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Potential of two floating aquatic macrophytes in improving water quality: A case study in two tropical streams

Potencial de duas macrófitas aquáticas flutuantes na melhoria da qualidade da água: Um estudo de caso em dois riachos tropicais

David Silva Alexandre[1], *Allan Pretti Ogura*[1], *Rodrigo de Almeida Mohedano*[2], *Lorena Bittencourt Guimarães Thibau*[3]

ABSTRACT

The expansion of urbanization has led to significant adverse environmental effects, including the disposal of domestic sewage without treatment in water bodies. This impact contributes to the deterioration of water quality and poses serious risks to human health and the environment. In this context, effective and sustainable methods to mitigate the impacts should be explored, such as the use of plants capable of removing or degrading contaminants from water. The present study aimed to assess the phytoremediation potential of two free-floating aquatic macrophytes (*Eichhornia crassipes* and *Pistia stratiotes*) systems for enhancing the water quality collected from two polluted urban streams. The trials were performed in 25-L experimental units for seven days under ambient conditions. The water quality variables after the exposure period were compared to those at the beginning of the experiment to assess the potential improvements due to the presence of macrophytes. The systems with *E. crassipes* exhibited good performance in water samples from both streams, with reductions reaching 29.2% in dissolved solids, 36.8% in electrical conductivity, 44% in biochemical oxygen demand, 57% in nitrogen, and 45% in phosphorus. The systems with *P. stratiotes* also exhibited satisfactory outcomes, including 90 and 76.2% reductions in phosphorus levels of Santa Rita Stream and Galinha Stream, respectively, and 54% turbidity, and 38% biochemical oxygen demand in both streams. These findings highlight the potential of the two plant species for phytoremediation of polluted waters, considering their performance on short-term exposure. Therefore, this approach consists of a sustainable alternative by utilizing natural elements for environmental restoration, and the outcomes can contribute to future applications of phytoremediation techniques in developing countries.

Keywords: *Eichhornia crassipes*; nature-based solution; nutrient removal; *Pistia stratiotes*; sustainable approach.

RESUMO

A expansão da urbanização levou a efeitos ambientais adversos significativos, incluindo o descarte de esgoto doméstico sem tratamento em corpos d'água. Esse impacto contribui para a deterioração da qualidade da água e representa sérios riscos à saúde humana e ao meio ambiente. Nesse contexto, métodos eficazes e sustentáveis para mitigar os impactos devem ser explorados, como o uso de plantas capazes de remover ou degradar contaminantes da água. O presente estudo teve como objetivo avaliar o potencial de fitorremediação de dois sistemas de macrófitas aquáticas flutuantes livres (*Eichhornia crassipes* e *Pistia stratiotes*) para melhorar a qualidade da água coletada de dois córregos urbanos poluídos. Os ensaios foram feitos em unidades experimentais de 25 L por sete dias em condições ambientais. As variáveis de qualidade da água após o período de exposição foram comparadas aos do início do experimento para avaliar as potenciais melhorias devido à presença de macrófitas. Os sistemas com *E. crassipes* apresentaram bom desempenho em amostras de água de ambos os córregos, com reduções de até 29,2% em sólidos dissolvidos, 36,8% em condutividade elétrica, 44% em demanda bioquímica de oxigênio, 57% em nitrogênio, e 45% em fósforo. Os sistemas com *P. stratiotes* também apresentaram resultados satisfatórios, incluindo reduções de 90 e 76,2% nos níveis de fósforo do córrego Santa Rita e do córrego Galinha, respectivamente, e 54% de turbidez e 38% de demanda bioquímica de oxigênio em ambos os córregos. Esses resultados destacam o potencial das duas espécies vegetais para fitorremediação de águas poluídas, considerando seu desempenho em exposição de curto prazo. Portanto, essa abordagem consiste em uma alternativa sustentável ao utilizar elementos naturais para restauração ambiental, e os resultados podem contribuir para futuras aplicações de técnicas de fitorremediação em países em desenvolvimento.

Palavras-chave: *Eichhornia crassipes*; solução baseada na natureza; remoção de nutrientes; *Pistia stratiotes*; abordagem sustentável.

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[1] University of São Paulo – São Paulo (SP), Brazil.

[2] Federal University of Santa Catarina – Florianópolis (SC), Brazil.

