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Performance analysis and spatial modeling for the use of *Eichhornia crassipes* in tertiary phosphorus removal from swine slaughterhouse effluents

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ABSTRACT

Eutrophication caused by phosphorus-rich agro-industrial effluents poses a major environmental and regulatory challenge, particularly in areas with limited wastewater treatment infrastructure. This study provides one of the first technical and environmental feasibility assessments of using *Eichhornia crassipes* as a complementary tertiary stage in swine slaughterhouse wastewater treatment plants. Based on operational data from a functioning treatment plant and an estimated phosphorus uptake rate of 0.000374 kg TP m^{-2} d^{-1}, a performance analysis was conducted to evaluate phosphorus removal efficiency and compliance with discharge standards. Spatial modeling projected the surface area required to remove up to 7.08 kg TP d^{-1}, identifying an operational equilibrium at 6.02 kg d^{-1}. At this point, a biomass density of 10 kg m^{-2} would ensure compliance with commonly referenced discharge standards (5 mg L^{-1}), requiring approximately 16,000 m^2. Scenarios involving spatial constraints and biomass reduction were assessed, along with potential mitigation strategies. A SWOT analysis was also conducted, addressing operational, environmental, and governance-related factors. The findings suggest that *E. crassipes* may serve as a viable complementary option with potential for cost efficiency in agro-industrial settings with available space, provided that appropriate harvesting, oxygenation, and monitoring practices are implemented, and pending confirmation through pilot-scale validation under site-specific conditions.

Keywords: *Eichhornia crassipes*, performance analysis, phosphorus removal, phytoremediation, swine slaughterhouse effluents.

Análise de desempenho e modelagem espacial para o uso de *Eichhornia crassipes* na remoção terciária de fósforo de efluentes de abatedouros suínos

RESUMO

A eutrofização causada por efluentes agroindustriais ricos em fósforo representa um desafio ambiental e regulatório significativo, especialmente em regiões com infraestrutura de tratamento de águas residuárias limitada. Este estudo apresenta uma das primeiras avaliações de viabilidade técnica e ambiental do uso de *Eichhornia crassipes* como etapa terciária complementar em estações de tratamento de efluentes de abatedouros suínos. Com base em dados operacionais de uma planta em funcionamento e em uma taxa estimada de absorção de fósforo de 0,000374 kg TP m^{-2} d^{-1}, foi realizada uma análise de desempenho para avaliar a eficiência de remoção de fósforo e o cumprimento dos padrões de descarte. A modelagem espacial projetou a área superficial necessária para remover até 7,08 kg TP d^{-1}, identificando um ponto de equilíbrio operacional em 6,02 kg d^{-1}. Nesse ponto, uma densidade de biomassa de 10 kg m^{-2} garantiria conformidade com padrões de descarga frequentemente adotados (5 mg L^{-1}), requerendo aproximadamente 16.000 m². Foram avaliados cenários envolvendo restrições de espaço e redução de biomassa, juntamente com potenciais estratégias de mitigação. Também foi realizada uma análise SWOT, abordando fatores operacionais, ambientais e de governança. Os resultados indicam que E. crassipes pode servir como uma opção complementar viável, com potencial de eficiência de custos em contextos agroindustriais com disponibilidade de espaço, desde que sejam implementadas práticas adequadas de colheita, oxigenação e monitoramento, e mediante confirmação em validações em escala piloto sob condições controladas.

Palavras-chave: análise de desempenho, efluentes de abatedouro suíno, *Eichhornia crassipes*, fitorremediação, remoção de fósforo.

1. INTRODUCTION

The swine industry, an essential component of the agri-food sector, faces the challenge of managing waste rich in nutrients such as nitrogen and phosphorus, which can become significant pollutants if not properly treated. Only 20–40% of dietary nitrogen is retained by the animal; the remainder is excreted primarily through feces and urine (Son and Kim, 2024). In the case of phosphorus, its low bioavailability in the form of phytate and dietary excesses lead to the excretion of up to 64%, generating a substantial environmental burden (Agudelo Trujillo *et al.*, 2010). It is estimated that a boar can excrete up to 18 kg of nitrogen per year, and an adult pig may eliminate approximately 70% of the phosphorus ingested (Petersen, 2018). In many regions, effluents from pig production and slaughterhouses have been associated with high nutrient loads in nearby water bodies, sometimes exceeding drinking water standards by up to tenfold (Tymczyna *et al.*, 2000; Kupkanchanakul *et al.*, 2011).

