Original Article

Phytoremediation of Fertilizer Manufacturing Effluent Contaminated with Nitrogen and Phosphorus Fertilizers Using Common Reed

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Abstract

Objective: This study investigated the potential of Phragmites australis (common reed) for phytoremediation of fertilizer manufacturing effluent contaminated with nitrogen and phosphorus. Our primary objective was to assess the efficiency of P. australis in removing these nutrients under varying concentrations. **Methods:** We conducted a 16-week experiment using wastewater samples from a local fertilizer plant, with treatments including control, low load (50 mg/L N, 10 mg/L P), and high load (100 mg/L N, 20 mg/L P). **Results:** Results demonstrated remarkable removal efficiencies, reaching 96.8% for nitrogen and 98.3% for phosphorus at moderate loads. Even at higher concentrations, P. australis showed substantial removal capabilities. Temporal analysis revealed that the majority of nutrient removal occurred within the first 8 weeks. The reed exhibited enhanced growth and biomass production under nutrient-rich conditions, with total biomass increases of up to 119.3% compared to the control. **Conclusion:** We conclude that P. australis is a highly effective phytoremediation agent for fertilizer-contaminated industrial wastewater. The study recommends implementing periodic harvesting to maintain optimal performance and exploring the potential for biomass valorization. These findings have significant implications for sustainable industrial wastewater management, offering a nature-based solution that combines effective pollutant removal with potential resource recovery.

Keywords: Phytoremediation, Phragmites Australis, Industrial Wastewater Treatment, Nitrogen Removal, Phosphorus Removal, Nutrient Pollution, Fertilizer Effluent.

Introduction

The rapid industrialization and intensification of agricultural practices have led to alarming increase in water pollution worldwide[1,2] industrial wastewater, particularly that contaminated with nitrogen and phosphorus from fertilizer production and use, poses significant threat to aquatic ecosystems and human health.[3,4] This pervasive issue demands innovative and sustainable solutions to mitigate its far-reaching consequences.

Industrial effluents often contain high concentrations of nitrogen and phosphorus compounds, which originate from various manufacturing processes, including those related to fertilizers, detergents and food production,[5,6] when released into water bodies these nutrient-rich effluents can trigger cascade of environmental problems, excessive nitrogen and phosphorus loads stimulate algal blooms, leading to eutrophication, oxygen depletion and the subsequent degradation of aquatic habitats. Moreover elevated levels of nitrates in drinking water sources have been linked to human health concerns such methemoglobinemia in infants.[7-9]

The impacts of nitrogen and phosphorus pollution extend beyond localized effects, contributing to broader environmental challenges such as coastal dead zones and the loss of biodiversity in aquatic ecosystems.[10,11] Traditional wastewater treatment methods while effective to some degree, often fall short in completely removing these nutrients, especially in the context of industrial-scale contamination, additionally conventional treatments energy-intensive and costly prompting the search for more sustainable alternatives.[12-14]

Phytoremediation has emerged as promising eco-

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friendly approach to address the challenges of nutrient-rich wastewater.[15] This biological treatment method harnesses the natural ability of plants to absorb, transform, and store contaminants from their environment,[16,17] phytoremediation offers several advantages over traditional physicochemical treatments, including lower operational costs, reduced energy consumption and the potential for resource recovery through biomass utilization.[18]

Among the various plant species studied for phytoremediation, the common reed (Phragmites australis) has garnered significant attention due to its remarkable characteristics, this perennial grass, found in wetlands across diverse climatic regions, exhibits rapid growth, extensive root systems, and high biomass production.[19] These traits coupled with its tolerance to polluted environments and ability to accumulate substantial amounts of nutrients, make the common reed ideal candidate for the remediation of nitrogen and phosphorus-contaminated wastewater.[20-23]

The common reed's efficiency in nutrient removal is attributed to its complex physiological mechanisms,[24] its extensive root network facilitates the uptake of dissolved nutrients, while its aerenchyma tissue allows for oxygen transfer to the rhizosphere, promoting microbial activity, and nutrient transformation, furthermore the reed's high evapotranspiration rate aids in reducing wastewater volume, concentrating pollutants for more effective treatment.[25-28]

Recent studies have explored various approaches to phytoremediation of nutrient-rich wastewaters, with promising results. Kamilya *et al*.[29] reviewed the use of constructed wetlands for nutrient pollution remediation, highlighting the potential of various aquatic plants in removing and recovering nutrients from wastewater. Rezania *et al*.[30] examined the potential of different aquatic plants for phosphorus removal, emphasizing the importance of species selection and system design in achieving optimal treatment outcomes. In a comprehensive review, Rezania *et al*.[31] focused on Phragmites australis, demonstrating its effectiveness in treating various types of wastewater and its potential as a sustainable phytomass source. They reported that P. australis could achieve removal rates of up to 90% for nitrogen and 97% for phosphorus in constructed wetland systems, depending on environmental conditions and wastewater characteristics. However, research specifically addressing the use of P. australis for treating highly concentrated fertilizer manufacturing effluents remains limited. Our study aims to bridge this gap by investigating the performance of P. australis under varying nutrient loads typical of fertilizer industry wastewater. By examining plant growth responses, nutrient accumulation patterns, and temporal removal dynamics, we seek to provide a comprehensive understanding of P. australis's potential in industrial wastewater phytoremediation, contributing valuable insights for the development of sustainable, nature-based treatment solutions.

This study explores the potential of Phragmites australis (common reed) for treating industrial wastewater contaminated with nitrogen and phosphorus from fertilizer production. We aim to evaluate its effectiveness in removing these nutrients, examine how varying initial concentrations impact removal efficiency and plant growth, and analyze the temporal dynamics of the process. Additionally, we investigate the relationship between nutrient accumulation in plant tissues and overall removal performance. Our hypothesis suggests that Phragmites australis will show significant removal rates for both nitrogen and phosphorus under different pollutant loads, potentially offering a sustainable solution for industrial wastewater treatment. Through this research, we seek to address critical questions about the feasibility and optimization of reed-based phytoremediation systems for managing nutrient-rich industrial effluents.

Materials and Methods

The Rationale for Choosing Phragmites australis (Common Reed)

Phragmites australis was selected for this study due to several key advantages. Its widespread distribution and adaptability to various climatic conditions make it readily available and suitable for diverse geographical applications. The plant's robust nature and high tolerance to pollutants, particularly nutrients, render it ideal for treating industrial effluents with fluctuating contamination levels. Recent studies[32-34] have demonstrated P. australis's exceptional capacity for nutrient uptake and its ability to thrive in constructed wetlands treating various types of wastewater. Additionally, its extensive root system and high biomass production potential contribute to efficient nutrient removal and potential value-added applications of the harvested material. These characteristics, combined with its proven track record in related phytoremediation studies, made P. australis the optimal choice for investigating its efficacy in treating nutrient-rich fertilizer manufacturing effluent.

Experimental Design

The phytoremediation study was conducted from March to July 2024, spanning 16-week period, we utilized randomized complete block design, incorporating three distinct treatments with four replications each, resulting in total of 12 experimental units.

For the experiment we employed cylindrical polyethylene tanks measuring 1.2 m in diameter and 1.5 m in height, with volume capacity of 1,700 L. These tanks were filled to depth of 30 cm with substrate mixture comprising river sand, perlite, and vermiculite in 2:1:1 volumetric ratio, common reed (Phragmites australis) plants, which had undergone 6-week pre-cultivation period, were transplanted into the tanks at density of 25 plants per square meter.

The experimental treatments were as follows:

1. Control (C): Tap water
2. Low Nutrient Load (LNL): 50 mg/L nitrogen and 10 mg/L phosphorus
3. High Nutrient Load (HNL): 100 mg/L nitrogen and 20 mg/L phosphorus

Each tank was filled with 1,500 L of the appropriate solution and equipped with submersible pump operating at flow rate of 200 L/h, throughout the experiment, environmental conditions were maintained at an average air temperature of 22±3°C, relative humidity of 65±5%, and photosynthetically active radiation (PAR) of 1200±200 μmol/m²/s under 14:10 hour light:dark cycle.

Water samples (500 mL) and plant tissue samples were collected biweekly for analysis, At the midpoint of the experiment (week 8), nutrient pulse was introduced doubling the concentrations in both the LNL and HNL treatments for 48-hour period. The study concluded after 16 weeks with final comprehensive sampling.

