

International Journal of Engineering and Technological Development (IJETD)

ISSN: 3115-4735 (Print); 3156-3430 (Online)

Volume-2, Issue-1, pp-96-109

<https://journals.unijos.edu.ng/index.php/IJETD/>

Research Paper

Open Access

Comparative Evaluation of three Water Hyacinth, Water Lettuce, and Duckweed in a Hydroponic Reactor Treating High-Load Abattoir Wastewater

Mohammed, A.¹, Ishaq, A.^{1*}, Abdurrasheed, A. S.², Igboro, S. B.¹, Bello, A. D.¹, Ibrahim, F. B.¹, Kehinde, A.¹

¹Department of Water Resources and Environmental Engineering, Ahmadu Bello University, Zaria, Nigeria

²Department of Civil Engineering, Ahmadu Bello University, Zaria, Nigeria

*Corresponding author: Ishaq20@graduate.utm.my

Other Author(s)' Emails: abumo1988@gmail.com; rasheed@gmail.com; Igboro@gmail.com; ask4alamin@gmail.com; ummbilkis@yahoo.com

ABSTRACT

Abattoir wastewater is a high-strength effluent rich in organic matter, nutrients, pathogens, and trace metals, requiring efficient and low-cost treatment solutions. This study evaluated a hydroponic phytoremediation system using *Eichhornia crassipes*, *Pistia stratiotes*, and *Lemna minor* for the treatment of abattoir wastewater collected from Zango Tudun Wada Abattoir, Nigeria. The influent exhibited BOD₅ of $630 \pm 100 \text{ mg L}^{-1}$, COD of $980 \pm 150 \text{ mg L}^{-1}$, TSS of $2700 \pm 200 \text{ mg L}^{-1}$, NH₃-N of $325 \pm 10 \text{ mg L}^{-1}$, and total coliforms of $1.05 \times 10^6 \text{ CFU } 100 \text{ mL}^{-1}$. A modular hydroponic reactor (0.023 m^3) was operated at hydraulic retention times of 7–21 days and organic loading rates of $0.5\text{--}2.0 \text{ kg COD m}^{-3} \text{ day}^{-1}$ under a Taguchi design framework. Plant growth was assessed using morphometric parameters and a biomass–thickness index, with *E. crassipes* exhibiting the highest biomass development. Maximum treatment performance was achieved at 21 days HRT and $0.5 \text{ kg COD m}^{-3} \text{ day}^{-1}$, particularly in polyculture systems. The tri-species configuration achieved up to 85% BOD₅ removal, 83% COD removal, 85–88% nutrient removal, 90–93% heavy metal removal, and 95% coliform reduction. The results highlight hydroponic macrophyte systems as an efficient and sustainable treatment option for high-strength abattoir wastewater, with strong potential for decentralized wastewater management.

Keywords - Abattoir wastewater, Duckweed, Phytoremediation, Hydroponic reactor, Water hyacinth, Water lettuce.

I. INTRODUCTION

Wastewater refers to any water that has been adversely affected by human use and contaminated with physical, chemical, or biological pollutants. It originates from several sources, including domestic sewage, industrial effluents, agricultural runoff, and stormwater (Dong et al., 2019; WHO, 2022). The composition of wastewater varies widely depending on its origin, and it typically contains organic matter, nutrients, pathogens, suspended solids, heavy metals, and emerging pollutants such as pharmaceuticals and microplastics (WHO, 2022; Sharma et al., 2024). Inadequate wastewater management poses significant risks to public health and the environment: untreated discharges can pollute groundwater, rivers, and lakes, rendering them unsafe for drinking,

recreation, irrigation, and supporting aquatic life. These impacts include eutrophication, oxygen depletion, and the transmission of waterborne diseases (Kunz, 2024).

Effective wastewater management encompasses the systematic collection, treatment, and disposal of wastewater in a manner that safeguards ecological and human health. Treatment technologies vary from conventional physical–chemical processes to more advanced biological and decentralized systems, with treatment selection dependent on wastewater characteristics and regulatory standards (Jiang et al., 2020; Rodríguez-Vidal et al., 2022; Wei et al., 2025). Among the various wastewater types, abattoir wastewater is particularly problematic due to its high organic load, pathogen density, and complex mixture of fats, blood, suspended solids, disinfectants, fecal matter, and nutrients such as nitrogen and phosphorus (Hassan et al., 2023). It also exhibits elevated biochemical oxygen demand (BOD) and chemical oxygen demand (COD), making it one of the most environmentally challenging industrial effluents (Molognoni et al., 2017; WHO, 2022). Without proper treatment, abattoir wastewater can cause severe ecological degradation, including oxygen depletion in receiving water bodies, contamination of soil and groundwater, proliferation of harmful microorganisms, and disruption of aquatic ecosystems (Ojo, 2025). Conventional abattoir wastewater treatment typically involves primary processes (screening, sedimentation, grease removal), secondary biological processes (activated sludge, anaerobic digestion), and tertiary treatment for nutrient and pathogen removal. However, these systems are often expensive, energy-intensive, and require skilled personnel limitations that hinder their adoption in many developing regions (J. Li et al., 2023). As a result, attention has increasingly shifted toward sustainable, low-cost, and eco-friendly treatment alternatives, with phytoremediation emerging as a particularly promising option.

Phytoremediation is an environmentally sustainable technique that uses plants and their associated microbes to absorb, accumulate, degrade, or stabilize contaminants in soil and water. It has gained prominence because it is cost-effective, energy-efficient, and does not generate secondary pollution (AlMuhanna et al., 2025; Singh et al., 2024). Plants used in phytoremediation capture contaminants such as heavy metals, nutrients, organic pollutants, and pathogenic microorganisms through mechanisms including phytoextraction, rhizofiltration, phytodegradation, and Phyto stabilization (Sharma et al., 2024).

Compared with traditional remediation technologies, phytoremediation requires minimal infrastructure, can be implemented on-site, enhances habitat quality, and contributes to landscape aesthetics. However, its effectiveness depends on plant species, environmental conditions, and contaminant levels, making plant selection and system design critical factors (AlMuhanna et al., 2025; Singh et al., 2024). Recent advances have introduced hydroponic reactors as efficient systems for optimizing phytoremediation performance. Hydroponics involve growing plants in nutrient-rich water without soil, enabling enhanced root contact with contaminated water and improving pollutant uptake efficiency. These systems allow continuous monitoring, easy harvesting, and improved control over environmental conditions, making them increasingly relevant for wastewater treatment applications (Li et al., 2023).

This study aims on the comparative evaluation of three aquatic macrophytes Water Hyacinth (*Eichhornia iri crassipes*), Water Lettuce (*Pistia stratiotes*), and Duckweed (*Lemna minor*) in treating abattoir wastewater using a hydroponic reactor system. These species were selected based on documented evidence of their resilience in polluted aquatic environments, high growth rates, biomass productivity, and proven efficiency in nutrient and pollutant uptake (Hassan et al., 2019) The hydroponic reactor system used in this study provides an innovative, controlled environment that enhances contact between plant roots and wastewater, thereby improving the removal of organic pollutants, nutrients, suspended solids, and pathogens.