Although conventional treatment systems such as activated sludge or anaerobic reactors have proven effective in removing ammoniacal nitrogen, they often fail to efficiently remove phosphorus, which remains in soluble form—primarily as orthophosphate (Carrillo *et al.*, 2024). This element, even at low concentrations, acts as a limiting nutrient and is one of the main drivers of eutrophication in aquatic ecosystems, triggering algal blooms, dissolved oxygen depletion, and alterations in aquatic biota (Zhang *et al.*, 2010). While there is no uniform international regulation for nitrogen and phosphorus in agricultural effluents, organizations such as the European Union have proposed strategies to mitigate their impact. In Europe, Directive 91/676/EEC (CCE, 1991) has played a key role, although it has been criticized for being insufficient to adequately control phosphorus balance in pig and poultry operations (Arata *et al.*, 2022). In the United States, the Environmental Protection Agency (USEPA, 1976) considers phosphorus concentrations above 1.0 mg/L (monthly average) to be environmentally harmful. In Mexico, the NOM-001-SEMARNAT-2021 sets maximum permissible limits of 10 mg/L for total nitrogen and 5 mg/L for total phosphorus in wastewater discharged into receiving water bodies (SEMARNAT, 2022).

Nature-based technologies using floating aquatic plants have attracted attention as low-cost and sustainable options for nutrient removal (Cui *et al.*, 2018; Hendriks *et al.*, 2023; Yang *et al.*, 2024). Among the available plant species, *Eichhornia crassipes* stands out due to its high nutrient removal efficiency and adaptability to tropical climates. The literature reports phosphorus removal rates ranging from 50 to 542 mg P m^{-2} d^{-1}, with removal efficiencies between 36% and 90%, depending on environmental conditions (Reddy *et al.*, 1990; Tripathi *et al.*, 1991; Zakova *et al.*, 1994). In tropical environments, rates up to 374 mg P m^{-2} d^{-1} have been reported, with efficiencies close to 97% (Petrucio and Esteves, 2000).

Despite this potential, little research has assessed the operational feasibility of *E. crassipes* for tertiary phosphorus removal in the specific context of swine slaughterhouse effluents. This study provides one of the first technical-environmental feasibility analyses of this approach, combining operational data from a functioning wastewater treatment plant with a performance analysis of nutrient removal and spatial modeling of surface area requirements. We also integrate a SWOT analysis to examine technical, environmental, and governance-related implications.

2. MATERIAL AND METHODS

2.1. Description of the wastewater treatment plant

The wastewater treatment plant (WWTP) of the swine slaughterhouse under study receives the effluents generated from the slaughtering and processing of approximately 54,000 pigs per month. The wastewater is initially collected in an on-site pit that concentrates effluents from all productive activities. From there, it is pumped into a WWTP comprising three main stages: pretreatment, biological treatment, and post-treatment (Figure 1).

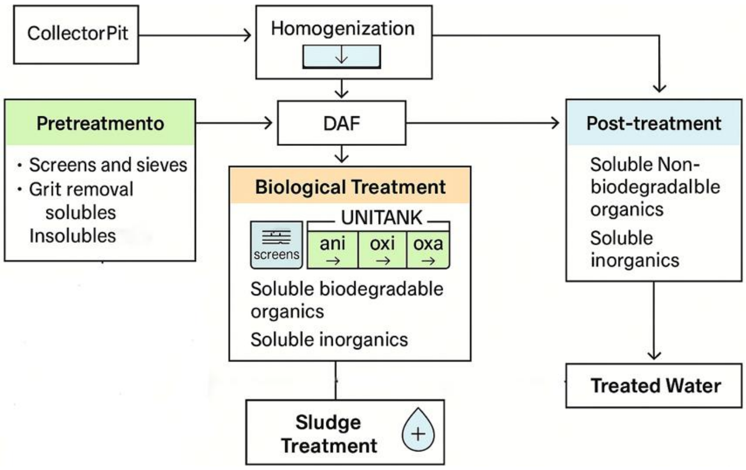

Figure 1. Flowchart of physical, chemical, and biological wastewater treatment stages in an integrated system with dissolved air flotation (DAF) and a UNITANK activated sludge reactor.

