm0.8$	$310^{i}\pm1.90$
LSD		0.10		43.8	10.67	14.9	20.6	11.5	0.66	0.48	16.3

Mean with the same superscript along the vertical array indicates no significant difference ($P<0.05$)

Table 3: Percentage reduction (%) in selected physicochemical parameters of landfill leachate treated with different plant extracts at varying concentrations relative to untreated leachate

Treatment	Conc. (mg/L)	EC (%)	Total Hardness (%)	Turbidity (%)	TDS (%)	BOD (%)	COD (%)
Persea americana (PA)	1	83.6	54.3	27.1	65.2	64.7	72.7
	2	83.7	74.3	28.5	67.1	57.8	72.9
	3	85.9	83.7	71.9	71.1	66.5	75.1
Chromolaena odorata (CO)	1	68.3	68.1	56.3	61.8	45.7	72.0
	2	87.4	75.2	56.6	67.3	57.2	72.4
	3	88.2	84.7	76.9	73.2	64.7	78.6
Azadirachta indica (AI)	1	76.2	66.3	74.4	66.9	46.2	75.1
	2	86.7	77.8	77.3	73.6	63.7	79.6
	3	87.7	78.5	77.8	79.2	75.7	81.6
PA + CO	1	87.4	74.3	69.7	64.6	66.5	79.3
	2	87.4	77.4	72.5	78.1	57.2	82.1
	3	89.0	84.5	79.3	83.6	71.7	83.4
PA + AI	1	87.6	78.5	63.7	73.2	52.6	83.0
	2	87.5	79.7	74.2	73.8	59.5	83.5
	3	89.5	83.7	78.1	84.1	77.0	86.2
CO + AI	1	87.9	76.7	65.6	70.4	67.1	82.2
	2	89.5	81.9	73.3	83.2	60.6	86.3
	3	89.6	85.8	76.6	86.2	68.7	86.9
PA + CO + AI	1	89.2	77.8	72.5	74.5	64.2	83.6
	2	89.3	83.7	76.8	83.1	63.0	89.1
	3	**89.7**	**86.5**	**81.0**	**85.7**	**75.1**	**89.6**

Table 3: Chemical properties of the leachate samples from Lemna landfill treated with ethanol leaf extracts of selected plants