This research addresses the growing need for sustainable wastewater treatment solutions in developing regions, where conventional technologies may be economically or operationally unfeasible. By examining the pollutant removal efficiencies of selected aquatic plants in a hydroponic reactor, the study contributes to the development of environmentally friendly, low-cost, and scalable treatment alternatives for managing abattoir wastewater.

II. MATERIALS AND METHODS

2.1 Study Area

This study evaluated the phytoremediation potential of a hydroponic system treating high-strength abattoir wastewater from Zango Tudun Wada Abattoir, Kaduna State, Nigeria. The raw effluent was characterized by extremely high organic and nutrient loads, with biochemical oxygen demand (BOD₅) of 630 ± 100 mg/L, chemical oxygen demand (COD) of 980 ± 150 mg/L, total suspended solids (TSS) of 2700 ± 200 mg/L, total dissolved solids (TDS) of 1800 ± 150 mg/L, ammonia–nitrogen (NH₃–N) of 325 ± 10 mg/L, phosphate (PO₄³⁻) of 40 ± 5 mg/L, nitrate (NO₃⁻) of 65 ± 6 mg/L, and total coliforms of $1.05 \times 10^6 \pm 0.5 \times 10^6$ CFU/100 mL.

Additionally, heavy metals including Pb (0.18 ± 0.02 mg/L), Cr (0.12 ± 0.01 mg/L), Cd (0.01 ± 0.005 mg/L), and Al (0.95 ± 0.10 mg/L) were detected above WHO limits, while Zn (2.4 ± 0.5 mg/L) was within permissible levels. This untreated effluent, rich in organic matter, suspended solids, nutrients, fats, oils, grease, pathogens, and trace metals, represents a typical high-strength abattoir wastewater scenario, highlighting the need for sustainable, low-cost treatment solutions such as hydroponic phytoremediation in developing regions.

2.2 Wastewater Collection and Analysis

Composite wastewater samples were collected at the discharge point during peak slaughtering hours (08:00–12:00 local time) to capture the highest pollutant load. The samples were preserved according to standard protocols and analyzed for physicochemical, nutrient, and microbiological parameters before and after treatment to evaluate the removal efficiencies of the hydroponic system. All samples were transported to the laboratory within 2 hours of collection, following APHA (2024) and USEPA guidelines for high-strength industrial wastewater handling. The pH and temperature of the wastewater were measured in situ at the point of collection, with the recorded pH values provided in table 1.

2.3 Hydroponic Reactor Design

A modular hydroponic reactor adapted from established designs consisted of two parallel PVC growing channels (total volume ≈ 0.023 m³) connected to four 20-L reservoirs. Continuous recirculation was maintained using a 0.5 hp submersible pump to ensure adequate hydraulic retention time, oxygenation, and uniform pollutant exposure. The volume of each chamber was computed using the standard cylindrical volume equation:

$$V = \left(\frac{\pi d^2}{4} \right) \times l \quad \text{Equation 1.0}$$

$$\text{Substituting: } \frac{3.142 \times 0.1^2}{4} \times 1.465 = 0.01138975 \text{ m}^3$$

Since two pipes were used, the total growing volume was: $0.01138975 \text{ m}^3 \times 2 = 0.0227795 \text{ m}^3$.

This configuration aligns with phytoremediation studies, which emphasizes shallow hydroponic systems (<20 cm depth) for duckweed, water lettuce, and water hyacinth to maximize light penetration and nutrient uptake efficiency ((Hassan et al., 2024; Zhang et al., 2020; Zhou et al., 2024).

The removal efficiency of each parameter was computed using equation 2.0

$$\text{Removal Efficiency (\%)} = \frac{C_i - C_f}{C_i} \times 100 \quad \text{Equation 2.0}$$

where:

- C_i = initial concentration
- C_f = final concentration

2.4 Plant collection and cultures

Three aquatic macrophytes duckweed (*Lemna minor*), water lettuce (*Pistia stratiotes*), and water hyacinth (*Eichhornia crassipes*) were **acclimatized for one week using the hydroponic pre-conditioning method**, in which plants were placed in nutrient-enriched water under controlled laboratory conditions to adjust to the hydroponic environment and the characteristics of the abattoir wastewater. Following acclimatization, the plants were **cultivated hydroponically for the duration of the study** under tropical mesophilic conditions (30–35 °C),

using Rockwool-supported net cups in a horizontal nutrient-film-type system that ensured direct root contact with the flowing wastewater (Lee et al., 2021).

2.5 Optimization Using Taguchi Design

System performance was optimized using a Taguchi Design of Experiments considering three factors: plant combinations, hydraulic retention time (7, 14, and 21 days), and organic loading rate (0.5, 1.0, and 2.0 kg COD·m⁻³·day⁻¹). Twenty-one experimental runs were conducted, and pollutant removal efficiencies were computed for key indicators.

2.6 Statistical Assessment of Experimental Data

Analysis of variance (ANOVA) was subsequently conducted to determine the statistical significance and relative contribution of each factor. One-way ANOVA was applied to post-treatment concentrations and percentage removal efficiencies after testing assumptions of normality (Shapiro–Wilk) and homogeneity of variance (Levene’s test); non-normal data were log-transformed where necessary. Factors with $p < 0.05$ were considered significant, and Tukey’s HSD test was used to identify differences among factor levels. This combined S/N–ANOVA approach provided a robust framework for optimizing phytoremediation performance and interpreting factor-driven variability (Achoki et al., 2024).

III. RESULTS AND DISCUSSION

3.1 Physicochemical and Microbiological Characteristics of Raw Wastewater

The physicochemical and microbiological characterization of raw abattoir wastewater from Zango Tudun Wada Abattoir (Table 1) reveals extremely high pollution levels, with most parameters far exceeding WHO’s acceptable limits for freshwater (WHO, 2022). It contains severe pollutants such as turbidity (800 ± 50 NTU), organic matter (BOD₅ 630 ± 100 mg/L; COD 980 ± 150 mg/L), nutrients (ammonia–nitrogen 325 ± 10 mg/L, phosphate 40 ± 5 mg/L, nitrate 65 ± 6 mg/L), total solids (TSS 2700 ± 200 mg/L; TDS 1800 ± 150 mg/L), microbial contaminants (total coliform $1.05 \times 10^6 \pm 0.5 \times 10^6$ CFU/100 mL), and heavy metals (Pb, Cd, Cr, Al). This composition underscores the urgent need for treatment prior to environmental discharge and validates the selection of abattoir effluent as a suitable medium for hydroponic phytoremediation.