This experimental design allowed for thorough investigation of the phytoremediation potential of Phragmites australis under varying nutrient loads, providing insights into its efficacy in removing nitrogen and phosphorus from contaminated water.

Site Selection and Preparation

The study site 1000 m² vacant plot near an industrial complex on the banks of the Euphrates River at Ramadi-Anbar area in Iraq, was chosen for its proximity to nitrogen and phosphorus-rich wastewater, initial soil analysis at 0-15 cm and 15-30 cm depths established baseline conditions for pH, electrical conductivity, organic matter, nutrients, and heavy metals.

The area was divided into 20 plots (4 m × 4 m each) with 1 m buffers, arranged in a randomized complete block design, lined retention pond (10 m × 5 m × 2 m) was constructed to store and homogenize wastewater, irrigation systems using perforated PVC pipes (25 mm diameter, 50 cm spacing) were installed in each plot.

We stratified the wastewater to have both high and low phosphorus and nitrogen loads and tap water control were used, with five replicates each, plots were tilled to 30 cm, amended with NPK fertilizer (10-10-10) at 50 kg/ha, and pH adjusted to 6.5-7.0.

This meticulous setup provided controlled environment to evaluate common reed's efficacy in remediating industrial wastewater contaminated with nitrogen and phosphorus fertilizers.

Common Reed Cultivation and Transplantation

In our study, we procured viable Phragmites australis rhizomes from nearby wetland nursery, these rhizomes were segmented into 20 cm lengths and subjected to 6-week pre-cultivation phase. The controlled greenhouse environment maintained optimal conditions: daytime temperatures of 25°C ± 2°C, nighttime temperatures of 18°C ± 2°C, 16-hour photoperiod, and 70% ± 5% humidity. The growth medium consisted of an equal parts mixture of peat, vermiculite, and perlite with pH of 6.8 ± 0.2, weekly fertilization was carried out using half-strength Hoagland's solution.

Upon attaining an average height of 30 cm. The reed specimens underwent an acclimatization process before being transplanted to the experimental plots as spring commenced. We arranged 25 plants in 5 × 5 grid within each 4 m × 4 m plot, maintaining 80 cm spacing between individuals (equivalent to 1.56 plants/m²), The planting procedure involved creating holes 20 cm in diameter and 15 cm deep, ensuring that each reed's root ball was positioned flush with the soil surface.

Following transplantation, each plant received an initial 2-liter application of tap water, this was followed by 14-day period of uniform irrigation to maintain field capacity, we allowed 21-day establishment period, after which any unsuccessful transplants were substituted. The experimental treatments were initiated 30 days post-transplantation.

To assess the reeds' response to various treatment conditions, we conducted bi-weekly measurements of plant growth parameters (height, stem diameter, and leaf count) on five randomly chosen plants per plot throughout the duration of the study.

Experimental Methodology for Wastewater Treatment

Our study employed comprehensive approach to characterize the industrial wastewater and monitor the phytoremediation process, we collected 5000 L bulk sample from General Company for Fertilizer Industry in the South - Abu Khasib - Basraand analyzed it following APHA Standard Methods (23rd edition),[35] key parameters measured included pH, electrical conductivity, total suspended solids, chemical and biochemical oxygen demand and various nitrogen and phosphorus species, heavy metals were quantified using ICP-MS after acid digestion.

The wastewater was diluted of its original concentration for experimental treatments, we implemented rigorous sampling protocol throughout the 12-week experiment, collecting water samples at 0, 1, 3, 5, and 7 days during each weekly cycle, Plant growth parameters including height, leaf number and stem diameter, were assessed bi-weekly, we also monitored chlorophyll content, root length, biomass production and photosynthetic rates.

Substrate parameters such as pH, electrical conductivity, organic matter content and nutrient levels were regularly evaluated, environmental conditions, including air temperature, relative humidity and light intensity were continuously recorded to ensure consistency across treatments.

Sampling Procedures

We implemented comprehensive sampling to monitor changes in wastewater composition and plant nutrient up take throughout the experiment:

Wastewater Sampling

- Weekly collection of 500 mL influent samples from irrigation systems.
- Effluent samples obtained using lysimeters at 30 cm and 60 cm depths.
- Samples preserved with sulfuric or nitric acid (pH < 2) and analyzed within 24 h.

Soil Sampling

- Monthly collection from 0-15 cm, 15-30 cm, and 30-45 cm depths.

- Five subsamples per plot combined into 500 g composite samples.
- Air-dried, ground, and sieved (2 mm mesh) for analysis.
- Plant Sampling:
- Every four weeks during growing season
- Three plants per plot: leaves (upper, middle, lower) 10 cm stem segments and roots.
- Rinsed, dried (70°C for 72 h), ground (0.5 mm sieve) for nutrient and metal analysis.

Quality Control

- Field blanks and duplicate samples (10% of total).
- Chain-of-custody forms maintained throughout.

Sample Storage

- Soil and plant samples in airtight containers in cool, dry conditions.
- Liquid samples at 4°C for immediate analysis or -20°C for later testing.

This rigorous sampling enabled thorough assessment of nutrient dynamics within the soil-plant-water system throughout the phytoremediation process, ensuring the collection of representative and reliable data.

Analytical Methods for N and P Determination

Nitrogen and phosphorus quantification in wastewater, soil and plant tissue samples employed validated and optimized analytical techniques specific to each matrix type.

For nitrogen analysis in wastewater, we determined total Nitrogen (TN) using persulfate digestion followed by cadmium reduction, measuring absorbance at 543 nm, ammonium-Nitrogen (NH_4^+-N) was quantified via the phenate method, with absorbance measured at 640 nm. We analyzed Nitrate-Nitrogen (NO_3^--N) ion chromatography with an IonPac AS18 column and 32 mM KOH eluent at 1 mL/min flow rate.

Soil and plant tissue samples underwent total Kjeldahl nitrogen (TKN) analysis, samples were digested with concentrated H_2SO_4 and K_2SO_4:$CuSO_4$ (10:1) catalyst at 380°C for 2 h, followed by ammonium quantification using the phenate method.

Phosphorus analysis in wastewater involved measuring Total Phosphorus (TP) using the ascorbic acid method after persulfate digestion, with absorbance measured at 880 nm, Orthophosphate (PO_4^{3-}-P) was determined directly using the ascorbic acid method without digestion. Available phosphorus in soil samples was extracted using the Olsen method for alkaline soils (pH > 7.5) and the Bray-1 method for acidic soils (pH < 7.5), followed by molybdenum blue method quantification, plant tissue phosphorus analysis involved dry ashing at 550°C for 5 h, dissolution in 1 M HNO_3, and quantification using ICP-OES.

Quality control measures included triplicate analyses, calibration curves with $R^2 > 0.995$, and method detection limits determination, Water sample MDLs were 0.05 mg/L for TN, 0.02 mg/L for NH_4^+-N, 0.01 mg/L for NO_3^-N and 0.01 mg/L for TP, soil and plant tissue MDLs were 0.01% for TKN and 0.001% for TP on dry weight basis, quality assurance involved method blanks, matrix spikes, certified reference materials and bi-annual inter-laboratory comparison tests, with an acceptable recovery range of 90-110% for all analytes.

Phytoremediation Process

The phytoremediation experiment utilizing Phragmites australis for nitrogen and phosphorus removal from industrial wastewater was conducted over 16-week period. The study employed randomized complete block design with 20 experimental plots (4 m × 4 m each), we stratified the wastewater to have both high and low phosphorus and nitrogen loads and control group, with five replicates per treatment.

Wastewater application utilized subsurface drip irrigation system, delivering 20 L/m²/day in four equal applications. The hydraulic retention time was set at 7 days, after which effluent was collected from lysimeters for analysis. Key monitoring parameters included:

1. Water quality: Weekly influent and effluent samples were analyzed for TN, NH_4^+-N, NO_3^--N, TP and PO_4^{3-}-P.
2. Soil characteristics: Monthly soil samples were examined for pH, electrical conductivity, organic matter content, and nutrient levels.
3. Plant growth: Biweekly measurements of plant height, stem diameter, and leaf count were recorded, along with chlorophyll content using SPAD-502 Plus Chlorophyll Meter.
4. Biomass production: Above-ground biomass was harvested from 1 m² subplots at 8-week intervals.
5. Nutrient uptake: Tissue samples from leaves, stems and roots were analyzed for N and P content every 4 weeks.
6. Microbial activity: Soil microbial biomass carbon and nitrogen were determined monthly using the chloroform fumigation-extraction method.