The pretreatment phase includes flow homogenization, screening, and sand removal to eliminate coarse solids, followed by an equalization tank to stabilize hydraulic and pollutant loads. A dissolved air flotation (DAF) unit is then used to remove fine suspended solids, fats, and nutrients such as nitrogen and phosphorus. The biological treatment is performed in a UNITANK reactor that integrates anoxic (ani), aerobic (oxi), and oxic (oxa) compartments in sequence, promoting the degradation of biodegradable organic matter and the transformation of nitrogen compounds. Excess biomass is separated by sedimentation, and the resulting sludge is thickened, dewatered, and dried in sludge beds. Final disinfection is carried out through chlorination to reduce microbial load before discharge or reuse.

2.2. Validation of physicochemical and biological treatment performance

To assess the operational behavior of the system, water quality data were collected over 23 consecutive weeks. The monitoring included physicochemical parameters measured before and after each treatment stage, allowing the identification of high-efficiency zones and potential critical points. The evaluated compartments were: (1) equalization tank, (2) DAF outlet, (3) anaerobic compartment, (4) anoxic compartment, (5) aerobic compartments, and (6) final effluent. Compliance was assessed based on the limits established by NOM-001-SEMARNAT-2021.

Monitoring was conducted on a weekly basis during 23 consecutive weeks from March 3 to August 15, 2023. Composite samples were collected at the six operational points described above (equalization tank, DAF outlet, anaerobic, anoxic, aerobic, and final effluent). Each measurement was performed in duplicate with field blanks and quality controls.

The monitoring period of 23 consecutive weeks (March–August 2023) covered more than five months, which in tropical regions corresponds to relatively stable operational conditions (27–32°C; SEMARNAT, 2022; Hendriks *et al.*, 2023).

2.3. Quantification of physicochemical water quality parameters

Physicochemical parameters were determined following the protocols established in the Standard Methods for the Examination of Water and Wastewater (APHA *et al.*, 2023). The analytical techniques applied included the following: Chemical Oxygen Demand (COD) was determined using the closed reflux dichromate method (Method 5220 D). Samples were digested in acidic medium with potassium dichromate and silver sulfate, followed by spectrophotometric measurement at 600 nm.; (2) Biochemical Oxygen Demand (BOD_5) was measured according to Method 5210 B, based on the reduction in dissolved oxygen after a 5-day incubation period at 20°C in the absence of light; (3) Total Suspended Solids (TSS) were analyzed using Method 2540 D, by filtration through glass fiber crucibles, drying at 103–105 °C, and gravimetric quantification; (4) Total Nitrogen (TN) was quantified via the modified Kjeldahl method (4500-Norg B and C), which includes acid digestion with sulfuric acid and a catalyst, followed by distillation and titration; (5) Nitrate Nitrogen (NO_3^--N) was determined using the cadmium reduction colorimetric method (4500-NO_3^- E), with absorbance measured at 220 or 275 nm depending on matrix composition; (6) Nitrite Nitrogen (NO_2^--N) was measured through the diazotization method (4500-NO_2^- B), where nitrite reacts with sulfanilamide and NED to form an azo dye quantified at 543 nm.; (7) Total Phosphorus (TP) was analyzed using Method 4500-P E, involving persulfate digestion and subsequent colorimetric determination of the phosphomolybdenum blue complex at 880 nm. All analyses were performed in duplicate using blanks, certified reference materials, and quality control standards. Instruments were calibrated in accordance with accredited laboratory procedures to ensure traceability and analytical precision.

2.4. Acclimation of *Eichhornia crassipes* in the STPAF

Two ponds measuring 45 m in length, 25 m in width, and 2 m in depth (2,250 m³ each) were used to acclimate *E. crassipes*. In each pond, water hyacinths were planted at a density of 10 kg/m², covering approximately three-quarters of the surface area. To regulate flow, 6-inch gate valves were installed and periodically inspected to ensure proper operation and prevent clogging. Every three weeks, when the hyacinths reached approximately 60 cm in height, they were partially harvested to avoid excessive biomass accumulation. This practice ensured proper hydraulic flow through the wetland system, preventing stagnation, and maintaining a hydraulic retention time of approximately one day.