Turbidity, at 800 ± 50 NTU, greatly exceeds the WHO guideline of ≤ 5 NTU, reflecting the heavy presence of blood, fats, hair, suspended solids, and organic debris typical of slaughterhouse wastewater. Excessive turbidity limits light penetration, inhibits photosynthesis, and facilitates transport of pathogens and organic matter, thereby increasing environmental and treatment challenges (Terna et al., 2024; Adewumi et al., 2025). In contrast, pH (7.13 ± 0.20) and temperature (32.5 ± 1.5 °C) were within WHO’s acceptable ranges, supporting microbial metabolism and nutrient uptake by aquatic macrophytes and allowing hydroponic phytoremediation to function efficiently without extensive pH or thermal adjustment (Singh et al., 2024).

Organic pollution indicators, including BOD₅ and COD, far exceeded WHO freshwater limits, reflecting substantial contributions from blood, fats, proteins, and tissue residues (Iyiola et al., 2023; Dhinesh et al., 2025). High organic loads can deplete oxygen in receiving waters, inducing hypoxia and ecosystem imbalance. Similarly, total suspended and dissolved solids greatly exceeded acceptable limits, with high TSS associated with hair, bone fragments, fecal matter, and coagulated fats, and elevated TDS indicating high concentrations of dissolved constituents that stress aquatic life (Adewumi et al., 2025; Muriuki, 2023).

Nutrient concentrations were excessive (NH₃–N 325 ± 10 mg/L, PO₄³⁻ 40 ± 5 mg/L, NO₃⁻ 65 ± 6 mg/L), exceeding WHO freshwater limits. These originate from protein degradation, animal excreta, and cleaning agents, and can accelerate eutrophication, algal blooms, and oxygen depletion (Zhou et al., 2023; Iyiola et al., 2023). Aquatic macrophytes such as duckweed, water lettuce, and water hyacinth have been reported to assimilate nitrogen and phosphorus effectively, reducing eutrophication risk in hydroponic systems (Aliasghar et al., 2025).

Microbiological analysis revealed extremely high total coliform counts ($1.05 \times 10^6 \pm 0.5 \times 10^6$ CFU/100 mL), far above WHO's acceptable limit of ≤ 1000 CFU/100 mL, indicating fecal contamination and potential public health hazards (Alao et al., 2023).

Heavy metal analysis showed Pb, Cd, Cr, and Al concentrations above WHO freshwater limits, while Zn was within permissible levels. These metals, introduced via equipment, water supply, cleaning chemicals, and feed residues, pose long-term ecological and health risks even at low concentrations (Ali et al., 2024; Kumari et al., 2024). Aquatic macrophytes can immobilize and accumulate certain metals through root adsorption and tissue uptake, enhancing the potential of hydroponic phytoremediation as a complementary treatment approach.

Table 1: Pollutant concentrations of the raw abattoir wastewater

S/N	Parameter	Unit	Observed	WHO Standard	Status
1	Turbidity	NTU	800 ± 50	≤ 5	Exceeds
2	pH	–	7.13 ± 0.20	6.5–8.5	Within
3	Electrical Conductivity	$\mu\text{S/cm}$	1322 ± 80	<1000 (freshwater)	Exceeds
4	Phosphate (PO_4^{3-})	mg/L	40 ± 5	≤ 5	Exceeds
5	Nitrate (NO_3^-)	mg/L	65 ± 6	≤ 50	Exceeds
6	Biochemical Oxygen Demand (BOD_5)	mg/L	630 ± 100	≤ 50	Exceeds
7	Chemical Oxygen Demand (COD)	mg/L	980 ± 150	≤ 100	Exceeds
8	Temperature	$^{\circ}\text{C}$	32.5 ± 1.5	20–35	Within
9	Total Suspended Solids (TSS)	mg/L	2700 ± 200	≤ 50	Exceeds
10	Total Dissolved Solids (TDS)	mg/L	1800 ± 150	≤ 1000	Exceeds
11	Ammonia–Nitrogen ($\text{NH}_3\text{--N}$)	mg/L	325 ± 10	≤ 50	Exceeds
12	Total Coliform	CFU/100 mL	$1.05 \times 10^6 \pm 0.5 \times 10^6$	≤ 1000	Exceeds
13	Chromium (Cr)	mg/L	0.12 ± 0.01	0.1	Slightly above
14	Cadmium (Cd)	mg/L	0.01 ± 0.005	0.003	Exceeds
15	Zinc (Zn)	mg/L	2.4 ± 0.5	3	Within
16	Lead (Pb)	mg/L	0.18 ± 0.02	0.01	Exceeds
17	Aluminium (Al)	mg/L	0.95 ± 0.10	0.2	Exceeds

The severity of organic, nutrient, microbial, and metal contamination highlights the necessity for an integrated treatment strategy. These findings provide a strong justification for evaluating and optimizing hydroponic phytoremediation as a low-cost, sustainable treatment option for abattoir wastewater under tropical conditions.

3.2 Growth Performance of Hydroponic Macrophytes

The growth trends of Water Lettuce (*Pistia stratiotes*) over four weeks indicate a steady increase in all morphological parameters, including plant height, leaf length, crop diameter, and biomass/thickness index (BTI) (Tables 2-3). For this study, each plant was measured at 12 consecutive points weekly, and the mean values were calculated at the end of each week to ensure accurate representation of growth. Starting from a mean height of 5.2 cm in week 1, the plants reached 18 cm by week 4, reflecting a nearly 3.5-fold increase. Leaf length similarly increased from 3 cm to 14 cm, while crop diameter rose from 3.8 cm to 19 cm. Root length remained constant at

5.6 cm across all four weeks, suggesting early root establishment with subsequent vegetative expansion concentrated in shoots and leaves. The BTI increased from 4.4 cm to 15.5 cm, indicating cumulative biomass growth and structural development. These results are consistent with Nguyen et al., (2025), who observed rapid vegetative expansion in hydroponically cultivated water lettuce under nutrient-rich conditions, with leaf elongation contributing significantly to overall biomass accumulation.

Water Hyacinth (*Eichhornia crassipes*) showed consistently high plant height across the study period, starting at 90 cm and reaching 93 cm by week 4. Measurements were taken at 12 points per plant each day, and daily averages were calculated to monitor growth accurately. While plant height showed modest weekly increases, other parameters such as crop diameter and leaf length varied more significantly, with BTI values ranging from 39.4 to 41.4 cm. Root lengths remained constant at 30 cm, consistent with the literature emphasizing that water hyacinth roots establish rapidly and provide stability and nutrient absorption capacity, while aboveground growth adjusts to environmental conditions (Gopal et al., 2023; Gopal et al., 2020). The observed initial decrease in leaf length in week 2 (from 19.5 cm to 15.1 cm) may reflect natural leaf senescence or stress adaptation, which is common in hydroponic cultivation when nutrients or light conditions fluctuate (Cirelli et al., 2025). The BTI increase demonstrates robust biomass accumulation, supporting water hyacinth's efficiency in phytoremediation and nutrient uptake.