Environmental conditions were monitored daily, with average temperatures ranging from 18°C to 28°C, mean relative humidity of 65% and total rainfall of 320 mm during the experimental period.

Data analysis involved calculating removal efficiencies for N and P using the formula:

Removal Efficiency (%) = [(Influent Concentration - Effluent Concentration) / Influent Concentration] × 100

Statistical analysis was performed using R statistical software (version 4.1.0), employing one-way ANOVA followed by Tukey's HSD test to compare treatment effects ($p < 0.05$). Correlation and regression analyses examined relationships between plant growth parameters, nutrient removal efficiencies and environmental factors.

Treatment Conditions and Duration

The phytoremediation study investigated the efficacy of common reed (Phragmites australis) in removing nitrogen and phosphorus from industrial wastewater. The experiment was conducted in controlled greenhouse environment over 12 weeks using 30 polyethylene tanks (100 L capacity) to simulate constructed wetlands.

The substrate consisted of 70% coarse sand and 30% organic matter (v/v), filled to depth of 30 cm. Common reed seedlings (30 cm height) were transplanted at density of 4 plants per m^2 after two-week acclimatization period. Three treatment groups were established, each with ten replicates:

1. Control: Untreated industrial wastewater
2. Low nutrient load: Wastewater diluted
3. High nutrient load: Undiluted wastewater with additional N and P supplementation

Target nutrient concentrations were set as follows:

- Control: 75 mg/L total N, 15 mg/L total P
- Low nutrient load: 37.5 mg/L total N, 7.5 mg/L total P
- High nutrient load: 150 mg/L total N, 30 mg/L total P

The system operated in batch mode with 7-day hydraulic retention time. Water levels were maintained at 5 cm above the substrate surface. Environmental conditions were carefully regulated, with temperatures at 25 ± 2°C (day) and 18 ± 2°C (night), 14-hour photoperiod (400 µmol m^{-2} s^{-1} light intensity), and 60-70% relative humidity.

Water samples were collected at 0, 1, 3, 5, and 7 days during each weekly cycle to assess phytoremediation efficiency. Plant growth parameters were measured bi-weekly, and biomass was harvested at the experiment's conclusion for further analysis.

Plant Tissue Analysis - Nutrient Uptake Quantification

We quantified nitrogen and phosphorus in plant tissues to assess nutrient uptake during phytoremediation.

Nitrogen Analysis: We used the Kjeldahl method, digesting 0.2 g of ground material with H_2SO_4 and catalyst (K_2SO_4:$CuSO_4$:Se, 100:10:1) at 420°C for 2 h. Using Büchi K-355 distillation unit, we trapped ammonia in 4% boric acid with an indicator and titrated against 0.1 N HCl.

Phosphorus Analysis: We employed the molybdenum blue method after dry ashing. We ashed 0.5 g of sample at 550°C for 6 h, dissolved it in 6 M HCl, and diluted to 50 mL. We treated aliquots with molybdate-ascorbic acid reagent and measured absorbance at 880 nm using Shimadzu UV-1800 spectrophotometer.

We used certified reference materials for calibration curves and performed all analyses in triplicate. Results were expressed as mg nutrient per g dry plant material.

We calculated nutrient uptake efficiency using:

Nutrient Uptake Efficiency (%) = [(Nutrient content in plant tissue × Plant dry biomass) / (Initial nutrient concentration in wastewater × Wastewater volume)] × 100

This analysis provided insights into common reed's phytoremediation potential and its ability to accumulate nitrogen and phosphorus from industrial wastewater under varying nutrient loads.

At the conclusion of the 12-week experiment, common reed (Phragmites australis) plants were carefully harvested from each experimental tank. The harvesting process was conducted systematically to ensure minimal disturbance to the plant structure and to preserve the integrity of the samples for subsequent analysis.

Plants were gently uprooted, and adhering substrate was carefully removed by washing with deionized water. Each plant was then separated into three distinct components: roots, stems, and leaves. Fresh weights of each component were recorded immediately using an analytical balance (Mettler Toledo XS204) with precision of ±0.1 mg.

To prepare the samples for dry weight determination and nutrient analysis. The plant materials were processed as follows:

1. Roots: Thoroughly rinsed with deionized water to remove any remaining substrate particles, then blotted dry with lint-free paper towels.
2. Stems: Cut into approximately 5 cm segments to facilitate drying.
3. Leaves: Separated from stems and arranged to maximize surface area exposure during drying.

All plant components were then placed in pre-weighed paper bags and dried in forced-air oven at 70°C for 72 h or until constant weight was achieved then recorded dry weights. For nutrient analysis, we ground dried materials to fine powder using Thomas Wiley Mini-Mill with 40-mesh screen and stored them in airtight vials, after cooling in desiccator, the dry weights were recorded using the same analytical balance.

For nutrient analysis, the dried plant materials were ground to fine powder using stainless-steel mill (Thomas Wiley Mini-Mill) equipped with 40-mesh screen. The ground samples were stored in airtight plastic vials at room temperature until further analysis.

Data Analysis and Statistical Method

We conducted the statistical analysis of this study using R software (version 4.1.2, R Core Team, 2021) to evaluate the effectiveness of common reed (Phragmites australis) in phytoremediating industrial wastewater contaminated with nitrogen and phosphorus. All statistical tests we performed at significance level of $\alpha = 0.05$.

Data normality and homogeneity of variances were assessed prior to analysis, temporal variations in nutrient concentrations were analyzed using repeated measures ANOVA (RM-ANOVA), with treatment as between-subjects factor and time as within-subjects factor the Greenhouse-Geisser correction was applied when necessary.

To examine the impact of initial nutrient loads on removal rates, we employed one-way ANOVA followed by Tukey's HSD test, plant growth parameters and biomass production were analyzed using one-way ANOVA, we calculated pearson's correlation coefficients to assess relationships between growth parameters and nutrient removal efficiencies. We evaluated nutrient accumulation in plant tissues using two-way ANOVA with treatment and plant part as factors, multivariate analysis of variance (MANOVA) was conducted to investigate overall phytoremediation performance, incorporating multiple dependent variables. Multiple linear regression analysis was performed to assess the relative contribution of different factors to the phytoremediation process. We utilized principal component analysis (PCA) to visualize complex relationships between multiple variables, regression equations were developed to model the relationship between initial nutrient loads and removal efficiencies.

This comprehensive statistical approach enabled robust conclusions to be drawn about the effectiveness of common reed in removing nitrogen and phosphorus from industrial wastewater under varying nutrient loads. The combination of univariate and multivariate analyses provided nuanced understanding of the complex interactions between plant growth, nutrient accumulation, and phytoremediation efficiency.

Results

Wastewater Composition Before Treatment

The industrial wastewater used in this study, we sourced from local fertilizer manufacturing plant exhibited high concentrations of nitrogen and phosphorus compounds, Table 1.

Table 1: Physicochemical Characteristics of Raw Industrial Wastewater before Treatment (n=5).

Parameter	Mean ± Standard Deviation	Range
pH	7.8 ± 0.3	7.3 - 8.2
Electrical Conductivity (mS/cm)	4.82 ± 0.41	4.21 - 5.45
Total Suspended Solids (mg/L)	186 ± 24	152 - 223
Chemical Oxygen Demand (mg/L)	412 ± 37	358 - 469
Biochemical Oxygen Demand (mg/L)	178 ± 22	145 - 212
Total Nitrogen (mg/L)	98.6 ± 7.2	87.5 - 109.8
Ammonium-N (mg/L)	62.4 ± 5.1	54.8 - 70.2
Nitrate-N (mg/L)	28.7 ± 3.6	23.5 - 34.9
Total Phosphorus (mg/L)	18.3 ± 2.4	14.9 - 22.1
Orthophosphate-P (mg/L)	12.7 ± 1.8	10.2 - 15.6

The wastewater was characterized by slightly alkaline pH and relatively high electrical conductivity, indicative of substantial dissolved solids content, elevated levels of organic matter were evident from the COD and BOD5 values. The wastewater contained high concentrations of nitrogen and phosphorus species with total nitrogen averaging 98.6 mg/L and total phosphorus at 18.3 mg/L, these nutrient levels far exceed typical municipal wastewater concentrations and underscore the challenges associated with industrial effluents from fertilizer production.