Plant extract	Conc mg/ml./ratio	Chloride (mg/L)	Sulphate (mg/L)	Nitrate (mg/L)	Nitrite (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Phosphate (mg/L)	Potassium (mg/L)
Persea	Control	88.6^{a}±0.26	84.8^{a}±0.23	89.4^{a}±0.31	6.48^{a}±0.10	124^{a}±0.21	142^{a}±0.47	1.63^{a}±0.08	80.4^{a}±0.24
americana	1	52.3^{d}±0.18	34.6^{c}±0.36	45.6^{b}±0.17	2.03^{b}±0.08	84.8^{b}±0.15	89^{b}±0.25	0.62^{b}±0.05	20.8^{c}±0.15
	2	40.8^{d}±0.20	20.8^{c}±0.12	40.8^{b}±0.35	1.04^{c}±0.06	60.8^{d}±0.23	64^{d}±0.27	0.42^{b}±0.08	20.4^{c}±0.12
	3	28.9^{e}±0.36	19.4^{c}±0.16	38.1^{b}±0.23	1.0^{c}±0.10	49.6^{e}±0.19	54^{e}±0.20	0.38^{b}±0.04	18.6^{c}±0.15
	1	64.8^{c}±0.38	43.2^{b}±0.20	48.2^{b}±0.17	1.92^{b}±0.11	80.6^{b}±0.65	62^{d}±0.29	0.81^{b}±0.03	30.4^{b}±0.18
Chromolaena	2	49.4^{d}±0.26	30.2^{c}±0.18	38.4^{b}±0.36	0.94^{c}±0.03	54.3^{e}±0.23	49^{e}±0.18	0.74^{b}±0.02	18.6^{c}±0.12
odorata	3	36.4^{d}±0.43	20.8^{c}±0.12	28.6^{b}±0.12	0.84^{c}±0.04	50.4^{e}±0.76	32^{g}±0.11	0.36^{b}±0.02	12.4^{d}±0.11
	1	45.2^{d}±0.26	34.3^{c}±0.19	40.1^{b}±0.20	1.86^{b}±0.06	74.3^{c}±0.23	74^{c}±0.15	0.74^{b}±0.02	27.4b±0.16
Azadirachta	2	41.2^{d}±0.21	30.6^{c}±0.26	32.4^{b}±0.31	0.74^{c}±0.02	54.8^{e}±0.17	37^{f}±0.12	0.40^{b}±0.01	20.2^{c}±0.12
indica	3	40.0^{d}±0.16	21.3^{c}±0.20	26.8^{b}±0.14	0.61^{c}±0.01	45.6^{e}±0.20	31^{g}±0.26	0.26^{b}±0.01	13.4^{d}±0.17
PA+ CO	1 (1:1)	54.2^{d}±0.23	34.4^{c}±0.26	39.8^{b}±0.16	1.62^{b}±0.08	78.9^{b}±0.38	64^{d}±0.23	0.62^{b}±0.02	28.4^{b}±0.20
	2 (1:1)	46.3^{d}±0.29	28.3^{c}±0.18	28.1^{b}±0.13	1.21^{c}±0.07	55.4^{e}±0.34	42^{f}±0.32	0.52^{b}±0.03	19.4^{c}±0.18
	3 (1:1)	40.8^{b}±0.31	19.4^{c}±0.17	22.8^{b}±0.12	0.83^{c}±0.05	40.8^{f}±0.30	40^{f}±0.20	0.31^{b}±0.02	12.6^{d}±0.13
PA + AI	1 (1:1)	74.3^{b}±0.24	27.2^{c}±0.25	43.1^{b}±0.21	0.94^{c}±0.06	72.4^{c}±0.16	56^{e}±0.23	0.74^{b}±0.04	20.1c±0.18
	2 (1:1)	50.4^{d}±0.34	24.3^{c}±0.37	29.4^{b}±0.16	0.63^{c}±0.07	53.6^{e}±0.25	49^{e}±0.28	0.53^{b}±0.05	16.4^{c}±0.20
	3 (1:1)	39.4^{d}±0.26	18.7^{c}±0.32	20.4^{b}±0.18	0.54^{c}±0.08	39.4^{f}±0.29	29^{g}±0.15	0.43^{b}±0.02	8.40^{d}±0.23
CO + AI	1 (1:1)	44.3^{d}±0.48	40.3^{b}±0.28	34.2^{b}±0.26	0.98^{c}±0.08	74.1^{c}±0.23	53^{e}±0.56	0.84^{b}±0.03	19.4^{c}±0.11
	2 (1:1)	29.8^{e}±0.38	32.8^{c}±0.16	30.6^{b}±0.30	0.90^{c}±0.04	50.2^{e}±0.16	40^{f}±0.21	0.34^{b}±0.02	16.2^{c}±0.10
	3 (1:1)	27.4^{e}±0.25	30.9^{c}±0.26	25.6^{b}±0.18	0.67^{c}±0.05	39.4^{f}±0.19	39^{f}±0.23	0.29^{b}±0.02	12.0^{d}±0.12
PA+CO+AI	1 (1:1:1)	48.6^{d}±0.38	29.4^{c}±0.42	28.6^{b}±0.19	0.88^{c}±0.03	48.5^{e}±0.20	43^{f}±0.18	0.48^{b}±0.05	16.9^{c}±0.14
	2(1:1:1)	39.4^{d}±0.23	18.9^{c}±0.17	18.4^{b}±0.15	0.70^{c}±0.04	40.9^{f}±0.54	29^{g}±0.21	0.42^{b}±0.04	11.2^{d}±0.12
	3(1:1:1)	28.9^{e}±0.31	16.2^{c}±0.14	18.2^{b}±0.23	0.54^{c}±0.05	39.0^{f}±0.36	28^{g}±0.23	0.22^{b}±0.02	7.6^{d}±0.08
LSD		5.8	4.6	4.0	0.48	4.2	3.90	0.20	2.85

Mean with the same superscript along the vertical array indicates no significant difference ($P<0.05$)

Effects of Ethanol Leaf Extracts on the Chemical Properties of Landfill Leachate

The effects of the plant extracts on selected chemical properties of the landfill leachate are presented in Table 3.

Chloride and Sulphate

Chloride concentration decreased significantly ($p < 0.05$) following treatment with all extracts. The untreated leachate recorded the highest chloride concentration (88.6 ± 0.26 mg L^{-1}), whereas the lowest concentrations (27.4 ± 0.25 mg L^{-1} and 28.9 ± 0.31 mg L^{-1}) were recorded in the *C. odorata* + *A. indica* and ternary treatments, respectively, at 3 mg mL^{-1}. Similarly, sulphate concentration declined significantly from 84.8 ± 0.23 mg L^{-1} in the untreated leachate to 16.2 ± 0.14 mg L^{-1} following treatment with the ternary extract at 3 mg mL^{-1}. Across all treatments, sulphate concentration generally decreased with increasing extract concentration.