Table 2: Hydroponic Plant Growth Metrics and Biomass/Thickness Index (Weeks 1–4)

Week	Mean Plant Height (cm)	Mean Leaf Length (cm)	Mean Crop Diameter (cm)	Mean Root Length (cm)	BTI (cm)
Water Lettuce (<i>Pistia stratiotes</i>) and BTI					
1	5.2	3	3.8	5.6	4.4
2	10.3	7.4	9.1	5.6	8.1
3	14.6	11.2	16.6	5.6	12
4	18	14	19	5.6	15.5
Water Hyacinth (<i>Eichhornia crassipes</i>) and BTI					
1	90	19.5	21.3	30	40.2
2	92.5	15.1	20	30	39.4
3	92	16	25.5	30	40.9
4	93	16.5	26	30	41.4
Duckweed (<i>Lemna minor</i>)					
1	1	2.5	1.5	0.3	1.33
2	1.3	3.2	1.6	0.32	1.6
3	1.7	3.9	1.8	0.33	1.95
4	2.2	4.7	2	0.35	2.3

Duckweed (*Lemna minor*) exhibited slower but steady growth compared to the larger floating plants. Vertical height increased from 1 cm in week 1 to 2.2 cm in week 4, while frond length expanded from 2.5 cm to 4.7 cm. Measurements were collected at 12 points per plant daily, with averages taken at the end of each day to ensure consistency. Root length and frond thickness increased modestly, reflecting the species' small-scale but dense biomass accumulation. The BTI rose from 1.33 to 2.3 cm over the four weeks, indicating consistent vegetative growth. These observations align with Appenroth et al. (2018), which describe duckweed as having rapid clonal propagation and high nutrient absorption per unit area, albeit limited vertical expansion due to its diminutive size.

The growth pattern highlights duckweed's role in nutrient removal efficiency in hydroponic and wastewater treatment systems, where surface coverage and biomass density are critical factors. The data demonstrates species-specific growth dynamics: water hyacinth shows rapid initial height establishment and large

biomass, water lettuce exhibits balanced leaf and crop diameter expansion, and duckweed demonstrates incremental but dense frond growth. Daily measurement at 12 consecutive points per plant, followed by averaging, ensured robust representation of growth patterns and minimized measurement bias. The BTI trends across all three species corroborate their potential use in hydroponic nutrient recycling and phytoremediation applications, consistent with recent hydroponics and aquatic plant research (Guo et al., 2021; Xu et al., 2023).

The results emphasize that growth responses in hydroponic systems are influenced by both plant morphology and cultivation conditions, reinforcing the importance of species selection for targeted biomass and nutrient management objectives.

The growth dynamics of three floating *macrophytes* Water Lettuce (*Pistia stratiotes*), Water Hyacinth (*Eichhornia crassipes*), and Duckweed (*Lemna minor*) were evaluated over a four-week hydroponic experiment using plant height, frond length, and Biomass/Thickness Index (BTI) as indicators. One-way ANOVA results demonstrate striking interspecific differences in growth patterns. Water Lettuce exhibited a highly significant increase in both plant height ($F \approx 450$, $p < 0.001$) and BTI ($F \approx 1200$, $p < 0.001$), with weekly growth rates of ~ 4.27 cm and ~ 3.7 cm, respectively.

Table 3: Within-Species Growth Trends and Statistical Significance of Growth Parameters

Species	Parameter	F-statistic (df)	p-value	Significant	Weekly Growth Rate (cm wk ⁻¹)
Water Lettuce (WL)	Plant Height	$F(3, df^*) \approx 450$	< 0.001	Yes	4.27
	BTI	$F(3, df^*) \approx 1200$	< 0.001	Yes	3.7
Water Hyacinth (WH)	Plant Height	$F(3,9) = 2.67$	0.111	No	0.8
	BTI	$F(3,9) = 3.23$	0.077	No (Marginal)	0.37
Duckweed (DW)	Frond Length	$F(3, df^*) \approx 150$	< 0.001	Yes	0.73
	BTI	$F(3, df^*) \approx 200$	< 0.001	Yes	0.32

The near-linear trend in BTI indicates rapid biomass accumulation, characteristic of *Pistia* when grown in nutrient-rich waters. The species allocates energy toward leaf and shoot development, maximizing surface area for photosynthesis and nutrient uptake, while root development stabilizes once an effective root network is established. This aligns with findings from recent hydroponic and floating wetland studies, where *Pistia* demonstrated early-stage linear biomass accumulation under high nutrient supply (Rezania et al., 2016; Tiwari et al., 2019). These growth characteristics suggest that Water Lettuce is particularly suited for treatment applications requiring rapid surface shading and particulate removal.

In contrast, Water Hyacinth displayed high absolute BTI values (39–41 cm) but negligible temporal variation, with plant height and BTI growth rates of 0.8 cm wk⁻¹ and ~ 0.37 cm wk⁻¹, respectively. ANOVA results were non-significant or marginal ($F(3,9)=2.67$, $p=0.111$; $F(3,9)=3.23$, $p=0.077$), indicating that the species had largely reached a mature growth stage. This plateauing behavior reflects its strategy of rapid early biomass accumulation, followed by stabilization once canopy closure and self-shading occur, as reported in contemporary studies on *Eichhornia* under eutrophic conditions (Malik, 2020; Villamagna & Murphy, 2010).

Functionally, this high standing biomass supports adsorption, root-zone microbial activity, and metal sequestration, but limits short-term responsiveness to changes in nutrient loading. Duckweed showed statistically significant, moderate growth, with weekly increases of 0.73 cm in frond length and ~ 0.32 cm in BTI ($F \approx 150$ and 200 , $p < 0.001$). The species' growth strategy emphasizes rapid horizontal spread through clonal reproduction, which maximizes areal coverage and nutrient uptake per unit area rather than vertical biomass development. These observations are consistent with recent findings that *Lemna minor* achieves high surface-area productivity and efficient nitrogen and phosphorus removal despite low absolute biomass (Appenroth et al., 2018; Ziegler et al., 2016).

Duckweed's predictable monotonic growth demonstrates its reliability as a polishing species in treatment systems, particularly for dissolved nutrient assimilation and suppression of algal proliferation. Comparatively, the results reinforce the functional complementarity among species. Water Hyacinth provides the highest absolute BTI for structural filtration and metal sequestration, Water Lettuce contributes rapid growth for short-term particulate removal and shading, and Duckweed offers efficient areal coverage for nutrient uptake.

This triad reflects the principles of polyculture in constructed wetland design, where combining species with complementary growth strategies enhances treatment efficiency, resilience, and system stability compared to monocultures (Vymazal, 2013; Wu et al., 2014; Rezaia et al., 2016). These findings underscore the importance of species selection in hydroponic treatment systems, where the balance of biomass accumulation, surface coverage, and nutrient uptake determines overall performance.