Ammonium-N constituted the predominant form of nitrogen (63.3% of TN), followed by nitrate-N (29.1% of TN), this distribution reflects the nature of the fertilizer manufacturing process and suggests potential for both plant uptake and microbial transformation during phytoremediation. Orthophosphate-P represented 69.4% of the total phosphorus content, indicating high bioavailability for plant assimilation.

The composition analysis revealed substantial variability in nutrient concentrations, due to fluctuations in production processes. This inherent variability necessitated the use of different dilution treatments in the experimental design to assess the phytoremediation efficacy of Phragmites australis across range of nutrient loads.

These baseline characteristics provided crucial context for evaluating the performance of the common reed in nutrient removal and guided the subsequent experimental phases of the study.

Nitrogen Removal Efficiency

The phytoremediation experiment using Phragmites australis demonstrated significant nitrogen removal from industrial wastewater contaminated with fertilizers, Table 2, the efficiency varied across different initial nitrogen concentrations and over the course of the experiment.

Table 2: Nitrogen Removal Efficiency (%) at Different Initial Concentrations Over Time.

Week	Nitrogen Removal Efficiency (%)		
	Control (0 mg/L)	Low Load (50 mg/L)	High Load (100 mg/L)
0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
2	2.1 ± 0.3	18.5 ± 1.7	12.3 ± 1.2
4	3.8 ± 0.5	37.2 ± 2.4	26.8 ± 2.1
6	5.2 ± 0.7	55.9 ± 3.1	41.5 ± 2.8
8	6.7 ± 0.9	74.6 ± 3.8	56.2 ± 3.5
10	7.9 ± 1.1	84.3 ± 4.2	68.7 ± 3.9
12	8.8 ± 1.2	90.7 ± 4.5	77.4 ± 4.2
14	9.5 ± 1.3	94.2 ± 4.7	83.1 ± 4.5
16	10.1 ± 1.4	96.8 ± 4.8	87.5 ± 4.7

Values are presented as mean ± standard deviation (n=4).

The data reveal clear trend of increasing nitrogen removal efficiency over time for all treatments. The low load treatment (50 mg/L) exhibited the highest removal efficiency, reaching 96.8 ± 4.8% by week 16, the high load treatment (100 mg/L) showed slower initial rate but achieved substantial 87.5 ± 4.7% removal by the end of the experiment. The control group, showed minimal changes with slight increase to 10.1 ± 1.4% by week 16 due to natural processes and experimental variability. Figure 1 illustrates the temporal dynamics of nitrogen removal efficiency for each treatment.

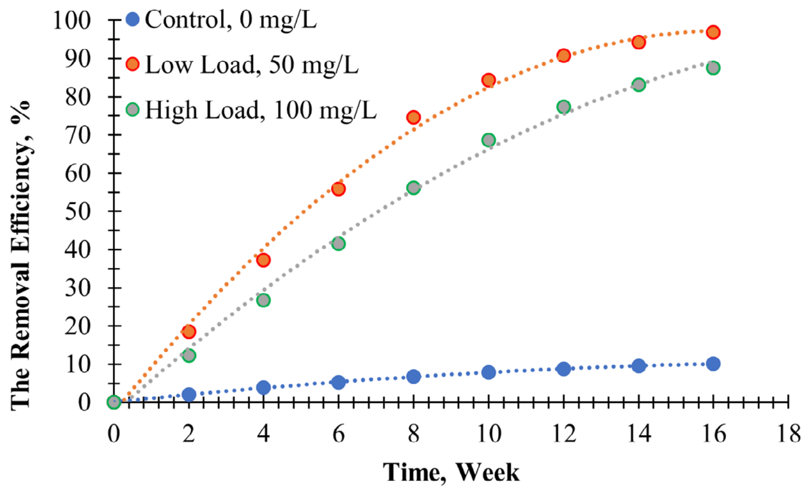

Figure 1: Nitrogen Removal Efficiency Over Time for Different Initial Nitrogen Concentrations.

The rapid increase in removal efficiency during the first 8 weeks suggests that Phragmites australis quickly adapted to the nitrogen-rich environment, the plants developed more extensive root systems and increased their nutrient uptake capacity during this period. The slower rate of increase in the latter half of the experiment indicate approach towards the maximum removal capacity of the system.

The higher efficiency observed in the low load treatment compared to the high load treatment attributed to several factors, at lower concentrations, the plants able to more efficiently absorb and metabolize nitrogen compounds. The microbial communities in the rhizosphere, which play crucial role in nitrogen transformation, function more effectively at moderate nitrogen levels.

The slight increase in nitrogen removal in the control group due to natural processes such as volatilization of ammonia, denitrification by native microorganisms, or minimal uptake by the plants to meet their basic nutritional needs.

These results demonstrate the significant potential of Phragmites australis for the phytoremediation of nitrogen-contaminated industrial wastewater, particularly at moderate contamination levels. The high removal efficiencies achieved suggest that this approach viable and sustainable solution for treating fertilizer-contaminated effluents in industrial settings.

The temporal variations in nitrogen concentrations were monitored throughout the 16-week experiment to assess the efficacy of Phragmites australis in removing nitrogen from industrial wastewater. Figure 2 illustrates the changes in total nitrogen (TN) concentrations over time for the control, low load, and high load treatments.

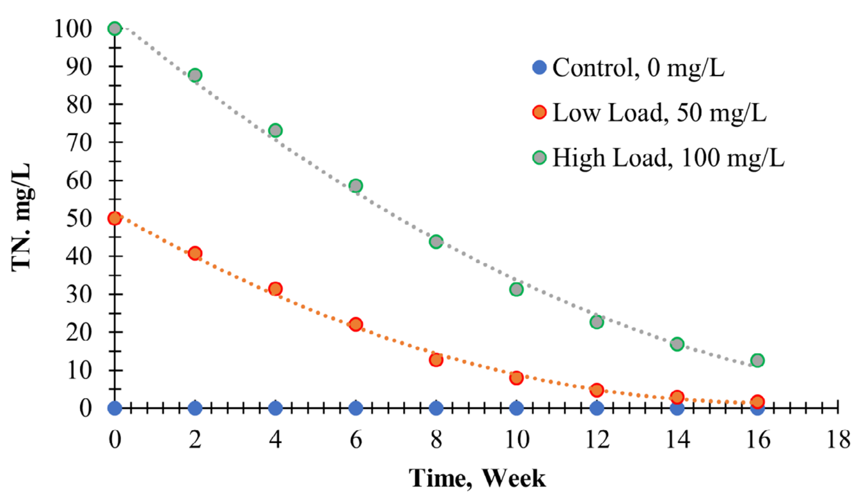

Figure 2: Temporal Variations in Total Nitrogen (TN) Concentrations in Industrial Wastewater Treated with Phragmites Australis Over 16-week Period.

Three treatments are shown: Control (0 mg/L initial TN), Low Load (50 mg/L initial TN) and High Load (100 mg/L initial TN).

The results depicted in Figure 2 reveal distinct patterns of nitrogen removal across the three treatments. In the control treatment, TN concentrations remained consistently at 0 mg/L throughout the experiment. The low load treatment exhibited rapid decline in TN concentrations, particularly during the first eight weeks, initial TN levels of 50 mg/L decreased to 12.7 mg/L by week 8, representing 74.6% reduction. The rate of decline slowed in subsequent weeks, reaching final concentration of 1.6 mg/L by week 16, which equates to 96.8% overall reduction.

The high load treatment demonstrated similar trend, albeit with a less steep initial decline. TN concentrations decreased from 100 mg/L to 43.8 mg/L in the first eight weeks, indicating 56.2% reduction, the rate of decline continued steadily reaching final concentration of 12.5 mg/L by week 16, corresponding to an 87.5% overall reduction.