2.5. Estimation of phosphorus load and required surface area for *Eichhornia crassipes*

Based on operational flow ($m^3\ d^{-1}$) and phosphorus concentration data ($mg\ L^{-1}$), the daily phosphorus load (TP) was calculated using the formula (Equation 1):

$$\text{TP Load (kg } d^{-1}) = \text{Flow } (\text{m}^3\ \text{d}^{-1}) \times \text{Concentration } (\text{mg L}^{-1}) \times 10^{-3} \quad (1)$$

According to values reported by Petrucio and Esteves (2000), an average phosphorus uptake rate of 0.000374 kg TP m^{-2} d^{-1} was adopted for *E. crassipes*, which is representative of tropical conditions. The required surface area of macrophytes was estimated as (Equation 2):

$$\text{Required Surface Area } (m^2) = \text{TP Load } (kg\ d^{-1}) / 0.000374 \quad (2)$$

To account for uncertainty, a sensitivity analysis was performed by adjusting the uptake rate ±50% (0.000187–0.000561 kg TP m^{-2} d^{-1}). For the equilibrium load of 6.02 kg TP d^{-1}, the required area ranged between 10,700 m^2 and 32,200 m^2, with the nominal estimate at ~16,100 m^2. This highlights the importance of site-specific validation under swine slaughterhouse effluent conditions since the high organic content and colloidal load may influence the effective uptake rate. The hydraulic retention time (HRT) of the proposed ponds was calculated as (Equation 3):

$$\text{HRT (d)} = (\text{Area} \times \text{depth}) / \text{Flow} \quad (3)$$

Where depth was assumed at 1.0 m, consistent with acclimation ponds described in Section 2.4. This value allows direct comparison of surface area requirements with hydraulic conditions.

Different load scenarios were modeled, projecting 10%, 20%, and 30% increases in slaughter volume, to estimate the impact on surface area requirements to comply with NOM-001-SEMARNAT-2021.

2.6. SWOT analysis

To assess operational feasibility, a SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats) was conducted regarding the implementation of *E. crassipes* as a tertiary treatment. The analysis considered technical, economic, and environmental aspects and was structured as a strategic decision-making tool for agro-industrial contexts seeking sustainable solutions for nutrient management.

3. RESULTS AND DISCUSSION

3.1. Performance of the STPAF system under operational conditions

Over a 23-week monitoring period, the STPAF system demonstrated stable performance in treating swine wastewater under real operational conditions. The average flow was 392.9 ± 20.8 m^3 d^{-1}, and Table 1 summarizes the physicochemical and biological parameters across each treatment stage. The system achieved a marked reduction in organic load, with COD decreasing from 3,874 ± 1,711 to 54.6 ± 26.3 mg/L, and BOD_5 from 1,814 ± 769 to 22.8 ± 11.9 mg L^{-1}, complying with the discharge limit of 30 mg L^{-1} set by NOM-001-SEMARNAT-2021. This performance reflects effective integration of the anaerobic, anoxic, and aerobic chambers in the UNITANK reactor, which enabled sequential degradation of biodegradable and partially recalcitrant organic matter.

TSS decreased after DAF treatment but increased in the biological compartments due to biomass accumulation, with final effluent levels of 15.3 ± 5.4 mg L^{-1}. Correspondingly, VSS progressively increased through the biological units, indicating healthy microbial growth. Settleable solids dropped sharply from 159 to 1 mL L^{-1}·h, confirming efficient clarification.

In terms of nutrient removal, total nitrogen was reduced from 143.2 to 10.6 ± 2.2 mg L^{-1}, remaining below the 15 mg L^{-1} regulatory limits. The presence of NO_3^- (11.5 ± 8.1 mg L^{-1}) and low concentrations of NO_2^- in the final effluent confirm effective nitrification. However, the persistence of residual nitrate suggests incomplete denitrification, potentially caused by limited anoxic retention time or insufficient availability of readily biodegradable carbon sources. Improving the carbon-to-nitrogen ratio and increasing contact time under anoxic conditions, as proposed by Vassiljev (2006), could enhance denitrification efficiency. Despite this limitation, nitrogen removal remained within permissible bounds.