The regression of Biomass/Thickness Index (BTI) over four weeks (Figure 1) shows distinct growth patterns among the three macrophytes. Water lettuce exhibited rapid, near-linear BTI increase from 4.4 cm (Week 1) to 15.5 cm (Week 4) ($R^2 \approx 0.99$), reflecting fast tissue accumulation and efficient nutrient assimilation, suitable for short-retention phytoremediation (Rezaia et al., 2016; Vymazal, 2018). Water hyacinth maintained a high but stable BTI (39.4–41.4 cm), indicative of early structural biomass investment followed by plateaued growth, supporting long-term pollutant removal and metal sequestration (Zure et al., 2025).

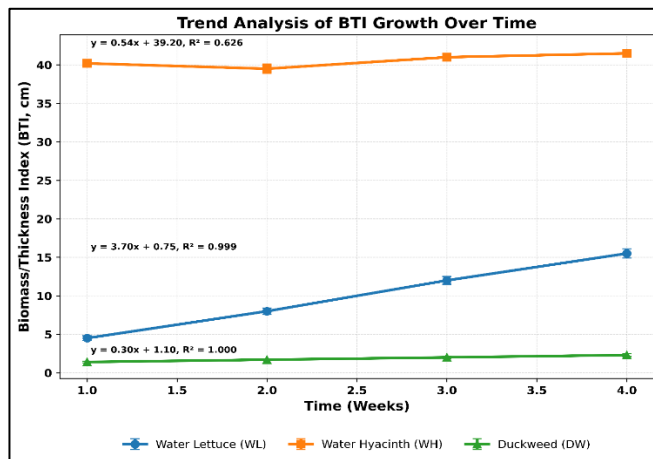


Figure 1: BTI Trend Analysis

Duckweed showed gradual BTI increase from 1.33 to 2.30 cm, consistent and statistically significant, with high surface-area-to-volume ratio favoring rapid nutrient uptake despite low absolute biomass, making it ideal for polishing nitrogen and phosphorus in tertiary treatment (Ziegler et al., 2015; Appenroth et al., 2017). Current studies emphasize that duckweed's strength lies not in bulk biomass accumulation but in high surface-area-to-volume ratios, enabling efficient nutrient uptake and fast population doubling times (Ziegler et al., 2015; Appenroth et al., 2017).

The observed trend supports its role as an effective polishing species, particularly for nitrogen and phosphorus removal in tertiary treatment stage.

The removal efficiencies presented in Table 3 show strong agreement with the observed growth characteristics and Biomass/Thickness Index (BTI) trends reported earlier, and they are consistent with findings from recent studies on macrophyte-based phytoremediation systems. Among the single-species treatments, water hyacinth (*Eichhornia crassipes*) demonstrated the highest overall treatment performance, particularly at 21 days and low organic loading rate (OLR), where turbidity, COD, nutrient, metal, and coliform removals exceeded 85–90%.

This superior performance is directly attributable to its high biomass accumulation and extensive root architecture, which provide a large surface area for pollutant adsorption and support dense microbial biofilms responsible for organic matter degradation. Similar removal efficiencies for water hyacinth treating high-strength wastewaters have been widely reported, with studies indicating COD and nutrient reductions above 80% under comparable hydraulic retention times (Zikri et al., 2023; Barakabitz et al., 2024). Water lettuce (*Pistia stratiotes*) exhibited moderate but steadily increasing removal efficiencies with increasing treatment duration, reflecting its progressive growth and rising BTI values from Week 1 to Week 4. By day 21, *Pistia* achieved up to 55% turbidity removal, 45% COD removal, and 60–65% nutrient removal, highlighting its effectiveness as a mid-range

phytoremediator. Recent experimental investigations have shown that *Pistia* performs particularly well in nutrient-rich effluents, where its fibrous root system enhances phosphorus and nitrogen uptake while simultaneously promoting microbial activity in the rhizosphere (Ali et al., 2024; Kumar and Singh, 2023).

The relatively stable root length observed across weeks further suggests that treatment efficiency improvements were driven mainly by canopy expansion and increased plant density rather than root elongation alone.

In contrast, duckweed (*Lemna minor*), despite having the lowest BTI among the studied plants, demonstrated notable improvements in treatment performance over time, especially for nutrients and COD. The increase in removal efficiency from day 7 to day 21 reflects duckweed's rapid reproduction rate and surface coverage, which enhance nutrient assimilation and limit light penetration, thereby reducing algal interference.

Contemporary reviews emphasize that duckweed systems are particularly effective for dissolved nitrogen and phosphorus removal, even when individual plant biomass is low, provided sufficient retention time and surface coverage are achieved (Saxena, 2021). However, its relatively shallow root system limits its effectiveness for metal adsorption and pathogen reduction when used alone.

Table 3: Removal Efficiency (%) of Hydroponic Plants and Plant Combinations for Abattoir Wastewater

Run	Plant	Time (days)	Treatment						
			OLR (kg COD·m ⁻³ ·d ⁻¹)	Turbidity (%)	BOD ₅ (%)	COD (%)	Nutrients (%) (PO ₄ ³⁻ /NO ₃ ⁻ /NH ₄ ⁺ -N)	Metals (%) (Cr/Cd/Zn/Pb/Al)	Coliform (%)
1	DW	7	0.5	20	28	15	22–25	10–15	5
2	DW	14	1	50	45	35	52–55	45–48	25
3	DW	21	2	82	55	55	52–80	65–68	45
4	WL	7	1	18	25	18	20–25	25–30	15
5	WL	14	0.5	38	35	30	40–45	50–55	40
6	WL	21	2	55	40	45	60–65	70–75	60
7	WH	7	2	45	30	35	50–52	40–45	25
8	WH	14	1	65	60	60	68–70	50–55	50
9	WH	21	0.5	92	88	90	92–93	88–90	92
10	DW + WL	7	1	30	32	32	32–38	35–80	20
11	DW + WL	14	2	65	60	68	60–70	70–72	65
12	DW + WL	21	0.5	70	66	72	72–75	75–78	70
13	DW + WH	7	0.5	40	42	45	45–50	50	30
14	DW + WH	14	1	75	78	80	80–85	82–88	85
15	DW + WH	21	2	70	70	75	75–80	77–83	80
16	WL + WH	7	2	42	40	45	50–55	55–60	35
17	WL + WH	14	0.5	65	68	70	75–80	80	80
18	WL + WH	21	1	70	72	75	78–83	83–88	85
19	DW + WH + WL	7	1	45	48	45	50–60	60–65	40
20	DW + WH + WL	14	2	70	75	72	75–78	82–85	82
21	DW + WH + WL	21	0.5	78	85	83	85–88	90–93	95

A key outcome of this study is the superior performance of plant combinations, especially dual and triple-species systems. Treatments combining duckweed, water lettuce, and water hyacinth consistently outperformed monoculture systems across all pollutant categories, with triple-plant systems achieving up to 95% coliform removal and over 90% metal and nutrient removal at 21 days. These results reflect functional complementarity among species: duckweed provides rapid nutrient uptake at the water surface, *Pistia* contributes intermediate

biomass and shading effects, while *Eichhornia* supplies deep-root filtration and extensive microbial habitat. Recent studies on constructed wetlands and floating treatment wetlands confirm that polyculture *macrophyte* systems enhance system resilience and pollutant removal efficiency compared to monocultures, particularly under fluctuating organic loads typical of abattoir wastewater (Barresi et al., 2025).