Nitrate and Nitrite

Nitrate concentration was significantly reduced ($p < 0.05$) following treatment with the plant extracts. The untreated leachate contained 89.4 ± 0.31 mg L^{-1} nitrate, whereas the lowest concentration (18.2 ± 0.23 mg L^{-1}) was obtained in the ternary treatment at 3 mg mL^{-1}. Nitrite concentration followed a similar trend, decreasing from 6.48 ± 0.10 mg L^{-1} in the untreated sample to 0.54 ± 0.05 mg L^{-1} in both the *P. americana* + *A. indica* and ternary treatments at the highest extract concentration. Reductions in both nitrate and nitrite became more pronounced with increasing extract concentration.

Calcium and Magnesium

Significant reductions ($p < 0.05$) were observed in calcium and magnesium concentrations following treatment (Table 3). Calcium decreased from 124 ± 0.21 mg L^{-1} in the untreated leachate to 39.0 ± 0.36 mg L^{-1} in the ternary treatment at 3 mg mL^{-1}, while magnesium decreased from 142 ± 0.47 mg L^{-1} to 28 ± 0.23 mg L^{-1} under the same treatment conditions. Combined extract treatments generally produced lower calcium and magnesium concentrations than individual plant extracts.

Phosphate and Potassium

Treatment with the plant extracts also significantly reduced phosphate and potassium concentrations relative to the untreated leachate. Phosphate concentration declined from 1.63 ± 0.08 mg L^{-1} in the untreated sample to 0.22 ± 0.02 mg L^{-1} in the ternary treatment at 3 mg mL^{-1}. Likewise, potassium concentration decreased from 80.4 ± 0.24 mg L^{-1} to 7.6 ± 0.08 mg L^{-1} following treatment with the ternary extract at the highest concentration.

Overall, the reductions in phosphate and potassium were concentration-dependent, with combined extract treatments consistently producing lower concentrations than the corresponding individual extracts. Across all measured physicochemical parameters, treatment with the ethanol leaf extracts significantly improved the quality of landfill leachate compared with the untreated control. Increasing extract concentration from 1 to 3 mg mL^{-1} generally enhanced remediation efficiency. Although all three plant species demonstrated pollutant removal potential, binary combinations consistently outperformed the individual extracts, while the ternary combination of *Persea americana*, *Chromolaena odorata*, and *Azadirachta indica* produced the greatest overall improvement in leachate quality.

DISCUSSION

The present study demonstrated that ethanol leaf extracts of *Persea americana*, *Chromolaena odorata*, and *Azadirachta indica* significantly improved the physicochemical quality of landfill leachate, with remediation efficiency increasing as extract concentration increased from 1 to 3 mg mL^{-1}. All treated samples exhibited significantly lower concentrations of dissolved solids, organic pollutants, nutrients, and major ions than the untreated control, indicating that the plant extracts possess considerable remediation potential. More importantly, the binary combinations consistently produced greater pollutant removal than the corresponding single extracts, while the ternary combination (*P. americana* + *C. odorata* + *A. indica*) demonstrated the highest overall remediation efficiency. These findings suggest that combining different plant extracts enhances pollutant removal through complementary interactions among their phytochemical constituents.

The improvement in the physical characteristics of the leachate following treatment reflects the ability of the plant extracts to destabilize suspended particles and remove dissolved contaminants. The progressive increase in pH from an acidic value of 4.08 in the untreated leachate to near-neutral values after treatment indicates partial neutralization of acidic components and suggests that the extracts may have enhanced buffering reactions within the leachate. The accompanying reductions in electrical conductivity (EC), total dissolved solids (TDS), total hardness, turbidity and alkalinity further demonstrate substantial removal of dissolved and suspended materials. Electrical conductivity and TDS are widely recognized indicators of ionic strength and salinity in contaminated water, while turbidity reflects the abundance of suspended colloidal particles. Their simultaneous reduction therefore indicates effective removal of both dissolved ions and particulate matter. The superior performance of the combined extracts may be attributed to the diverse phytochemical constituents present in the different plant species. Plant-derived compounds including tannins, flavonoids, saponins, phenolics and polysaccharides possess numerous functional groups such as hydroxyl, carboxyl and amino groups capable of interacting with dissolved pollutants through adsorption, ion exchange, coagulation, flocculation and complexation reactions (Demirbas, 2008; Vijayaraghavan & Yun, 2008; Crini & Lichtfouse, 2019).