Table 1. Mean values of physicochemical and biological parameters monitored over 23 weeks in the different stages of wastewater treatment.

Water parameters	Equalization Tank	DAF Outlet	Anaerobic Chamber	Anoxic Chamber	Aerobic Chamber 1	Aerobic Chamber 2	Final Effluent
pH	7.1 ±0.2	7.1 ±0.2	7.5 ±0.2	7.6 ±0.2	7.2 ±0.0	7.3 ±0.0	7.3 ±0.3
T (°C)	29.3 ±1.9	29.0 ±3.2	29.5 ±2.2	30.7 ±2.4	32.5 ±0.2	32.3 ±0.3	29.0 ±3.3
COD (mg L^{-1})	3874 ±1711	2138 ±1196				54.6 ±26.3	
BOD_5 (mg L^{-1})	1814 ±769	1312 ±631.6				22.8 ±11.9	
TSS (mg L^{-1})	1688 ±454	761.8 ±742.3	3858 ±995	4287 ±1117	4203 ±486.4	4238 ±502.5	15.3 ±5.4
VSS (mg L^{-1})	1035 ±152	1035 ±152	3262 ±780	3418 ±467	3560 ±348	3624 ±311	
TN (mg L^{-1})	143.2 ±61.5	103.2 ±52.3				10.6 ±2.2	
NO_3^--N (mg L^{-1})				0.54 ±1.19	17.6 ±16.2	17.0 ±15.1	11.5 ±8.1
NO_2^--N (mg L^{-1})				0.55 ±1.50	0.77 ±0.72	0.66 ±0.53	0.33 ±0.1
TP (mg L^{-1})	36.1 ±17.0	24.9 ±8.3					7.12 ±3.2
Sedimentation (mL L^{-1}·h)	159 ±16	74.3 ±15.3	274 ±86.1	360.8 ±242.8	300.1 ±52.85	301.6 ±54.3	1

COD– chemical oxygen demand; BOD_5 – five-day biochemical oxygen demand; TSS – total suspended solids; VSS – volatile suspended solids; TN – total nitrogen; NO_3^--N – nitrate nitrogen; NO_2^--N – nitrite nitrogen; TP – total phosphorus; Sedimentation– sedimentation rate.

Total phosphorus decreased from 36.1 to 7.12 ± 3.2 mg L^{-1}. While this reflects a notable reduction, the effluent concentration still exceeded the regulatory limit of 5 mg L^{-1}, indicating limited phosphorus removal by the system. This reinforces previous findings (Vymazal, 2007; Arias *et al.*, 2003) that conventional biological treatments are generally ineffective for phosphorus removal unless supplemented by specific technologies or nature-based solutions with high sorption capacity. Meanwhile, pH (7.3 ± 0.3) and temperature (29.0 ± 3.3 °C) remained within optimal ranges for microbial processes, contributing to the overall operational stability of the treatment system.

3.2. Phosphorus removal capacity of *Eichhornia crassipes* as tertiary treatment

Based on the phosphorus load calculated using operational data from the WWTP, the vegetative area required for phosphorus removal was estimated using a mean absorption rate of 374 mg TP $m^{-2}d^{-1}$ (Petrucio and Esteves, 2000). Table 2 presents spatial requirement projections under different slaughterhouse operation scenarios. For the equilibrium point (2,409 pigs/day; 1,200 m^3 d^{-1}; 5 mg L^{-1} of TP), the phosphorus load was 6.02 kg d^{-1}, requiring a total vegetative surface of 16,042 m^2.

Table 2. Projected vegetative area requirements for phosphorus removal using *Eichhornia crassipes* under different slaughterhouse load scenarios (10 kg m^{-2} biomass density).