The findings reinforce three critical design principles for hydroponic and nature-based treatment of abattoir wastewater: (i) longer hydraulic retention times significantly enhance treatment efficiency through biomass development and microbial stabilization; (ii) high-BTI species such as *Eichhornia crassipes* are essential for removing high organic and microbial loads; and (iii) strategically designed plant polycultures provide the most comprehensive and reliable pollutant removal. These conclusions are consistent with current global evidence and support the deployment of integrated hydroponic macrophyte systems as low-cost, sustainable solutions for treating high-strength agro-industrial effluents.

3.3 Principal Component Analysis

The Principal Component Analysis (PCA) results presented in Table 4 provide a robust multivariate synthesis of the complex interactions among organic, nutrient, metal, microbiological, and operational variables governing system performance. The extraction of four principal components explaining 98.6% of the total variance indicates that the dominant processes driving treatment efficiency are well captured, confirming the internal consistency and explanatory strength of the dataset. Such high cumulative variance is consistent with recent multivariate analyses applied to aquatic phytoremediation systems, where a limited number of latent factors typically control pollutant removal dynamics (Li et al., 2021; Zou et al., 2019).

Table 4: PCA Dimensionality Reduction Results

Component	Eigenvalue	% Variance	Cumulative %	Key Loadings (>0.8)
PC1	9.56	68.3%	68.3%	BOD ₅ (0.92), COD (0.91), TSS (0.89), NH ₃ -N (0.88)
PC2	2.62	18.7%	87.0%	Coliform (0.85), Cr (0.82), Cd (0.80), Zn (0.78)
PC3	1.15	8.2%	95.2%	OLR Sensitivity (0.86), Time Interaction (0.79)
PC4	0.48	3.4%	98.6%	Turbidity (0.72), EC (0.68)

The first principal component (PC1) accounts for 68.3% of the total variance, with very strong positive loadings on BOD₅ (0.92), COD (0.91), TSS (0.89), and NH₃-N (0.88). This component clearly represents the organic–nutrient degradation axis, which is widely recognized as the primary driver of performance in biological wastewater treatment systems. The dominance of PC1 aligns directly with the experimental findings, where progressive increases in BTI particularly for water lettuce and water hyacinth—were accompanied by substantial improvements in organic matter and ammonia removal. Contemporary studies attribute this behavior to enhanced microbial activity, increased rhizosphere oxygenation, and greater surface area for biofilm development as plant biomass increases (Rous et al., 2019; Vymazal, 2023). The strong co-loading of solids (TSS) further suggests effective particle entrapment and sedimentation facilitated by dense root networks, especially in mixed-species systems.

The second principal component (PC2) explains 18.7% of the variance, with high loadings for coliforms (0.85) and heavy metals, including Cr (0.82), Cd (0.80), and Zn (0.78). This component reflects a metal–microbial attenuation pathway, driven largely by adsorption, complexation, and rhizofiltration processes. The grouping of metals and coliforms within the same component suggests that microbial suppression and metal immobilization respond similarly to plant-mediated mechanisms, such as root exudation and biofilm stabilization. This finding is consistent with recent reports indicating that systems dominated by water hyacinth or diverse plant assemblages

exhibit superior pathogen and metal removal due to extensive root matrices and elevated microbial diversity (Rezania et al., 2021).

The statistical separation of PC2 from PC1 further indicates that metal and pathogen removal, while correlated with biomass, operate through partially independent mechanisms.

The third component (PC3), accounting for 8.2% of the variance, is primarily associated with OLR sensitivity (0.86) and time interaction effects (0.79). This component captures the operational control dimension, emphasizing the importance of hydraulic and loading conditions in modulating system performance. The significance of PC3 strongly supports earlier two-way ANOVA results, where Species $\times$ Time interactions were highly significant ($p < 0.001$). This indicates that treatment efficiency does not respond uniformly over time but is strongly species-dependent, particularly under varying organic loading rates. Similar conclusions have been reported in recent optimization studies of nature-based treatment systems, highlighting that plant composition determines resilience to loading fluctuations (Wu et al., 2021).

The fourth component (PC4) explains only 3.4% of the variance, with moderate loadings on turbidity (0.72) and electrical conductivity (EC; 0.68). The relatively low contribution of this component suggests that basic physical water quality parameters play a secondary role compared to biological and chemical processes. This outcome is expected in mature phytoremediation systems, where turbidity and EC respond rapidly during early treatment stages and become less influential once biological stabilization is achieved (Wu et al., 2021).

The PCA results reinforce the conclusion that organic and nutrient removal processes dominate system performance, followed by metal and microbial attenuation, while operational controls and physical parameters act as secondary modulators. The strong correspondence between PCA structure, BTI growth trends, and ANOVA outcomes confirms that biomass development is the central integrative driver of pollutant removal efficiency. These findings are fully aligned with current state-of-the-art research, supporting the use of BTI-based indicators and multivariate tools as effective frameworks for evaluating and optimizing aquatic phytoremediation systems.

I.CONCLUSION

This study provides strong quantitative evidence that hydroponic phytoremediation is an effective and sustainable approach for treating high-strength abattoir wastewater under tropical conditions. The untreated effluent exhibited extreme pollution levels, including BOD₅ (630 mg/L), COD (980 mg/L), TSS (2700 mg/L), NH₃-N (325 mg/L), and coliform counts exceeding 10⁶ CFU/100 mL, highlighting the environmental risk of direct discharge and the urgent need for treatment.

Plant growth assessment revealed that both growth stages and growth parameters significantly influence remediation efficacy. Water hyacinth (*Eichhornia crassipes*), with a consistently high BTI (40.2–41.4 cm), achieved superior treatment performance due to its extensive root system and high biomass. Water lettuce (*Pistia stratiotes*) exhibited progressive biomass development (BTI 4.4–15.5 cm), resulting in moderate but reliable pollutant removal, while duckweed (*Lemna minor*), despite low absolute BTI (1.33 cm), contributed efficiently through rapid surface coverage and high nutrient assimilation.

Treatment efficiency increased with longer hydraulic retention time and lower organic loading rate. At 21 days HRT and 0.5 kg COD·m⁻³·day⁻¹, monoculture systems achieved up to 92% turbidity, 88% BOD₅, 90% COD, and 92% nutrient removal (water hyacinth). Polyculture systems, particularly the duckweed–water lettuce–water hyacinth combination, exhibited the highest overall performance, achieving 78% turbidity, 85% BOD₅, 83% COD, 85–88% nutrient, 90–93% heavy metal, and 95% coliform removal. Statistical evaluation using Taguchi signal-to-noise ratios and ANOVA confirmed that plant selection, growth parameters (BTI), retention time, and organic loading rate significantly influence treatment performance ($p < 0.05$).