[3] Centro Universitário do Planalto de Araxá – Araxá (MG), Brazil.

Correspondence author: David Silva Alexandre – University of São Paulo – Rua João Ramalho, 516 – Jardim Centenário – CEP: 13564-090 – São Paulo (SP), Brazil. E-mail: davidalexandre@usp.br

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Introduction

Developing countries face significant challenges in managing and protecting water resources due to increasing urbanization and industrialization, including the need to improve sustainable strategies to mitigate anthropogenic impacts (Barletta et al., 2019). In tropical and subtropical environments, several watercourses have been contaminated by surface runoff and effluents from industrial and domestic activities (Martínez-Dalmau et al., 2021). Only 63% of Brazilian municipalities have adequate sewage collection networks, of which 74% undergo treatment (Brasil, 2024b). In such a scenario, several contaminants (*e.g.*, nutrients, metals, pharmaceuticals) are frequently released into water bodies, posing risks to aquatic ecosystems and human health (Martínez-Dalmau et al., 2021). The discharge of domestic sewage into surface waters can lead to environmental degradation by affecting several water quality variables, such as physical (*e.g.*, turbidity, conductivity, temperature), chemical (*e.g.*, nutrients, metals, biochemical oxygen demand, dissolved oxygen, pH), and biological (*e.g.*, fecal and thermotolerant coliforms); these impacts compromise water ecosystem services and multiple water uses (Ogura et al., 2022; Liu et al., 2024).

Implementing regulatory measures to control the incorrect disposal of domestic effluent and promoting remediation practices can help reduce or mitigate the introduction and effects of contaminants in aquatic ecosystems. Phytoremediation has emerged due to its effectiveness in decontamination, ease of implementation and operation, and cost-effectiveness when combined with proper management (Pinto Lamego and Antonio Vidal 2007; Sgroi et al., 2018). In this sense, aquatic macrophytes have been successfully applied to treating urban water bodies and mitigating the effects of water pollution (Ceschin et al., 2020). These plants can uptake nutrients and contaminants and rapidly grow under controlled conditions (Lu et al., 2010).

Eichhornia crassipes and *Pistia stratiotes* are free-floating aquatic macrophytes widely recognized as excellent plants for restoring contaminated water bodies (Gusti Wibowo et al., 2023). A conceptual model developed by Mayo and Hanai (2017) indicated that approximately 1.26 g N m^{-2} d^{-1} could be removed from water bodies by *E. crassipes* with biofilm. Macrophytes have demonstrated remarkable potential in the remediation of eutrophic lakes in coastal subtropical climates due to their ability to accumulate significant amounts of nutrients (*e.g.*, 28.50 g N kg^{-1} and 5.87 g P kg^{-1} in 60 days). Moreover, these plants have promising outcomes in attenuating potentially toxic metals, including chromium, nickel, copper, and iron, with removal rates ranging from 84 to 94% (Palma et al., 2012). They have also been effective in reducing suspended solids (*E. crassipes*: 59.3% and *P. stratiotes*: 52.1%), dissolved organic carbon (95% reduction), and pesticides (accumulation of 0.036 mg g^{-1} of the insecticide chlorpyrifos), among others (Wickramasinghe and Jayawardana, 2018; Anand et al., 2019; Said et al. 2020; Qayoom and Jaies, 2023).

In a study by Lu et al. (2010), water turbidity decreased by more than 60% in treatments with *P. stratiotes*. Inorganic nitrogen compounds (NH_4^+ and NO_3^-) concentrations in treated plots were more than 50% lower than those in the control. Additionally, there were approximately 14–31% reductions in both phosphate and total phosphorus levels. The use of *P. stratiotes* decreased concentrations of phosphate by up to 73%, ammonia by up to 70%, nitrite by up to 48%, and nitrate by up to 91% after five weeks (Gusti Wibowo et al., 2023). Although phytoremediation generates biomass residues, effective biomass management can include resource recovery, biogas production, combustion, composting, and degrading soils (Sharma et al., 2023). Also, biomass waste can be repurposed as a feedstock for bioenergy production and commercial-scale civil construction (Sidana and Yadav, 2022). However, it is important to consider that the application of this biomass may face limitations due to potential contamination and the presence of undesirable organisms, which could affect its safety and effectiveness (Munawar et al., 2021).