The greater reductions observed in the combined treatments suggest that the presence of multiple phytochemical classes increased the number and diversity of available adsorption sites, thereby improving contaminant removal efficiency. Similar improvements have been reported for plant-derived coagulants used in wastewater treatment, where combinations of botanical materials produced higher pollutant removal efficiencies than individual plant extracts (Maurya & Daverey, 2018).

Among the individual plant extracts, *Persea americana* consistently produced greater reductions in EC, total hardness, turbidity and TDS than either *Chromolaena odorata* or *Azadirachta indica*. This observation suggests that avocado leaves possess relatively higher concentrations or more effective combinations of phytochemicals involved in adsorption and coagulation processes. Previous studies have shown that avocado-derived biomaterials contain abundant polyphenols, flavonoids and other oxygen-containing functional groups capable of binding dissolved ions and organic molecules (Nkansah et al., 2018). In contrast, *Chromolaena odorata* exhibited comparatively lower remediation efficiency at the lowest concentration but showed marked improvement as dosage increased, indicating that sufficient concentrations of its bioactive constituents are required before appreciable pollutant removal can occur. *Azadirachta indica* demonstrated intermediate performance across most physical parameters but exhibited comparatively strong reductions in organic pollutants, which may reflect the well-documented antimicrobial and antioxidant properties of neem-derived phytochemicals (Saxena & Srivastava, 2019).

The marked reductions observed in biochemical oxygen demand (BOD) and chemical oxygen demand (COD) indicate that the plant extracts effectively reduced the organic pollution load of the landfill leachate. BOD and COD are among the most important indicators of wastewater contamination because they reflect the concentrations of biodegradable and chemically oxidizable organic matter, respectively. Elevated values are commonly associated with oxygen depletion, deterioration of aquatic ecosystems and increased ecological risk. The substantial decline in both parameters following treatment therefore indicates a considerable improvement in leachate quality. The increase in dissolved oxygen (DO) further supports this observation, suggesting that removal of oxygen-demanding substances improved oxygen availability within the treated leachate.

The reductions in BOD and COD are likely attributable to several complementary mechanisms. Polyphenolic compounds and tannins may adsorb dissolved organic molecules onto their surfaces, while proteins and polysaccharides present in the extracts may facilitate coagulation and sedimentation of suspended organic particles. In addition, the antimicrobial properties of *Azadirachta indica* may have suppressed microbial populations responsible for generating oxygen-demanding metabolites, thereby contributing to the observed decline in organic load. Similar reductions in BOD and COD following treatment with plant-derived coagulants have been reported in several wastewater remediation studies, supporting the growing interest in botanical materials as sustainable alternatives to conventional chemical coagulants (Crini & Lichtfouse, 2019; Ali et al., 2021).

The significant reductions in chloride, sulphate, calcium and magnesium concentrations further demonstrate the capacity of the extracts to remove dissolved inorganic ions from landfill leachate. These ions contribute substantially to salinity, conductivity and hardness and are often present at elevated concentrations in mature landfill leachates. Their removal suggests that the phytochemical constituents of the extracts participated in ion exchange, electrostatic attraction and complexation reactions. Functional groups such as hydroxyl and carboxyl moieties are capable of binding positively charged metal ions, whereas negatively charged phytochemicals may adsorb dissolved salts through surface interactions. The lower concentrations recorded in the combined treatments indicate that combining extracts broadened the range of available binding sites and enhanced overall ionic removal. Similar biosorption mechanisms have been described for numerous plant-based adsorbents used in wastewater treatment (Demirbas, 2008; Crini & Lichtfouse, 2019).

Nitrogen- and phosphorus-containing compounds are among the principal contributors to eutrophication in receiving water bodies. Consequently, the significant reductions in nitrate, nitrite and phosphate observed following treatment represent an important environmental benefit of the plant extracts. The progressive decline in nitrate and nitrite concentrations with increasing extract concentration suggests that adsorption and complexation became more efficient as the availability of reactive phytochemicals increased. Likewise, the substantial reduction in phosphate, particularly in the ternary treatment, indicates effective sequestration of phosphate ions, possibly through precipitation or adsorption onto phytochemical complexes. These findings are consistent with previous reports demonstrating that plant-derived biomaterials effectively reduce nutrient concentrations through a combination of adsorption, precipitation and ion exchange mechanisms (Ali et al., 2021; Ghosh et al., 2022).