The strong correlation between BTI and pollutant removal efficiency highlights BTI as a practical indicator for predicting system performance. Overall, integrated hydroponic macrophyte systems—especially polyculture configurations dominated by high-biomass species—can achieve >80–95% removal of key pollutants, providing a cost-effective, low-energy, and scalable alternative to conventional abattoir wastewater treatment technologies in resource-limited settings.

AUTHOR(S) CONTRIBUTIONS

Abubakar Mohammed conceptualized the study, designed and implemented the experiments, collected data, and drafted the initial manuscript. Aliyu Ishaq (corresponding author) provided supervision, project administration, methodology development, data analysis, manuscript review, and final approval. Abdurrasheed Sa'id Abdurrasheed contributed to experimental design, provided technical guidance on wastewater treatment processes, and critically revised the manuscript. Sunday Bamidele Igboro assisted with data acquisition, laboratory analysis, interpretation of results, and preparation of figures and tables. Al-amin Danladi Bello supported the hydroponic system setup, monitored plant growth parameters, and validated experimental results. Fatima B Ibrahim coordinated laboratory work, sample preservation, data entry, and contributed to literature review and manuscript formatting. All authors have read and approved the final manuscript and agree to be accountable for all aspects of the work.

AI DISCLOSURE

The authors declare that no artificial intelligence (AI) tools were used in the preparation, analysis, or writing of this manuscript, and all content is the result of the authors.

ACKNOWLEDGMENTS

We acknowledge the financial and logistical support provided by the research team members and their respective institutions, which made this study possible.

DECLARATION OF CONFLICT OF INTEREST

Authors declare that there is no conflict of interest.

REFERENCES

- Achoki, J. K., Kaingu, C. K., Oduma, J. A., Orina, P. S., Ondiba, R. N., Nyabwanga, R. N., & Getabu, A. M. (2024). Does duckweed (*Lemna minor*) feed inclusion play a role on growth, feed conversion ratio and reproductive performance (fertilization, hatchability and survivability rates) in omnivorous fish? Evidence in Nile tilapia (*Oreochromis niloticus*-Linnaeus, 1758). *Aquaculture, Fish and Fisheries*, 4(4), e70000.
- Adewumi, A., Olorunleke, J. O., Adeyemi, A. E., & Bekun, F. V. (2025). Socioeconomic Benefits of Wetland-Based Water Treatment: Discussing the Economic, Social, and Environmental Advantages Associated with Utilizing Wetlands for Water Treatment. In *Wetland Ecosystems: Conservation Strategies, Policy Management and Applications* (pp. 85–104). Springer.
- Alao, J. O., Fahad, A., Abdo, H. G., Ayejoto, D. A., Almohamad, H., Ahmad, M. S., Nur, M. S., Danjuma, T. T., Yusuf, M. A., Francis, O. T., & Joy, A. O. (2023). Effects of dumpsite leachate plumes on surface and groundwater and the possible public health risks. *Science of The Total Environment*, 897, 165469. <https://doi.org/10.1016/j.scitotenv.2023.165469>
- Ali, Y., Sabir, M., Afridi, S., & Ullah, Z. (2024). Pakistan's circular bio-economy: potential, opportunities and sustainable development. *Environment, Development and Sustainability*, 1–27.
- Aliasghar, A., Zhang, Z., Datta, R., Christodoulatos, C., & Sarkar, D. (2025). Accumulation of Nitrogen Species from Industrial Wastewater by Vetiver Grass (*Chrysopogon zizanioides*). *Water*, 17(10), 1464.
- AlMuhanna, K. J., Asiri, F., Abu-Arabi, M., & AlMansour, H. (2025). Treatment of Paper and Pulp Wastewater Using Coagulation-Flocculation with Alum: Optimization and Performance Evaluation. *Water, Air, & Soil Pollution*, 236(1), 52.
- Barresi, S., Marzo, A. C., & Milani, M. (2025). Constructed Wetlands for Dairy and Livestock Wastewater Treatment: A Review. *Water*, 17(24), 3492.

- Cirelli, C., Rodrigues, I. A., Vitória, J. G., Duarte-Andrade, F. F., Canuto, G. A. B., André, L. C., de Toledo, J. S., Fernandes, A. P., & Costa, A. O. (2025). Metabolic Profile Associated With Encystation in *Acanthamoeba*. *Journal of Eukaryotic Microbiology*, 72(5), e70034.
- Dhinesh, R., Kirthiga, S. S., Gopinath, A., & Taherzadeh, M. (2025). Future Trends and Innovations: Emerging Technologies in Wastewater Treatment and Potential Breakthroughs in Resource Recovery. *Resource Resurgence: Mitigating Wastewater, Smart Recycling and Novel Technologies*, 335–363.
- Dong, Y., Yuan, H., Zhang, R., & Zhu, N. (2019). Removal of ammonia nitrogen from wastewater: A review. *Transactions of the ASABE*, 62(6), 1767–1778. <https://doi.org/10.13031/trans.13671>
- Gopal, A. C., Alujević, K., & Logan, M. L. (2023). Temperature and the pace of life. *Behavioral Ecology and Sociobiology*, 77(5), 59.
- Gopal, G., Sankar, H., Natarajan, C., & Mukherjee, A. (2020). Tetracycline removal using green synthesized bimetallic nZVI-Cu and bentonite supported green nZVI-Cu nanocomposite: A comparative study. *Journal of Environmental Management*, 254, 109812.
- Guo, X., Zhu, L., Zhong, H., Li, P., Zhang, C., & Wei, D. (2021). Response of antibiotic and heavy metal resistance genes to tetracyclines and copper in substrate-free hydroponic microcosms with *Myriophyllum aquaticum*. *Journal of Hazardous Materials*, 413, 125444.
- Hassan, M. M., Haleem, N., Baig, M. A., & Jamal, Y. (2019). Phytoaccumulation of heavy metals from municipal solid waste leachate using different grasses under hydroponic condition. 3(2)(Article no.AJARR.46287), 1–12. <https://doi.org/10.1038/s41598-020-72800-2>
- Hassan, R. O., Othman Abdullah, F., Salahuddin Ali, D., Omar Othman, H., & Aziz Darwesh, D. (2024). Evaluating the health risks of heavy metal pollution in dust storms in the city of Erbil in the Kurdistan region of Iraq. *International Journal of Environmental Health Research*, 34(9), 3084–3100.
- Iyiola, A. O., Akinsorotan, A. M., Asiedu, B., & Ewutanure, J. S. (2023). Impacts of agrochemicals on fish composition in natural waters: A sustainable management approach. In *One health implications of agrochemicals and their sustainable alternatives* (pp. 659–697). Springer.
- Jiang, J., Wang, X., Ren, H., Cao, G., Xie, G., Xing, D., & Liu, B. (2020). Investigation and fate of microplastics in wastewater and sludge filter cake from a wastewater treatment plant in China. *Science of the Total Environment*, 746, 141378.
- Justin, L. D., & Olukanni, D. O. (2024). Efficiency evaluation of wastewater treatment by three macrophytes using a pilot-constructed wetland system in Ota, Nigeria. *Journal of Water and Health*, 22(11), 2040–2053.
- Kumari, S., Panda, R., Prasad, R., Alorro, R. D., & Jha, M. K. (2024). Sustainable process to recover metals from waste PCBs using physical pre-treatment and hydrometallurgical techniques. *Sustainability*, 16(1), 418.
- Kunz, J. M. (2024). Surveillance of waterborne disease outbreaks associated with drinking water—United States, 2015–2020. *MMWR. Surveillance Summaries*, 73.
- Li, J., Li, X., Liu, H., Gao, L., Wang, W., Wang, Z., Zhou, T., & Wang, Q. (2023). Climate change impacts on wastewater infrastructure: A systematic review and typological adaptation strategy. *Water Research*, 242, 120282.
- Li, L., Hua, Y., Zhao, S., Yang, D., Chen, S., Song, Q., Gao, J., & Dai, X. (2023). Worldwide research progress and trend in sludge treatment and disposal: A bibliometric analysis. *ACS ES&T Engineering*, 3(8), 1083–1097.
- Li, Y., Tang, F., Xu, D., & Xie, B. (2021). Advances in biological nitrogen removal of landfill leachate. *Sustainability (Switzerland)*, 13(11), 1–18. <https://doi.org/10.3390/su13116236>
- Molognoni, D., Chiarolla, S., Cecconet, D., Callegari, A., & Capodaglio, A. G. (2017). Industrial wastewater treatment with a bioelectrochemical process: Assessment of depuration efficiency and energy production. *Water Science and Technology*, 532, 1–12. <https://doi.org/10.2166/wst.2017.532>
- Nguyen-Sy, T., Hai, H., Do, H. H., Thi, P. T., Minh, T. T., Tran, N.-S., Chi, C. D., & Van, M. V. (2025). Removal of ammonium and nitrate by water lettuce (*Pistia Stratiotes*) under salinity stress. *Egyptian Journal of Aquatic Research*, 51(2), 143–149.