Several studies have highlighted the promising performance of *E. crassipes* and *P. stratiotes* in restoring eutrophic and polluted water bodies (Lu et al., 2010; Gusti Wibowo et al., 2023). These studies investigated the combination of plant species, variations in exposure periods, and quantification of contaminants uptake by macrophytes, among other relevant aspects. Therefore, the relevance of evaluating the use of phytoremediation to decontaminate polluted water bodies stands out for: 1. Phytoremediation offers a nature-based and sustainable method for decontaminating aquatic environments; 2. Implementing phytoremediation can be more cost-effective compared to traditional remediation methods; 3. Phytoremediation can be applied to a wide range of contaminants, including heavy metals, organic pollutants, and nutrients in excess (*e.g.*, nitrogen and phosphorus); and 4. The approach can be implemented without significant disruption to the existing ecosystem (Borges et al., 2005).

This study aimed to evaluate the effectiveness of two free-floating aquatic macrophytes, *E. crassipes* and *P. stratiotes*, in improving water quality in two polluted urban streams located in the state of Minas Gerais (Brazil), namely Santa Rita and Galinha. Water quality variables were assessed before and after the phytoremediation experiment (seven days of exposure), including pH, temperature, electrical conductivity, turbidity, dissolved oxygen, biochemical oxygen demand, ammonia-nitrogen, nitrite, nitrate, orthophosphate, total dissolved solids, and total suspended solids.

Methods

The experimental procedures consisted of six stages for the evaluated Santa Rita and Galinha streams (Figure 1): 1. Collection of water samples; 2. Collection of aquatic macrophytes; 3. Acclimatization and washing of organisms; 4. Installation of the treatment systems (surface water+macrophytes); 5. Exposure of macrophytes to the water samples; and 6. Evaluation of physical and chemical variables of water quality.

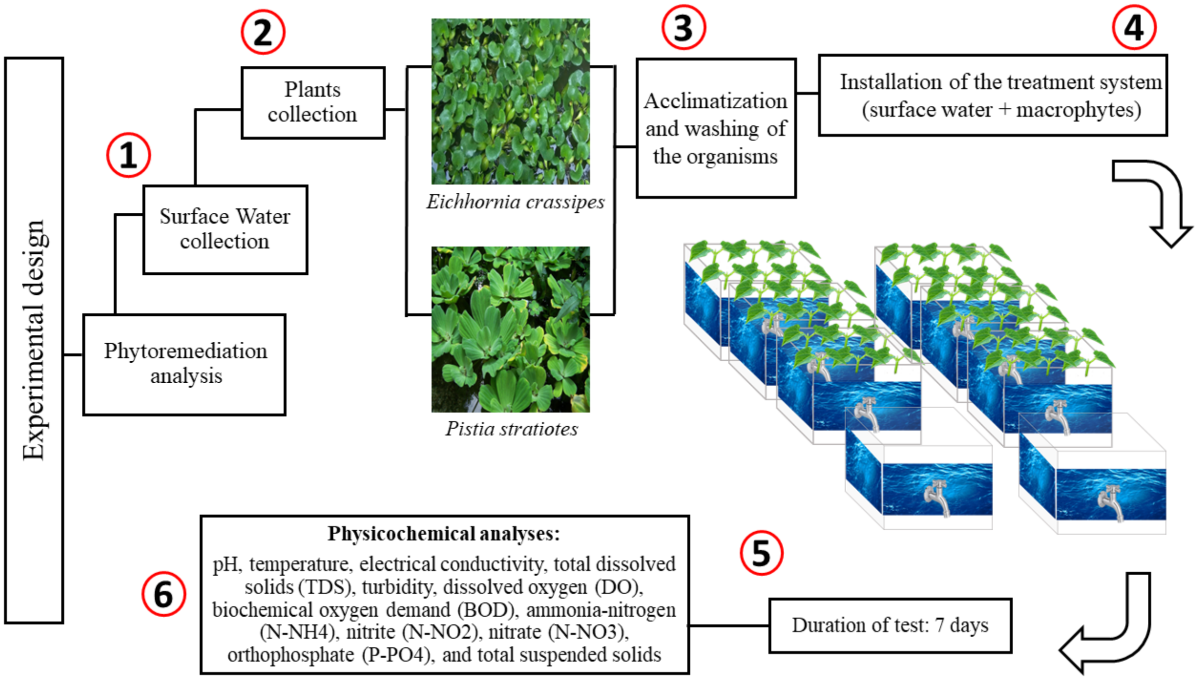

Figure 1 – Experimental design.