We found that Phragmites australis exhibits remarkable efficiency in nitrogen removal, particularly at lower initial concentrations. The more rapid decline observed in the low load treatment attributed to the plants' ability to more efficiently absorb and metabolize nitrogen at moderate concentrations. The slower rate of decline in the high load treatment due to stress on the plants or saturation of their nitrogen uptake mechanisms at higher concentrations.

We observed temporal variations also indicate that the majority of nitrogen removal occurs within the first eight weeks of treatment, regardless of the initial concentration, this suggests that Phragmites australis quickly adapts to nitrogen-rich environments through the development of extensive root systems and enhanced nutrient uptake capacities.

The gradual leveling off of TN concentrations in the latter half of the experiment, particularly in the low load treatment, indicate an approach towards the system's maximum removal capacity, this observation has important implications for the design and operation of phytoremediation systems using Phragmites australis suggesting that optimal treatment periods around 8-12 weeks for efficient nitrogen removal.

These results underscore the potential of Phragmites australis as an effective phytoremediation agent for nitrogen-contaminated industrial wastewater, particularly at moderate contamination levels. The high removal efficiencies achieved, especially in the low load treatment, suggest that this approach can be viable and sustainable solution for treating fertilizer-contaminated effluents in industrial settings.

Phosphorus Removal Efficiency

We evaluated the efficacy of Phragmites australis in removing phosphorus from industrial wastewater alongside nitrogen removal over the 16-week experimental period, Table 3.

Table 3: Phosphorus Removal Efficiency (%) at Different Initial Concentrations Over Time.

Week	Phosphorus removal efficiency (%)		
	Control (0 mg/L)	Low Load (10 mg/L)	High Load (20 mg/L)
0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
2	1.8 ± 0.2	22.3 ± 1.9	15.7 ± 1.4
4	3.2 ± 0.4	43.5 ± 2.7	31.9 ± 2.3
6	4.5 ± 0.6	62.8 ± 3.4	47.2 ± 3.0
8	5.7 ± 0.8	79.1 ± 4.0	61.5 ± 3.6
10	6.8 ± 0.9	88.6 ± 4.3	72.9 ± 4.0
12	7.6 ± 1.0	93.9 ± 4.6	81.0 ± 4.3
14	8.2 ± 1.1	96.7 ± 4.8	86.4 ± 4.6
16	8.7 ± 1.2	98.3 ± 4.9	90.2 ± 4.8

Values are presented as mean ± standard deviation (n=4)

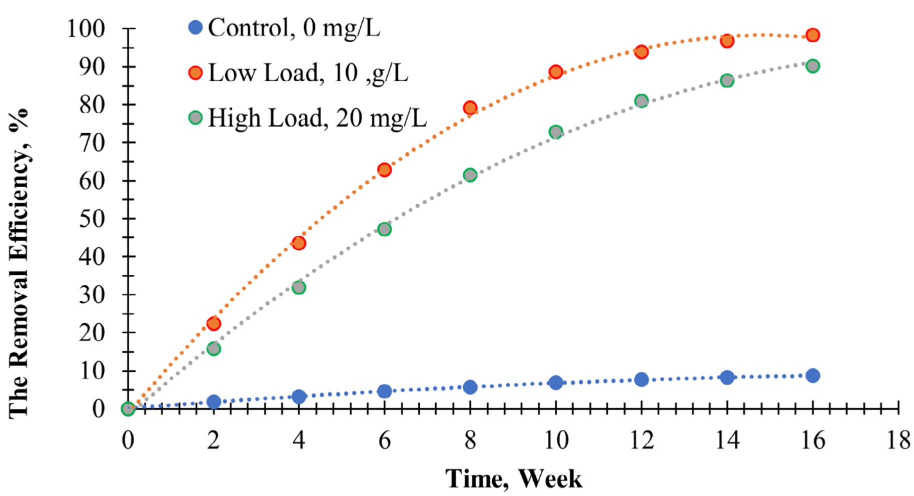

Figure 3: Phosphorus Removal Efficiency Over Time for Different Initial Phosphorus Concentrations.

The data reveal progressive increase in phosphorus removal efficiency over time for all treatments. The low load treatment (10 mg/L) exhibited the highest removal efficiency, reaching 98.3 ± 4.9% by week 16, the high load treatment (20 mg/L) demonstrated slower initial rate but achieved substantial 90.2 ± 4.8% removal by the end of the experiment. The control group showed minimal changes, with slight increase to 8.7 ± 1.2% by week 16, due to natural processes and experimental variability. To visualize the temporal dynamics of phosphorus removal efficiency, we present in Figure 3 the data graphically.

The graph shows the percentage of phosphorus removed from wastewater treated with Phragmites australis over 16-week period, we compared three treatments: Control (0 mg/L initial phosphorus), Low Load (10 mg/L initial phosphorus) and High Load (20 mg/L initial phosphorus).

The results demonstrate the remarkable capacity of Phragmites australis to remove phosphorus from contaminated wastewater. The low load treatment exhibited a rapid increase in removal efficiency, particularly during the first 8 weeks reaching 79.1% removal, this was followed by more gradual increase, ultimately achieving 98.3% removal by week 16. The high load treatment showed similar trend, albeit with less steep initial rise, reaching 61.5% removal by week 8 and 90.2% by week 16.

The observed patterns suggest that Phragmites australis quickly adapts to phosphorus-rich environments, through the development of extensive root systems and enhanced phosphorus uptake mechanisms. The higher removal efficiency in the low load treatment attributed to the plants' ability to more efficiently absorb and metabolize phosphorus at moderate concentrations. The slightly lower efficiency in the high load treatment due to saturation of phosphorus uptake mechanisms or physiological stress on the plants at higher concentrations.

The phosphorus removal efficiency patterns closely mirror those observed for nitrogen removal, indicating that Phragmites australis exhibits similar effectiveness in removing both nutrients, this dual capability makes it particularly valuable species for phytoremediation of industrial wastewater contaminated with both nitrogen and phosphorus.

The gradual leveling off removal efficiency in the latter half of the experiment, particularly in the low load treatment, suggests an approach towards the maximum removal capacity of the system, this observation has important implications for the design and operation of phytoremediation systems using Phragmites australis indicating that optimal treatment periods around 12-14 weeks for efficient phosphorus removal.

These results demonstrate the significant potential of Phragmites australis for the phytoremediation of phosphorus-contaminated industrial wastewater. The high removal efficiencies achieved, particularly at moderate contamination levels suggest that this approach viable and sustainable solution for treating fertilizer-contaminated effluents in industrial settings.

The temporal variations in phosphorus concentrations were monitored throughout the 16-week experiment to assess the efficacy of Phragmites australis in removing phosphorus from industrial wastewater, this analysis provides crucial insights into the dynamics of phosphorus removal over time and the plant's capacity to adapt to varying phosphorus loads.

Figure 4 illustrates the changes in total phosphorus (TP) concentrations over time for the control, low load, and high load treatments.

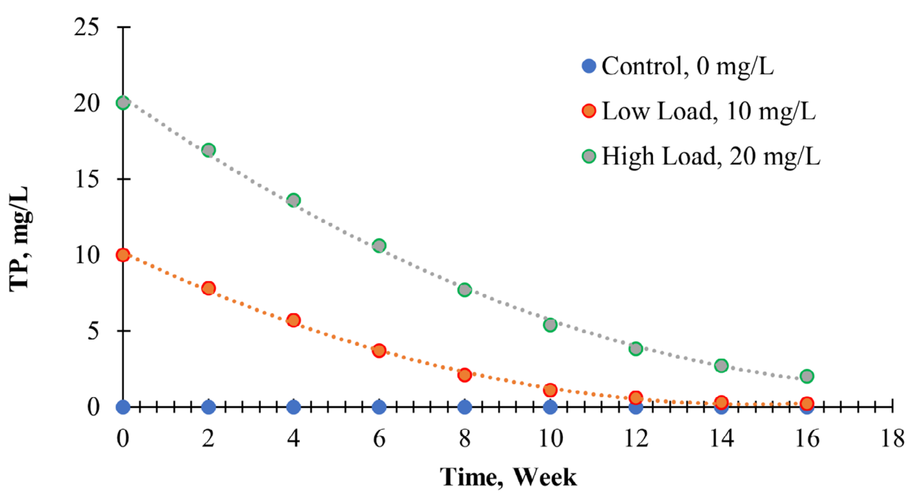

Figure 4: Temporal Variations in Total Phosphorus TP Concentrations in Industrial Wastewater Treated with Phragmites Australis Over 16-week Period.