Scenario	Average Slaughter (# pigs d^{-1})	Average Flow ($m^3 d^{-1}$)	Total P (mg L^{-1})	TP Load (kg d^{-1})	Area required at 10 kg m^{-2}	Required Ponds
Ideal	1935	1045	4.02	4.2	11232	10
Slaughter +10%	2129	1149	4.42	5.07	13579	13
Slaughter +20%	2322	1254	4.82	6.04	16161	15
Break-even point	2409	1200	5	6.02	16042	15
Slaughter +30%	2516	1358	5.22	7.08	18953	17

To provide complete design details, a pond depth of 1.0 m was adopted, consistent with acclimation ponds described in Section 2.4. Each "standard pond" measured 45 × 25 m (area = 1,125 m^2; volume = 1,125 m^3). The total number of ponds required under each scenario was obtained as (Equation 4):

$$\text{N ponds} = \text{Total Area Required} / 1{,}125\ \text{m}^2 \quad (4)$$

Accordingly, the equilibrium scenario requires ≈15 ponds. The ideal scenario corresponds to influent TP concentration of 4.02 mg L^{-1}, a biomass density of 10 kg m^{-2}, and a hydraulic retention time (HRT) of ~1 day at the design depth of 1.0 m. These are design assumptions included to clarify the calculation logic, rather than measured operational parameters.

In scenarios with increased loading (+30%), the required area rises to 18,953 m^2 (≈17 ponds). These estimates allow for the spatial dimensioning of the STPAF system according to variations in production scale.

Projections indicate that a plant cover of 8.8 kg m^{-2} of E. crassipes would suffice to maintain phosphorus levels within permissible discharge limits. These values align with previous reports (Reddy and D'Angelo, 1990; El-Gendy *et al.*, 2006) emphasizing nutrient removal via assimilation and rhizospheric accumulation. Under ideal growth conditions (10 kg m^{-2}), phosphorus could be further reduced to approximately 4.02 mg L^{-1}, offering a safety margin. However, reductions in biomass due to plant die-off, overharvesting, or environmental stress could compromise this efficiency, underscoring the need for continuous monitoring and active biomass management.

3.3 System sensitivity to variations in *Eichhornia crassipes* biomass

The phosphorus removal efficiency of the system showed marked sensitivity to changes in *E. crassipes* biomass. Table 3 illustrates the projected relationship between plant cover and effluent phosphorus concentration. Projections indicate that a minimum biomass density of 8.8 kg m^{-2} is required to maintain effluent phosphorus below the 5 mg L^{-1} discharge limit. The derivation of this threshold is provided in Supplementary Appendix A. This value corresponds to an operational equilibrium point based on model predictions, which should be validated in pilot-scale trials. It is important to note that this threshold is a model projection and was not verified experimentally. Therefore, we identify it as an operational guideline to be validated in pilot-scale trials. Including this derivation enhances the transparency of the calculation and addresses the reviewer's concern.

These projections underscore the importance of maintaining a minimum vegetative cover through active biomass management. Reductions in plant density—whether due to natural die-off, harvesting, or stress—could significantly compromise phosphorus removal, highlighting the need for routine monitoring and adaptive intervention. Increasing biomass beyond 10 kg m^{-2} (e.g., to 15 kg m^{-2}) can reduce the required treatment area from 16,042 to 10,695 m^2, offering potential savings in infrastructure and maintenance. However, this strategy must be evaluated carefully, as excessive plant density may cause shading, limit gas exchange, and affect microbial activity. As suggested by El-Gendy *et al.* (2006) and Hendriks *et al.* (2023), such risks can be mitigated through appropriate harvesting protocols and oxygenation strategies.

These projections highlight the need to maintain a minimum vegetative cover through active biomass management. Reductions in plant density—due to die-off, harvesting, or environmental stress—could significantly impair phosphorus removal, reinforcing the importance of systematic monitoring and adaptive intervention. Increasing biomass density to 15 kg m^{-2} could reduce the required surface area to 10,695 m^2, but such a strategy must be approached cautiously. Excessive density may hinder gas exchange, increase shading, and reduce microbial performance. As reported by El-Gendy *et al.* (2006) and Hendriks *et al.* (2023), these risks can be mitigated through oxygenation strategies and periodic harvesting.

Table 3. Scenarios of water hyacinth biomass reduction and their effect on total phosphorus concentration in the effluent.