Water samples collection

Two sampling stations were established for this study in the Santa Rita (19°34'57.60"S; 46°56'27.19"W) and Galinha (19°34'01"S; 46°56'66"W) streams in Araxá, Minas Gerais, Brazil (Figure 2). The Santa Rita Stream is primarily channeled within the urban area and receives some of the city's stormwater and sewage (Souza Junior, 2008). On the other hand, the Galinha Stream is not channeled but receives treated domestic and food industry effluents. Approximately 200 L of surface water samples were collected at the Santa Rita (June 2018) and Galinha (December 2019) stations.

Aquatic macrophytes

Free-floating aquatic macrophytes *E. crassipes* (13 organisms) and *P. stratiotes* (20 organisms) were collected from a lake in Parque do Barreiro (19°38'33.40"S and 46°57'05.29"W). This specific location receives treated domestic wastewater from the hotel zone.

The collected plants underwent a washing process and were acclimated for 20 days before the experiment started. The acclimatization was carried out using water samples from the Santa Rita Stream, reflecting the local environmental conditions, which included temperatures of 29°C maximum, 23.7°C average, and 20°C minimum (Brasil, 2024a). The maximum relative humidity was 84%, with an average of 78%, and a minimum of 48%. There were no recorded rainfall events during the collection period. The same procedure was performed for the Galinha Stream, where temperatures were 31°C maximum, 26°C average, and 20°C minimum. The maximum relative humidity was 80%, with an average of 79%, and a minimum of 75% (Brasil, 2024a). Light rains occurred during the collection period, and meteorological data were obtained from the regional meteorological station.

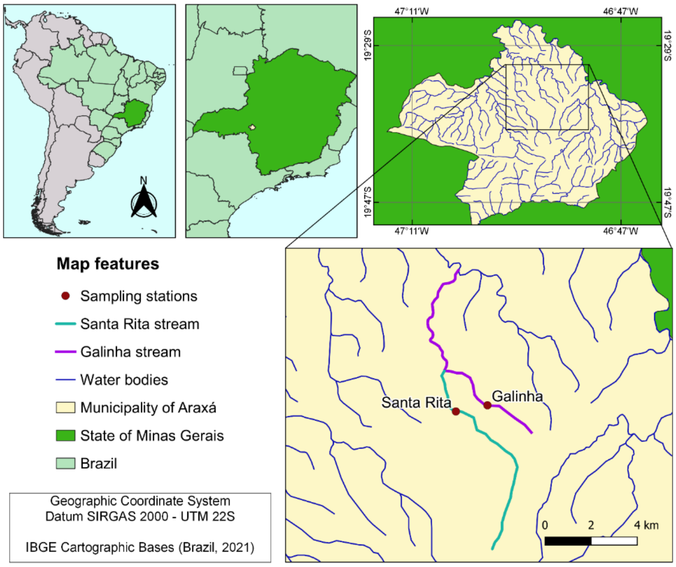

Figure 2 – Geographic location of both studied urban streams, located in the city of Araxá, state of Minas Gerais, Brazil.
SIRGAS: Geodesic Reference System for the Americas; UTM: Universal Transverse Mercator coordinate system; IBGE: Brazilian Institute of Geography and Statistics.

Phytoremediation experimental system

The phytoremediation experiment was conducted on a pilot scale to assess the potential of the studied aquatic macrophytes in treating the collected water samples. Each experimental unit consisted of a non-toxic plastic container with a storage capacity of 25 L, measuring 50 cm in length and 35 cm in width (*i.e.*, surface area of 0.175 m^2). The bottom of the system was equipped with intersecting polyvinyl chloride (PVC) tubes with a diameter of 3 mm (Figure 3).

Water samples collected from each stream were placed into the experimental units, considering three replicates for each species (n=3). The experimental period lasted seven days, during which the systems were exposed to ambient conditions, including natural light, but protected from rain. The experiment operated without water renewal as the reduction in water level was below 10% across all treatments. The contact time between plant and water was adopted based on previous studies (Ceschin et al., 2020; Panneerselvam and Priya, 2023).