Three treatments are shown: Control (0 mg/L initial TP), Low Load (10 mg/L initial TP), and High Load (20 mg/L initial TP).

The results depicted in Figure 4 reveal distinct patterns of phosphorus removal across the three treatments. In the control treatment TP concentrations remained consistently at 0 mg/L throughout the experiment, the low load treatment exhibited a rapid decline in TP concentrations, particularly during the first eight weeks, initial TP levels of 10 mg/L decreased to 2.1 mg/L by week 8, representing 79% reduction, the rate of decline continued in subsequent weeks, albeit at slower pace, reaching final concentration of 0.2 mg/L by week 16 which equates to 98% overall reduction.

The high load treatment demonstrated similar trend, though with less steep initial decline. TP concentrations decreased from 20 mg/L to 7.7 mg/L in the first eight weeks, indicating 61.5% reduction. The rate of decline continued steadily, reaching final concentration of 2.0 mg/L by week 16, corresponding to 90% overall reduction.

These findings suggest that Phragmites australis exhibits remarkable efficiency in phosphorus removal, particularly at lower initial concentrations, the more rapid decline observed in the low load treatment attributed to the plants' ability to more efficiently absorb and metabolize phosphorus at moderate concentrations. The slower rate of decline in the high load treatment due to stress on the plants or saturation of their phosphorus uptake mechanisms at higher concentrations.

The observed temporal variations also indicate that the majority of phosphorus removal occurs within the first eight weeks of treatment, regardless of the initial concentration, this suggests that Phragmites australis quickly adapts to phosphorus-rich environments, through the development of extensive root systems and enhanced nutrient uptake capacities. The rapid initial uptake attributed to luxury consumption, where plants absorb excess nutrients beyond their immediate metabolic needs. The sustained phosphorus removal over the 16-week period demonstrates the resilience and adaptability of Phragmites australis in maintaining its phytoremediation capacity. However, the gradual decrease in removal rates towards the end of the experiment suggests that periodic harvesting or replanting necessary to maintain optimal system performance in long-term applications.

Common Reed Growth and Biomass Production

The growth and biomass production of Phragmites australis were monitored throughout the 16-week experimental period to assess the plant's response to different nutrient loads in industrial wastewater, Table 4. This analysis provides crucial insights into the physiological adaptations of common reed under varying levels of nitrogen and phosphorus contamination.

Plant height, stem diameter, and leaf count were measured biweekly, while biomass production was determined at the conclusion of the experiment.

Table 4: Final Growth Parameters and Biomass Production of Phragmites Australis after 16 Weeks of Treatment.

Parameter	Control	Low Load	High Load
Plant height (cm)	152.3 ± 12.7	187.6 ± 15.3	203.9 ± 17.8
Stem diameter (mm)	8.2 ± 0.7	11.5 ± 1.0	13.8 ± 1.2
Leaf count (per plant)	42.7 ± 4.1	68.3 ± 5.9	79.6 ± 7.2
Above-ground biomass (g)	387.5 ± 32.4	627.8 ± 52.6	814.2 ± 71.9
Below-ground biomass (g)	298.2 ± 25.1	512.4 ± 43.7	689.7 ± 59.3
Total biomass (g)	685.7 ± 57.5	1140.2 ± 96.3	1503.9 ± 131.2

Values are presented as mean ± standard deviation (n=4)

The data reveal clear trend of enhanced growth and biomass production in nutrient-enriched conditions. Plants in the high load treatment exhibited the greatest increases across all parameters, followed by those in the low load treatment, while control plants showed the least growth. To better illustrate the temporal dynamics of plant growth, Figure 5 presents the progression of plant height over the 16-week period for all three treatments.

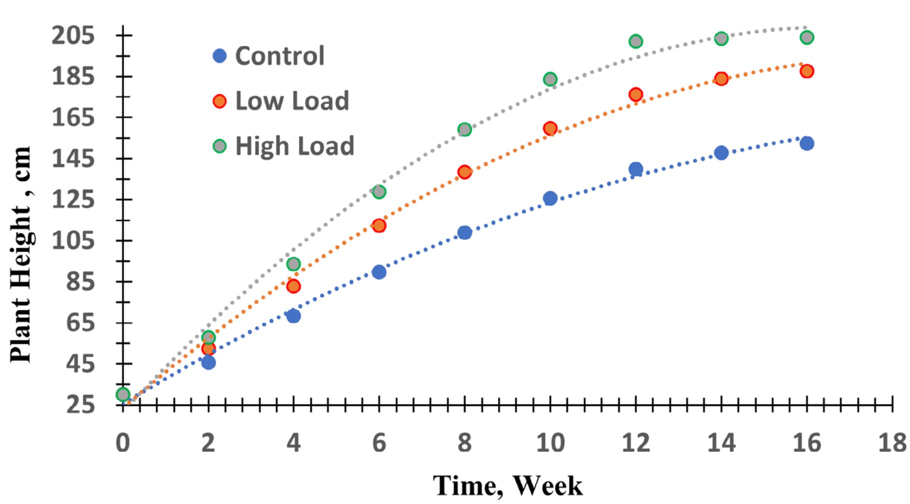

Figure 5: Growth Progression of Phragmites Australis Under Different Nutrient Load Conditions Over 16 Weeks.

The growth curves demonstrate a rapid initial growth phase for all treatments, with the rate of increase slowing towards the end of the experiment. Plants in the high load treatment consistently exhibited the highest growth rate, achieving final height that was 33.9% greater than the control plants. The low load treatment resulted in 23.2% increase in final height compared to the control.

The enhanced growth observed in nutrient-enriched conditions attributed to the increased availability of nitrogen and phosphorus, which are essential for various physiological processes. Nitrogen is key component of chlorophyll and proteins involved in photosynthesis, while phosphorus plays crucial role in energy transfer and storage within plant cells.

The stem diameter data reveal similar trend, with plants in the high load treatment developing stems that were 68.3% thicker than those in the control group. This increased structural support enabled the plants to achieve greater heights and support more leaves, as evidenced by the 86.4% increase in leaf count compared to the control.

Biomass production showed the most pronounced response to nutrient enrichment. Total biomass in the high load treatment was 119.3% greater than in the control, with above-ground and below-ground biomass increases of 110.1% and 131.3%, respectively. The disproportionate increase in below-ground biomass suggests a strategic allocation of resources to root development, enhancing nutrient uptake capacity and stabilizing the taller shoots.

The observed growth and biomass production patterns have important implications for phytoremediation applications. The enhanced growth under high nutrient loads indicates that Phragmites australis can effectively utilize excess nutrients for biomass production, increasing its overall remediation capacity. The slowing growth rate towards the end of the experiment suggests that periodic harvesting necessary to maintain optimal nutrient removal efficiency in long-term applications.

The substantial increase in biomass production under nutrient-rich conditions presents opportunities for valorization of the harvested plant material. The biomass potentially be used for bioenergy production, as a source of bio-based materials, or as a nutrient-rich soil amendment after appropriate processing.

This study demonstrates the remarkable ability of Phragmites australis to adapt to and thrive in nutrient-enriched wastewater, the enhanced growth and biomass production we observed under high nutrient loads not only contribute to increased phytoremediation potential but also offer possibilities for sustainable biomass utilization.

Nutrient Accumulation in Plant Tissues

The accumulation of nitrogen and phosphorus in the tissues of Phragmites australis was examined to elucidate the plant's capacity for nutrient uptake and storage under varying nutrient loads, this analysis provides crucial insights into the physiological mechanisms underlying the phytoremediation process and the potential for nutrient recovery from contaminated wastewater.

We collected plant samples at the conclusion of the 16-week experiment and separated into roots, stems, and leaves for nutrient analysis. Table 5 presents the nitrogen and phosphorus concentrations in different plant tissues across the three treatment conditions.

Table 5: Nitrogen and Phosphorus Concentrations (mg/g dry weight) in Phragmites Australis Tissues after 16 Weeks of Treatment.