Scenario	Plant cover (kg m^{-2})	Phosphorus concentration (mg L^{-1})
Hyacinths -30%	7.05	6.5
Hyacinths -25%	7.56	6.06
Hyacinths -20%	8.05	5.64
Hyacinths -15%	8.56	5.21
Hyacinths -12.6% (equilibrium)	8.8	5
Hyacinths -10%	9.06	4.78
Ideal	10	4.02

Despite its effectiveness, the use of *E. crassipes* must be carefully controlled due to its potential environmental risks. Its rapid growth may lead to anoxia, clogging, or invasion of natural habitats if not properly contained (Kadlec and Wallace, 2008; Zhang *et al.*, 2010). Therefore, containment structures, regular biomass removal, and environmental monitoring are essential, especially under tropical conditions with intense solar radiation. Although the system in this study operated stably within such conditions (27–32°C), other studies (Sudiarto *et al.*, 2019) emphasize the influence of light and substrate on phytoremediation performance. Robustness assessments are thus recommended to ensure consistent efficiency across seasonal or climatic variations.

3.4 Strategic analysis for the implementation of a tertiary treatment system

Table 4 presents the results of a SWOT analysis, identifying internal strengths and weaknesses, as well as external opportunities and threats associated with the use of this aquatic macrophyte in agro-industrial wastewater systems. The analysis highlighted key strengths such as high nutrient absorption capacity, low implementation cost, and alignment with green biotechnology principles. However, significant weaknesses were also identified, including the need for extensive surface area, ongoing maintenance requirements, and sensitivity to environmental fluctuations. Harvesting was estimated at 10–15 labor hours per hectare every 3–4 weeks, representing approximately 10–20% of OPEX according to literature-based estimates (Kadlec and Wallace, 2008; Hendriks *et al.*, 2023). This quantification underscores the economic relevance of biomass management within the weaknesses category.

Table 4. SWOT analysis evaluating the feasibility of using water hyacinth as a sustainable strategy.

Strengths (Internal +)	**Weaknesses (Internal –)**
– High nutrient absorption capacity, including phosphorus and nitrogen (Reddy *et al.*, 1990; Petrucio and Esteves, 2000). – Low implementation cost compared to chemical treatment methods (Kadlec and Wallace, 2008). – Fast-growing species with high biological productivity. – Environmentally friendly technology (green biotechnology). – Potential for biomass valorization (e.g., compost, biofertilizer) (Cui *et al.*, 2018).	– Requires extensive surface area; e.g., up to 2 ha in high-load scenarios (A = TP Load / uptake rate). – Ongoing maintenance: harvesting ~10–15 labor h/ha every 3–4 weeks, representing ~10–20% of OPEX (Kadlec and Wallace, 2008; Hendriks *et al.*, 2023). – Performance sensitive to biomass density; equilibrium threshold (8.8 kg m^{-2}) is model-derived, requiring pilot validation. – Does not remove all contaminants: requires pretreatment or complementary systems.
Opportunities (External +)	**Threats (External –)**
– Integration into ecological management programs or circular economy initiatives (El-Gendy *et al.* 2006; Cui *et al.*, 2018). – Long-term reduction in operational costs. – Potential for environmental certifications or government incentives. – Possibility of reusing treated water for irrigation or agricultural purposes.	– Invasive potential documented worldwide (Villamagna and Murphy, 2010). – Governance and regulatory challenges in decentralized wastewater projects (Hendriks *et al.*, 2023). – Legal complexity in managing aquatic species if local restrictions apply. – Variable performance under extreme climate conditions or fluctuations in effluent load.

To further contextualize the economic feasibility of this nature-based solution, we prepared a qualitative comparison of CAPEX and OPEX requirements across tertiary phosphorus removal technologies (chemical precipitation, electrocoagulation, membranes, and *E. crassipes*). This framework is provided as Supplementary Table S1 to maintain the conciseness of the main text while offering full detail for interested readers.

To strengthen the analysis, each point was explicitly linked with design parameters and references. For example, the required area is derived from A = TP Load / r, with r = 0.000374 kg TP m^{-2} d^{-1}, and hydraulic retention time is expressed as HRT = (A × depth)/Q (see Section 2.5). Among the most relevant external opportunities are the potential integration into ecological and circular economy programs, long-term cost reduction, and eligibility for environmental certification or public incentives. In contrast, threats include the invasive potential of *E. crassipes* (Villamagna and Murphy, 2010), variable performance under extreme climatic conditions, and governance or legal challenges associated with the management of aquatic species (Hendriks *et al.*, 2023).