Physical and chemical analysis

Water quality analyses were conducted in triplicate (n=3) for pre- and post-phytoremediation samples. A multiparameter probe (Edge® HI2020-01) was used to measure hydrogen potential (pH), temperature, electrical conductivity (EC), and total dissolved solids (TDS), while turbidity was determined using a TB2000 turbidimeter. Dissolved oxygen (DO) and biochemical oxygen demand (BOD) were determined by the Winkler Method (American Public Health Association [APHA] et al., 2012). Ammoniacal nitrogen ($N\text{-}NH_4$), nitrite ($N\text{-}NO_2$), nitrate ($N\text{-}NO_3$), orthophosphate ($P\text{-}PO_4$), and total suspended solids (TSS) analyses followed the guidelines outlined in the Standard Methods for the Examination of Water and Wastewater (APHA, 2012). The results were compared to the Brazilian thresholds established by the National Environment Council (CONAMA, *Conselho Nacional do Meio Ambiente*) Resolution 357, considering the allowable limits for Class 2 water bodies, which target water quality for human consumption after conventional treatment and for the protection of aquatic ecosystems (Brasil, 2005).

Phytoremediation potential

The overall phytoremediation efficiency was calculated using Equation 1, considering BOD and nutrients in the two studied streams. This formula estimated the percentage of improvement in the quality of the influent when treated with the phytoremediation plants in the system.

$$\text{Efficiency}\ (\%) = [(C - T)/C] \times 100 \qquad (1)$$

Where:

Efficiency = percentage improvement in water quality;
C = initial concentration of the variable in the influent; and
T = concentration of the variable after phytoremediation treatment.

Data analysis

The efficiency of phytoremediation using both macrophytes was compared using Analysis of Variance (ANOVA), followed by *post-hoc* tests such as Tukey's and Dunnett's, conducted with the Bioestat® 5.4 software. The results were evaluated based on statistically significant differences (considering $p<0.05$) in efficiency between the treatment and control groups for each evaluated stream.

Results and discussion

Results and discussion were divided into three subsections: 3.1 presents the physical and chemical variables of the Santa Rita Stream; 3.2 focuses on the variables of the Galinha Stream; and in 3.3, each macrophyte's phytoremediation potential (expressed in %) was estimated for both streams. Figures 4 and 5 present the results of the physicochemical analyses conducted on the phytoremediation specimens in the Santa Rita Stream. Meanwhile, Figures 6 and 7 display the results of the physical and chemical analyses for the variables examined concerning the Galinha Stream.

Water temperature in both streams (from 21 to 27°C) was within the expected range for Araxá, based on meteorological data (Santa Rita in June 2018 and Galinha in December 2019). The temperatures are within the optimal range for photosynthesis of aquatic macrophytes, typically around 25°C, standard deviation (±) 5°C (Pang et al., 2023).

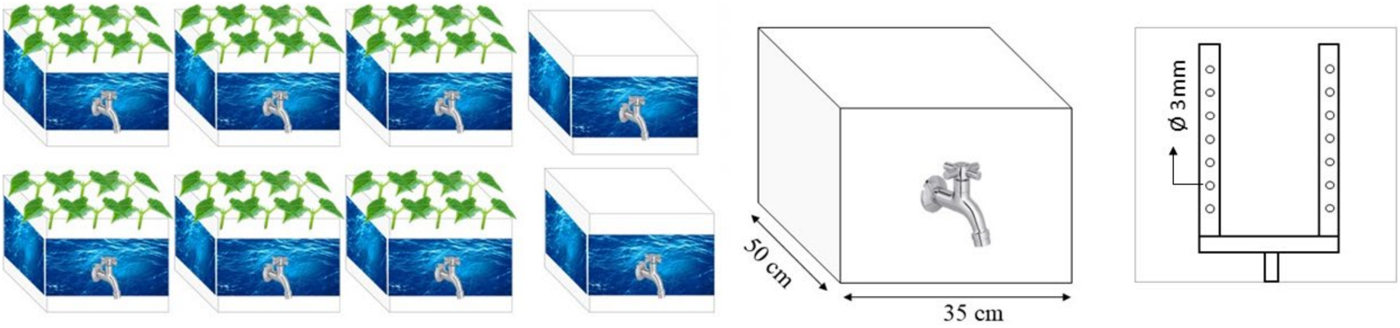

Figure 3 – Physical characteristics of the phytoremediation prototype.