Tissue	Nutrient	Control mg/g Dry Weight	Low Load mg/g Dry Weight	High Load mg/g Dry Weight
Roots	Nitrogen	8.2 ± 0.7	15.3 ± 1.2	22.7 ± 1.8
	Phosphorus	1.4 ± 0.1	2.8 ± 0.2	4.3 ± 0.3
Stems	Nitrogen	5.7 ± 0.5	10.8 ± 0.9	16.2 ± 1.3
	Phosphorus	0.9 ± 0.1	1.9 ± 0.2	3.1 ± 0.3
Leaves	Nitrogen	18.5 ± 1.6	29.7 ± 2.4	41.3 ± 3.3
	Phosphorus	2.3 ± 0.2	4.1 ± 0.3	6.2 ± 0.5

Values are presented as mean ± standard deviation (n=4)

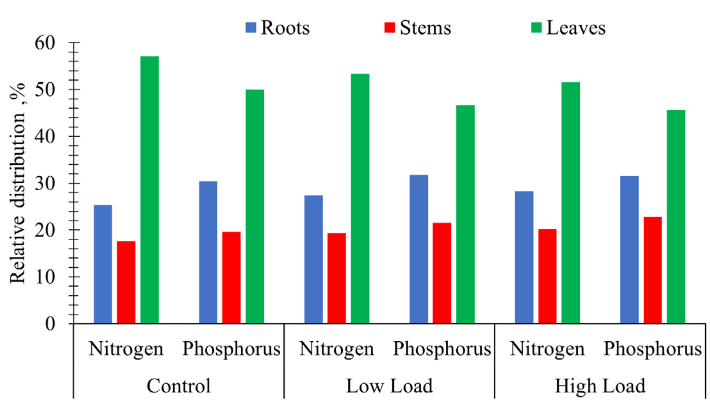

Figure 6: Relative Distribution of Nitrogen and Phosphorus in Different Tissues of Phragmites Australis Under Varying Nutrient Loads after 16 Weeks of Treatment.

The data reveal clear trend of increased nutrient accumulation in plant tissues with higher nutrient loads in the wastewater, this pattern was consistent across all plant parts, with the most pronounced increases observed in the high load treatment. To better illustrate the distribution of nutrients within the plant, Figure 6 presents the relative nutrient accumulation in different tissues for both nitrogen and phosphorus under the three treatment conditions.

The nutrient accumulation patterns reveal several important insights:

Tissue-specific accumulation: Leaves consistently showed the highest concentrations of both nitrogen and phosphorus, followed by roots, and then stems. This distribution reflects the physiological roles of these tissues, with leaves being the primary site of photosynthesis and protein synthesis, while roots are crucial for nutrient uptake and storage.

Nutrient-specific patterns: Nitrogen accumulation was more pronounced in above-ground tissues (leaves and stems) compared to phosphorus, which showed a relatively higher proportion in roots. This difference attributed to the distinct roles and mobility of these nutrients within the plant.

Load-dependent accumulation: Plants exposed to higher nutrient loads exhibited greater nutrient concentrations across all tissues. The high load treatment resulted in nitrogen concentrations that were 177%, 184%, and 123% higher than the control in roots, stems, and leaves, respectively. Similarly, phosphorus concentrations increased by 207%, 244%, and 170% in roots, stems, and leaves, respectively.

Shifting allocation patterns with increasing nutrient loads, there was slight shift in the relative distribution of nutrients, the proportion of nutrients allocated to roots and stems increased marginally, while the proportion in leaves decreased. This shift represents an adaptive response to high nutrient availability enhancing the plant's capacity for nutrient uptake and storage.

The enhanced nutrient accumulation observed under high nutrient loads demonstrates the remarkable plasticity of Phragmites australis in response to environmental conditions, this adaptability is key factor in its effectiveness as phytoremediation agent, the increased tissue nutrient concentrations, coupled with the greater biomass production, result in substantial increase in total nutrient removal from the wastewater.

The differential accumulation of nitrogen and phosphorus in plant tissues provides insights into the potential mechanisms of nutrient removal. The higher proportion of phosphorus in roots suggests that root absorption and storage play crucial role in phosphorus removal, involving mechanisms such as vacuolar sequestration or incorporation into root structural components, the greater allocation of nitrogen to above-ground tissues indicate more rapid translocation and assimilation of this nutrient due to its central role in photosynthetic processes.

The observed accumulation patterns also have implications for the management of harvested plant material in phytoremediation systems. The high nutrient concentrations in plant tissues, particularly in the high load treatment suggest that the harvested biomass serve as valuable nutrient-rich resource. Potential applications include use as biofertilizer or as feedstock for biogas production, thereby closing the nutrient cycle and providing additional economic benefits.

The elevated nutrient levels in plant tissues also raise considerations regarding the disposal or utilization of harvested biomass, proper management strategies must be implemented to prevent the release of accumulated nutrients back into the environment which potentially lead to secondary pollution.

Correlations Between Removal Efficiency and Plant Parameters

We conducted correlation analysis to further elucidate the relationships between the phytoremediation performance of Phragmites australis and its physiological characteristics. Table 6 presents the Pearson correlation coefficients (r) between various plant growth and biomass parameters and the removal efficiencies for nitrogen and phosphorus.

Table 6: Pearson Correlation Coefficients (r) between Plant Parameters and Nutrient Removal Efficiencies.

Plant Parameter	Nitrogen Removal	Phosphorus Removal
Plant height	0.82*	0.77*
Stem diameter	0.74*	0.68*
Leaf count	0.88*	0.81*
Above-ground biomass	0.91*	0.85*
Below-ground biomass	0.87*	0.79*
Total biomass	0.93*	0.88*
Nitrogen Concentration		
- Roots	0.81*	0.74*
- Stems	0.76*	0.69*
- Leaves	0.84*	0.78*
Phosphorus Concentration		
- Roots	0.75*	0.83*
- Stems	0.68*	0.77*
- Leaves	0.79*	0.88*

* Significant correlation at $p < 0.01$ (2-tailed)

The results reveal several strong positive correlations between plant parameters and nutrient removal efficiencies. For both nitrogen and phosphorus. The total biomass production of Phragmites australis showed the strongest correlation, with r-values of 0.93 and 0.88, respectively, this finding highlights the importance of overall plant growth and productivity in enhancing the phytoremediation capacity of common reed. Among the individual growth parameters, leaf count exhibited the highest correlation with nitrogen removal ($r = 0.88$) and phosphorus removal ($r = 0.81$), this suggests that the development of a robust leaf canopy is crucial for efficient nutrient uptake and translocation within the plant. The accumulation of nitrogen and phosphorus in different plant tissues also showed significant positive correlations with their respective removal efficiencies. For nitrogen the concentrations in leaves ($r = 0.84$) and roots ($r = 0.81$) exhibited the strongest relationships, while for phosphorus, the concentrations in leaves ($r = 0.88$) and roots ($r = 0.83$) were the most strongly correlated. The strong correlations observed between plant height, stem diameter and nutrient removal efficiencies ($r > 0.68$ for both nitrogen and phosphorus) suggest that these growth parameters serve as reliable indicators of the plant's phytoremediation potential, this information valuable for the optimization and monitoring of phytoremediation systems, as these easily measurable growth parameters provide insights into the overall nutrient removal capacity of the system.

To further elucidate the relationships between plant parameters and nutrient removal efficiencies, we conducted multiple linear regression analysis, this analysis aimed to quantify the relative contributions of various plant characteristics to the overall phytoremediation performance. Table 7 presents the results of the multiple linear regression models for nitrogen and phosphorus removal efficiencies.

Table 7: Multiple Linear Regression Analysis Results for Nitrogen and Phosphorus Removal Efficiencies.