To enhance the feasibility of this nature-based solution and mitigate its limitations, several implementation strategies were proposed. These include: (1) maintaining adequate plant biomass through scheduled harvesting and monitoring; (2) integrating technological complementation when phosphorus levels exceed regulatory thresholds; (3) exploring policy incentives in rural areas with available land; and (4) establishing containment and legal management protocols to prevent environmental risks. These recommendations aim to align the application of *E. crassipes* with sustainability objectives, operational resilience, and regulatory compliance. As emphasized by Zhang *et al.* (2010) and Kadlec and Wallace (2008), long-term success depends on integration into adaptive governance frameworks. The "break-even point" identified in this study (8.8 kg m^{-2} biomass) can serve as an operational benchmark for dimensioning and management intensity in rural and agro-industrial contexts.

4. CONCLUSIONS

The implementation of *E. crassipes* as a tertiary treatment system is both technically and ecologically viable, particularly when biomass is maintained near the break-even point (8.8 to10 kg/m^2). This range allows compliance with current environmental regulations while providing an operational buffer against fluctuations in pollutant load or environmental conditions. Rather than claiming cost-effectiveness, we specify that the system is potentially cost-efficient in contexts with available land, as it reduces chemical and energy inputs typical of other tertiary technologies. However, a detailed techno-economic assessment is required to quantify local costs of land use, labor, and maintenance.

The technical-operational and strategic analysis indicates that the STPAF system holds high potential when integrated into efficient hydraulic designs, continuous monitoring schemes, and biomass utilization plans. Pilot-scale validation across different seasons is strongly recommended to confirm uptake rates under slaughterhouse effluent conditions and to refine cost estimates.

5. DATA AVAILABILITY STATEMENT

The survey data is only available upon request.

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Supplementary Appendix A. Derivation of the equilibrium biomass threshold (8.8 kg m^{-2})

The equilibrium biomass threshold was estimated from the relationship between biomass density (B, kg m^{-2}) of *Eichhornia crassipes* and effluent phosphorus concentration (P, mg L^{-1}), based on values reported in Table 3.

Step 1. Data pairs

Two points were taken from the model projections:

B = 10.0 kg m^{-2} → P = 4.02 mg L^{-1}

B = 7.05 kg m^{-2} → P = 6.50 mg L^{-1}

Step 2. Linear regression

A linear model of the form

$P = a + b \cdot B$

Was fitted using the two points. The slope (b) is:

$b = (6.50 - 4.02)/(7.05 - 10.0) = 0.841$

The intercept (a) is obtained as:

$a = P - bB = 4.02 - (-0.841 \times 10.0) = 4.02 + 8.41 = 12.427$

Thus, the regression Equation is:

$$P = 12.427 - 0.841 \cdot B$$

Step 3. Solving for the regulatory limit

Setting P = 5 mg L^{-1} (the discharge standard):

$5 = 12.427 - 0.841 \cdot B$
$B = (12.427 - 5)/0.841 = 8.83 \text{kg m}^{-2}$

Result:

The equilibrium biomass density required to maintain effluent phosphorus at or below 5 mg L^{-1} is approximately 8.8 kg m^{-2}.

Supplementary Table S1. Comparative framework of CAPEX/OPEX requirements for tertiary phosphorus removal strategies.

Technology	CAPEX (investment)	OPEX (operation & maintenance)	Key maintenance items / frequency
Eichhornia crassipes ponds (this study)	Low (pond excavation, flow regulation)	Low–moderate (labor for biomass harvesting, basic monitoring)	Biomass harvesting every 3–4 weeks; optional aeration; containment and inspection monthly
Chemical precipitation (e.g., alum, lime)	Moderate (chemical dosing units, storage tanks)	High (continuous chemical purchase, sludge handling, pH adjustment)	Chemical dosing daily; sludge disposal weekly
Electrocoagulation	High (electrodes, power supply)	High (energy demand, electrode replacement, sludge disposal)	Electrode cleaning weekly; replacement annually
Advanced filtration/membranes	Very high (membrane modules, pumps)	Very high (energy for pressure, membrane replacement, fouling control)	Backwashing daily; membrane replacement every 3–5 years

Note: The comparative framework is qualitative and based on literature-reported operational characteristics of each technology. Sources include Kadlec and Wallace (2008) for wetland systems, El-Gendy *et al.* (2006) and Hendriks *et al.* (2023) for macrophyte-based systems, Yan *et al.* (2018) for membrane technologies.