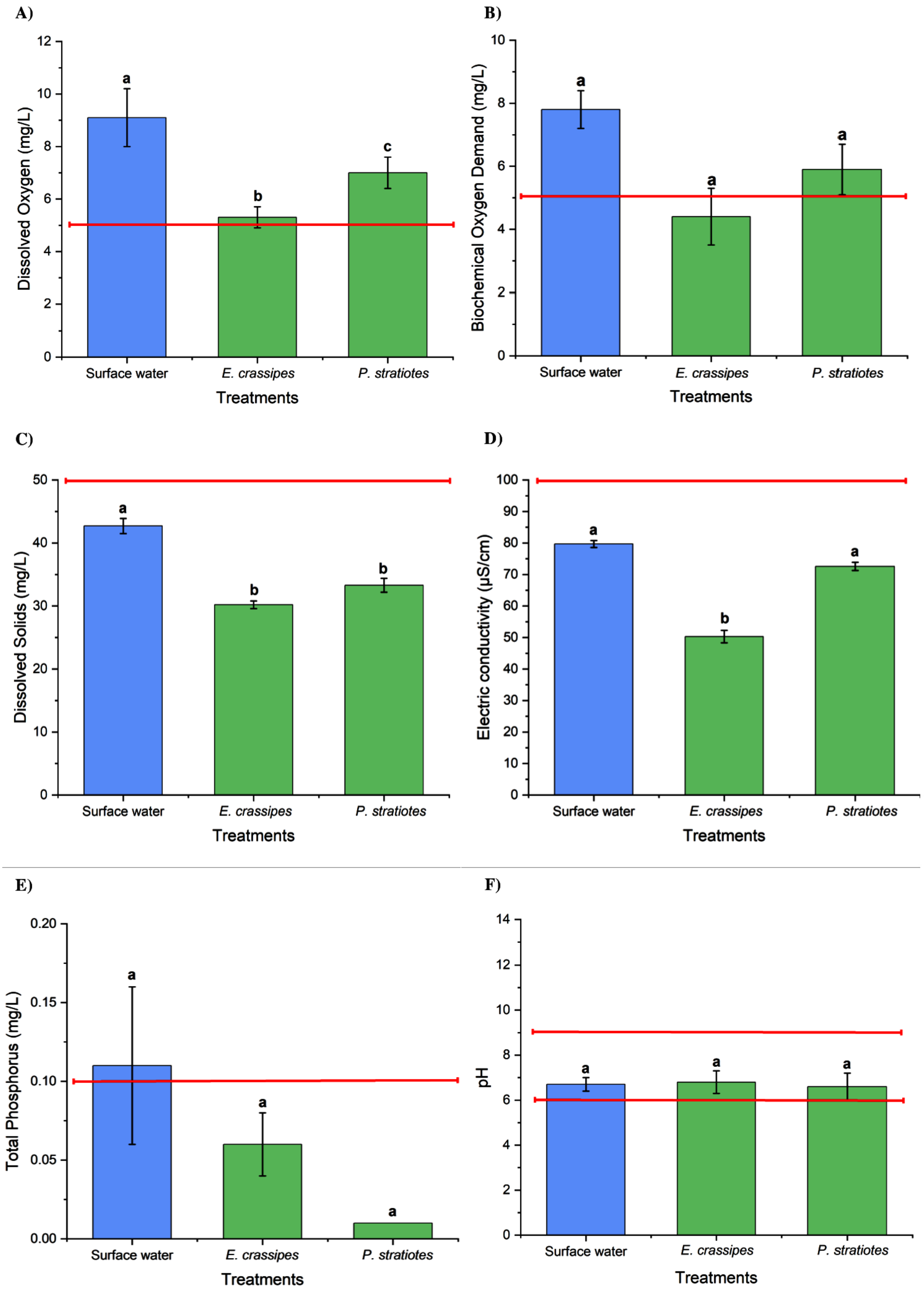

Figure 4 - Limnological variables analyzed for the Santa Rita Stream in surface waters before and after treatments with both macrophytes.
The red line indicates the limits established by Brazilian guidelines. Different letters indicate differences between treatments before and after treatment with macrophytes (compared to surface water) ($p<0.05$).