Potassium concentrations also declined significantly across treatments, with the lowest values recorded in the combined extracts. Although potassium is generally more mobile than divalent ions, it can still be removed through adsorption onto negatively charged functional groups present in plant-derived biomaterials.

The greater reduction observed in the ternary treatment further supports the hypothesis that combining different phytochemical constituents increases the diversity of adsorption sites and enhances removal efficiency across multiple classes of pollutants simultaneously.

One of the most important findings of this study is the clear evidence of synergistic interactions among the three plant species. Across virtually all measured physicochemical parameters, the ternary combination consistently produced greater pollutant removal than either the single or binary treatments. This suggests that the phytochemical constituents of the different species complemented one another, thereby increasing adsorption capacity, improving coagulation efficiency and broadening the range of contaminants removed. Previous investigations have similarly reported that composite biosorbents frequently outperform individual materials because heterogeneous surfaces provide multiple functional groups capable of interacting with chemically diverse pollutants (Crini et al., 2017; Wang et al., 2022). The present findings therefore provide further evidence that mixed botanical extracts may represent a more effective remediation strategy than the use of individual plant species.

The observed concentration-dependent improvement across all treatments also demonstrates that remediation efficiency is strongly influenced by extract dosage. Increasing concentration provides greater quantities of reactive phytochemicals, thereby increasing the probability of pollutant adsorption and complex formation. This dose-dependent relationship has been widely reported for natural biosorbents and supports the potential optimization of extract concentration for practical wastewater treatment applications (Deng et al., 2016). However, beyond a certain concentration, adsorption sites may become saturated, suggesting that future studies should determine the optimum dosage under different leachate characteristics.

From an environmental perspective, the findings of this study highlight the considerable potential of locally available plant resources for sustainable landfill leachate remediation. Unlike conventional chemical coagulants, plant extracts are biodegradable, renewable and environmentally benign, while generating comparatively smaller quantities of secondary sludge. Their widespread availability, particularly in tropical regions, also makes them attractive alternatives for developing countries where the high operational costs of advanced wastewater treatment technologies often limit implementation. The successful use of *Persea americana*, *Chromolaena odorata* and *Azadirachta indica* therefore supports the growing global interest in green remediation technologies that align with the principles of circular economy and sustainable environmental management.

Despite these promising findings, the present study was conducted under controlled laboratory conditions and evaluated only the physicochemical characteristics of the treated leachate. Further investigations should examine the long-term stability of treated effluents under field conditions, evaluate the removal of heavy metals and emerging organic contaminants, characterize the specific phytochemical constituents responsible for pollutant removal using advanced analytical techniques, and investigate adsorption kinetics and equilibrium behaviour. Such studies would provide a more comprehensive understanding of the mechanisms underlying pollutant removal and facilitate the development of optimized plant-based remediation systems suitable for large-scale landfill leachate treatment.

Overall, the present study demonstrates that ethanol leaf extracts of *Persea americana*, *Chromolaena odorata* and *Azadirachta indica* possess considerable potential as environmentally friendly biosorbents for landfill leachate remediation. While all three plant species improved leachate quality, their combined application, particularly the ternary extract, consistently produced the greatest reductions in both physical and chemical pollutants, indicating that synergistic interactions among plant-derived phytochemicals substantially enhance remediation efficiency.

CONCLUSION

This study demonstrated that ethanol leaf extracts of *Persea americana*, *Chromolaena odorata*, and *Azadirachta indica* possess considerable potential for the remediation of landfill leachate by significantly improving its physicochemical quality. The treatments effectively reduced major indicators of pollution, including dissolved solids, organic load, turbidity, hardness, and nutrient concentrations, thereby enhancing the overall quality of the leachate. Remediation efficiency increased with extract concentration, while combined plant extracts consistently exhibited superior performance compared with individual extracts. Notably, the ternary combination of *P. americana*, *C. odorata*, and *A. indica* achieved the greatest overall improvement, demonstrating the synergistic effects of their phytochemical constituents in removing both organic and inorganic contaminants. The findings highlight the potential of these readily available plant species as low-cost, biodegradable, and environmentally sustainable alternatives to conventional chemical treatment methods for landfill leachate remediation. Their application offers a promising green technology for improving wastewater quality, particularly in developing countries where access to advanced treatment systems is often constrained by financial and technical limitations.

Future studies should focus on identifying the specific phytochemical compounds responsible for pollutant removal, investigating adsorption mechanisms and kinetics, evaluating the removal of heavy metals and emerging contaminants, and validating the effectiveness of these plant extracts under pilot-scale and field conditions to facilitate their practical application in landfill leachate treatment.

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