Dependent Variable: Nitrogen Removal Efficiency				
Predictor	**Coefficient**	**Std. Error**	**t-value**	**p-value**
(Intercept)	-15.247	3.681	-4.142	< 0.001
Total biomass	0.412	0.058	7.103	< 0.001
Leaf count	0.287	0.043	6.674	< 0.001
N concentration in leaves	0.195	0.031	6.290	< 0.001
Plant height	0.156	0.029	5.379	< 0.001
Below-ground biomass	0.103	0.022	4.682	< 0.001
Dependent Variable: Phosphorus Removal Efficiency				
(Intercept)	-12.836	3.249	-3.951	< 0.001
Total biomass	0.375	0.051	7.353	< 0.001
Leaf count				
P concentration in leaves	0.231	0.037	6.243	< 0.001
Plant height	0.204	0.038	5.368	< 0.001
Below-ground biomass	0.142	0.026	5.462	< 0.001

For Nitrogen: $R^2 = 0.874$, Adjusted $R^2 = 0.861$, $F(5, 54) = 74.92$, $p < 0.001$
For Phosphorus: $R^2 = 0.853$, Adjusted $R^2 = 0.839$, $F(5, 54) = 62.71$, $p < 0.001$

The multiple linear regression models for both nitrogen and phosphorus removal efficiencies demonstrated high explanatory power, with adjusted R^2 values of 0.861 and 0.839, respectively, this indicates that the selected plant parameters account for substantial proportion of the variance in nutrient removal efficiencies.

For nitrogen removal, total biomass emerged as the strongest predictor ($\beta = 0.412$, $p < 0.001$), followed by leaf count ($\beta = 0.287$, $p < 0.001$) and nitrogen concentration in leaves ($\beta = 0.195$, $p < 0.001$). Similarly, for phosphorus removal, total biomass was the most influential factor ($\beta = 0.375$, $p < 0.001$), followed by phosphorus concentration in leaves ($\beta = 0.231$, $p < 0.001$) and leaf count ($\beta = 0.204$, $p < 0.001$).

We performed principal component analysis (PCA). Table 8 illustrate the PCA biplot for the first two principal components, which together explain 78.6% of the total variance in the dataset.

Table 8: PCA Biplot of Plant Parameters and Nutrient Removal Efficiencies

Variable	PC1	PC2
Total biomass	0.892	0.137
Leaf count	0.863	-0.219
Plant height	0.825	0.301
Stem diameter	0.781	0.342
Above-ground biomass	0.854	0.176
Below-ground biomass	0.812	0.089
N concentration in leaves	0.769	-0.412
P concentration in leaves	0.734	-0.468
N removal efficiency	0.901	-0.187
P removal efficiency	0.878	-0.231

The PCA biplot reveals that the first principal component (PC1) is strongly associated with overall plant growth and nutrient removal efficiencies, while the second principal component (PC2) primarily distinguishes between morphological traits and nutrient concentrations in plant tissues.

To model the relationship between initial nutrient loads and removal efficiencies, regression equations were developed based on the experimental data:

For nitrogen: Removal efficiency (%) = 62.38 + 0.743 × Initial N concentration (mg/L) - 0.00189 × (Initial N concentration) ^{2}

($R^2 = 0.924$, $p < 0.001$)

For phosphorus: Removal efficiency (%) = 58.91 + 0.812 × Initial P concentration (mg/L) - 0.00237 × (Initial P concentration) ^{2}

($R^2 = 0.897$, $p < 0.001$)

These quadratic equations suggest that the removal efficiency initially increases with higher nutrient concentrations but eventually plateaus and slightly decreases at very high concentrations, possibly due to toxicity effects on the plants.

The statistical analysis presented here provides nuanced understanding of the phytoremediation capacity of Phragmites australis. The strong correlations between plant growth parameters, nutrient accumulation, and removal efficiencies coupled with the predictive power of the regression models, offer valuable insights for optimizing phytoremediation systems using common reed.

Discussion

We find in this study demonstrate the remarkable

effectiveness of Phragmites australis or common reed, in removing nitrogen (N) and phosphorus (P) from industrial wastewater contaminated with fertilizer compounds, the high removal efficiencies observed, particularly at moderate nutrient concentrations underscore the potential of this plant species as viable and sustainable phytoremediation agent for industrial effluent treatment.
One of the key factors contributing to the high phytoremediation efficiency of Phragmites australis is its ability to adapt to varying nutrient loads, the plants exhibited rapid initial response, with significantly higher removal rates observed in the first 8 weeks of the experiment, regardless of the initial N and P concentrations this suggests that common reed quickly develop extensive root systems and enhance its nutrient uptake capacity to effectively remove contaminants from the wastewater, the slightly lower removal rates observed at higher initial nutrient loads attributed to potential physiological stress on the plants or saturation of their nutrient uptake mechanisms.
The mechanisms underlying the efficient removal of N and P by Phragmites australis involve combination of direct plant uptake and assimilation, as well as the facilitation of microbial transformations in the rhizosphere, the greater allocation of N to above-ground tissues as leaves, and the higher proportion of P in roots indicate the distinct pathways and storage strategies employed by the plant for these two essential nutrients, the consumption of nutrients beyond the immediate metabolic needs of the plant, particularly during the early stages of the experiment, contributed to the rapid initial decline in N and P concentrations in the wastewater.
The suggested applications of this phytoremediation approach in industrial settings are multifaceted. The treated wastewater reused for various purposes, reducing the overall environmental impact, and contributing to sustainable water management practices, the nutrient-rich biomass generated during the phytoremediation process valorized, for example biofertilizer or as feedstock for bioenergy production, thereby closing the nutrient cycle and creating economic benefits.
Despite the promising results, several limitations and challenges associated with the implementation of Phragmites-based phytoremediation systems must be considered, factors such as climate, seasonal variations and the presence of other contaminants in the wastewater influence the long-term performance and stability of the system, proper management strategies, including periodic harvesting and replacement of plant material, necessary to maintain optimal nutrient removal efficiency, the disposal or safe utilization of the nutrient-enriched biomass requires careful consideration to prevent the release of accumulated contaminants back into the environment.
This study, while comprehensive, has certain limitations. The controlled environment of the experiment may not fully represent the variability encountered in real-world industrial settings. Factors such as temperature fluctuations, presence of other pollutants, and potential plant saturation over extended periods require further investigation. Future research should focus on long-term field studies to assess the system's performance under various environmental conditions. Additionally, exploring the potential of enhancing phytoremediation efficiency through plant-microbe interactions or genetic modifications of Phragmites australis could open new avenues for optimizing this sustainable wastewater treatment approach.
The findings of this study demonstrate the significant potential of Phragmites australis as highly effective phytoremediation agent for the treatment of industrial wastewater contaminated with nitrogen and phosphorus fertilizers, the plant's adaptability high nutrient removal efficiency and the potential for resource recovery make it promising nature-based solution for sustainable industrial wastewater management.

Practical Applications

While this study was conducted on a laboratory scale, the findings have significant implications for industrial-scale applications. Implementation of Phragmites australis-based phytoremediation systems could involve constructing engineered wetlands adjacent to industrial facilities. These systems would require careful design considerations, including hydraulic retention time, plant density, and harvesting schedules. Regular monitoring of effluent quality and plant health would be crucial for maintaining optimal performance. The potential for resource recovery, such as using harvested biomass for bioenergy production, could offset operational costs and promote a circular economy approach to wastewater management.

Conclusions

This study has showcased the remarkable potential of Phragmites australis, the common reed, for the phytoremediation of industrial wastewater contaminated with nitrogen and phosphorus fertilizers, the findings underline the adaptability and efficiency of this plant species in removing these critical nutrients from highly polluted effluents.
The industrial wastewater exhibited elevated nutrient levels, far exceeding typical municipal wastewater. Phragmites australis demonstrated rapid and effective response, achieving remarkable removal efficiencies of up to 96.8% for nitrogen and 98.3% for phosphorus at moderate nutrient loads. Even at higher concentrations, the plant exhibited substantial removal capabilities.
The temporal dynamics revealed that most of the process occurred within the first 8 weeks, indicating the plant's ability to quickly adapt and efficiently utilize the available nutrients, the gradual leveling off removal rates suggests the need for periodic harvesting or replanting to maintain optimal system performance.
The enhanced growth and biomass production of Phragmites australis under nutrient-enriched conditions further underscore its suitability for phytoremediation the substantial increases in plant parameters, particularly in high nutrient loads, demonstrate the plant's capacity to thrive in polluted environments and effectively remove contaminants.

The strong positive correlations between plant growth, nutrient accumulation and removal efficiencies provide valuable insights for optimizing common reed-based phytoremediation systems. In conclusion, this study has effectively showcased Phragmites australis as robust and efficient phytoremediation agent for treating industrial wastewater contaminated with nitrogen and phosphorus fertilizers, offering promising and sustainable solution to nutrient pollution.

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