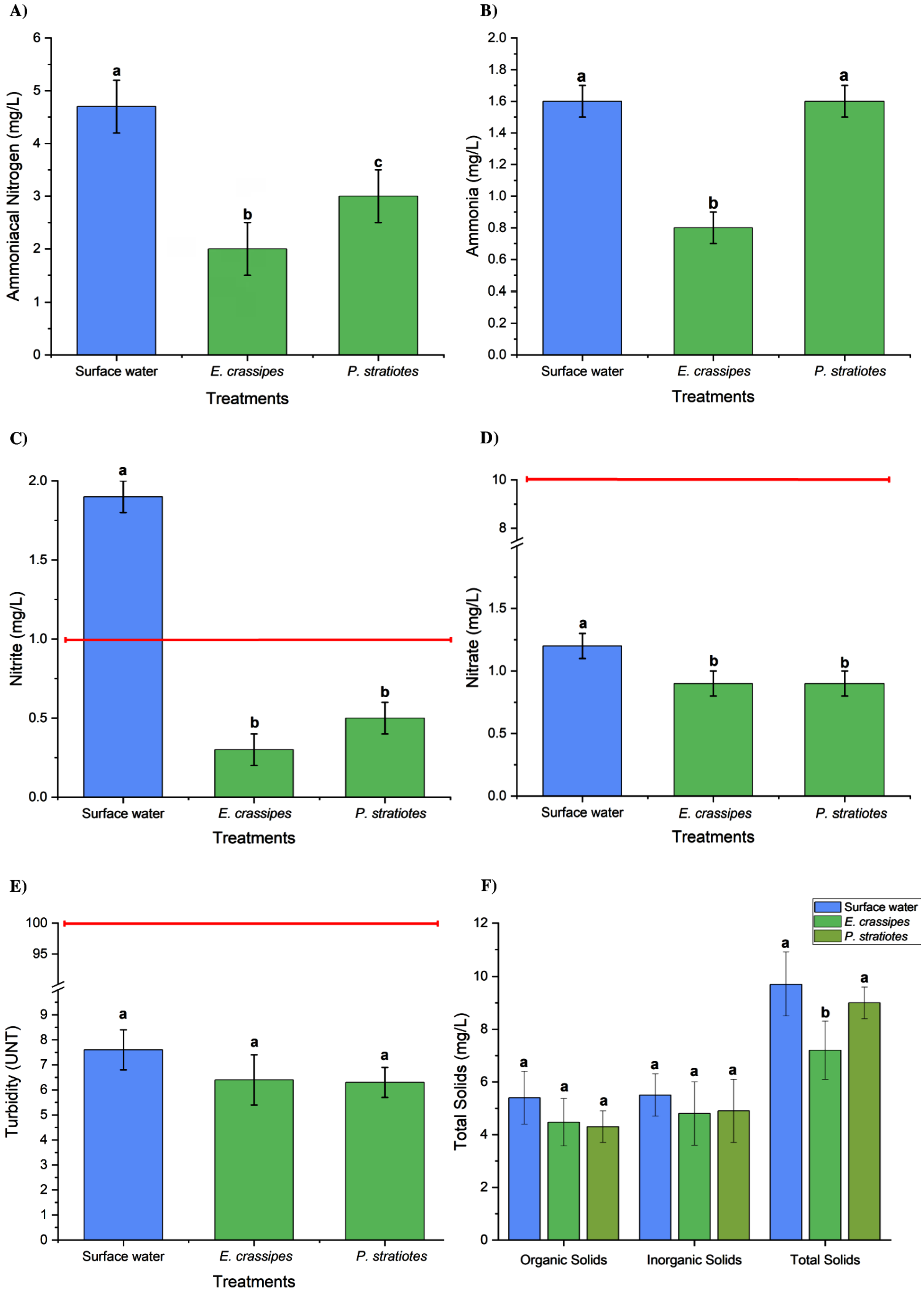

Figure 5 – Limnological variables analyzed for the Santa Rita Stream in surface waters before and after treatments with both macrophytes.
The red line indicates the limits established by Brazilian guidelines. Different letters indicate differences between treatments before and after treatment with macrophytes (compared to surface water) ($p<0.05$).