- Ojo, O. M. (2025). Anaerobic Digestion for Wastewater Treatment: A Review of Principles, Processes and Performance. *Journal of Energy Technology and Environment*, 7(1), 52–60.
- Organization, W. H. (2022). WHO consolidated guidelines on tuberculosis. Module 4: treatment-drug-resistant tuberculosis treatment, 2022 update. World Health Organization.
- Rezania, N., Hasani Zonoozi, M., & Saadatpour, M. (2021). Coagulation-flocculation of turbid water using graphene oxide: simulation through response surface methodology and process characterization. *Environmental Science and Pollution Research*, 28(12), 14812–14827.
- Rodríguez-Vidal, F. J., Ortega-Azabache, B., González-Martínez, Á., & Bellido-Fernández, A. (2022). Comprehensive characterization of industrial wastewaters using EEM fluorescence, FT-IR and ¹H NMR techniques. *Science of the Total Environment*, 805, 150417. <https://doi.org/10.1016/j.scitotenv.2021.150417>
- Rous, V., Vymazal, J., & Hnátková, T. (2019). Treatment wetlands aeration efficiency: A review. *Ecological Engineering*, 136, 62–67.
- Saxena, V. (2021). Simultaneous removal of carbon , nitrogen , and phosphorus from landfill leachate using an aerobic granular reactor. i, 1–19.
- Sharma, M., Rawat, S., Kumar, D., Awasthi, A., Sarkar, A., Sidola, A., Choudhury, T., & Kotecha, K. (2024). The state of the Yamuna River: a detailed review of water quality assessment across the entire course in India. *Applied Water Science*, 14(8), 175.
- Singh, P. K., Kumar, U., Kumar, I., Dwivedi, A., Singh, P., Mishra, S., Seth, C. S., & Sharma, R. K. (2024). Critical review on toxic contaminants in surface water ecosystem: sources, monitoring, and its impact on human health. *Environmental Science and Pollution Research*, 31(45), 56428–56462.
- Terna, A. T., Legbo, M. I., Abdullahi, M., Gogo, M. R., & Ndejiko, M. J. (2024). Bioremediation of Abattoir Effluent: Implication for Bioproduct Synthesis. *Journal of Biochemistry, Microbiology and Biotechnology*, 12(1), 68–77.
- Vymazal, J. (2023). Thirty years of constructed wetlands for municipal wastewater treatment in the Czech Republic. *Ecological Engineering*, 194, 107054.
- Wei, C., Li, Z., Zhu, D., Xu, T., Liang, Z., Liu, Y., & Zhao, N. (2025). Regulation of the physicochemical properties of nutrient solution in hydroponic system based on the CatBoost model. *Computers and Electronics in Agriculture*, 229, 109729.
- Wu, S., Xu, J., Zou, L., Luo, S., Yao, R., Zheng, B., Liang, G., Wu, D., & Li, Y. (2021). Long-lasting renewable antibacterial porous polymeric coatings enable titanium biomaterials to prevent and treat peri-implant infection. *Nature Communications*, 12(1), 3303.
- Xu, L., Yu, H., Qin, H., Chai, Y., Yan, N., Li, D., & Chen, Y. (2023). Digital twin for aquaponics factory: Analysis, opportunities, and research challenges. *IEEE Transactions on Industrial Informatics*, 20(4), 5060–5073.
- Zhanfei He , Zhen Wei, Qingying Zhang, Jinte Zou, X. P. (2019). Metal oxyanion removal from wastewater using manganese-oxidizing aerobic granular sludge. *Chemosphere*, 236(11 july), 124353. <https://doi.org/10.1016/j.chemosphere.2019.124353>
- Zhang, Z., Teng, C., Zhou, K., Peng, C., & Chen, W. (2020). Degradation characteristics of dissolved organic matter in nanofiltration concentrated landfill leachate during electrocatalytic oxidation. *Chemosphere*, 255, 127055. <https://doi.org/10.1016/j.chemosphere.2020.127055>
- Zhou, J., Gilliard, A., & Ling, K.-S. (2024). Tomato Brown Rugose Fruit Virus Is Transmissible through a Greenhouse Hydroponic System but May Be Inactivated by Cold Plasma Ozone Treatment. *Horticulturae*, 10(4), 416.
- Zure, D., Drizo, A., Sung, M.-H., Mehari, A., Maiguo, E., & Kuo, D. H. W. (2025). Antiviral Phytoremediation for Sustainable Wastewater Treatment.