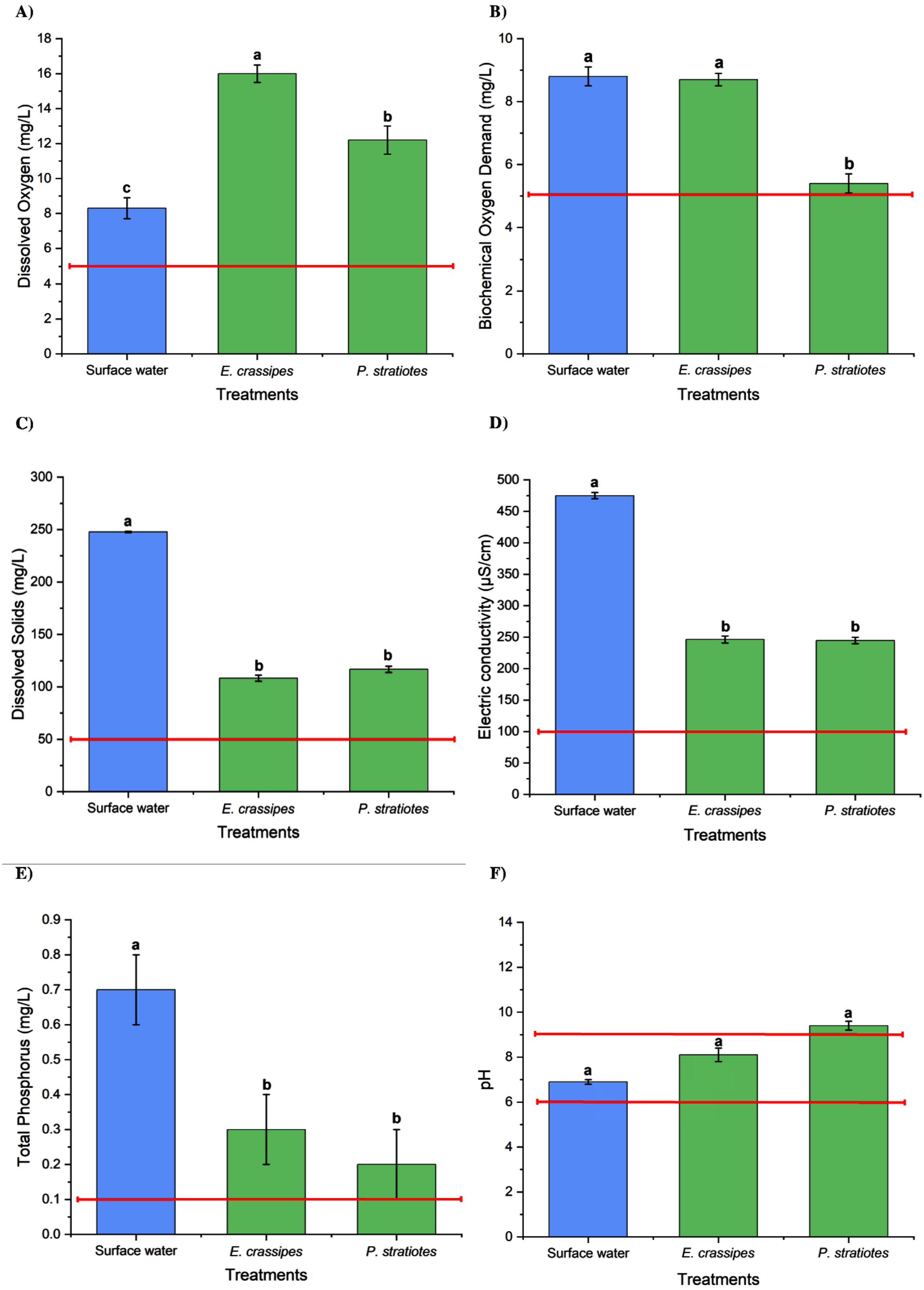

Figure 6 – Limnological variables analyzed for the Galinha Stream in surface waters before and after treatments with both macrophytes.
The red line indicates the limits established by Brazilian guidelines. Different letters indicate the difference between treatments before and after treatment with macrophytes (compared to surface water) ($p<0.05$).

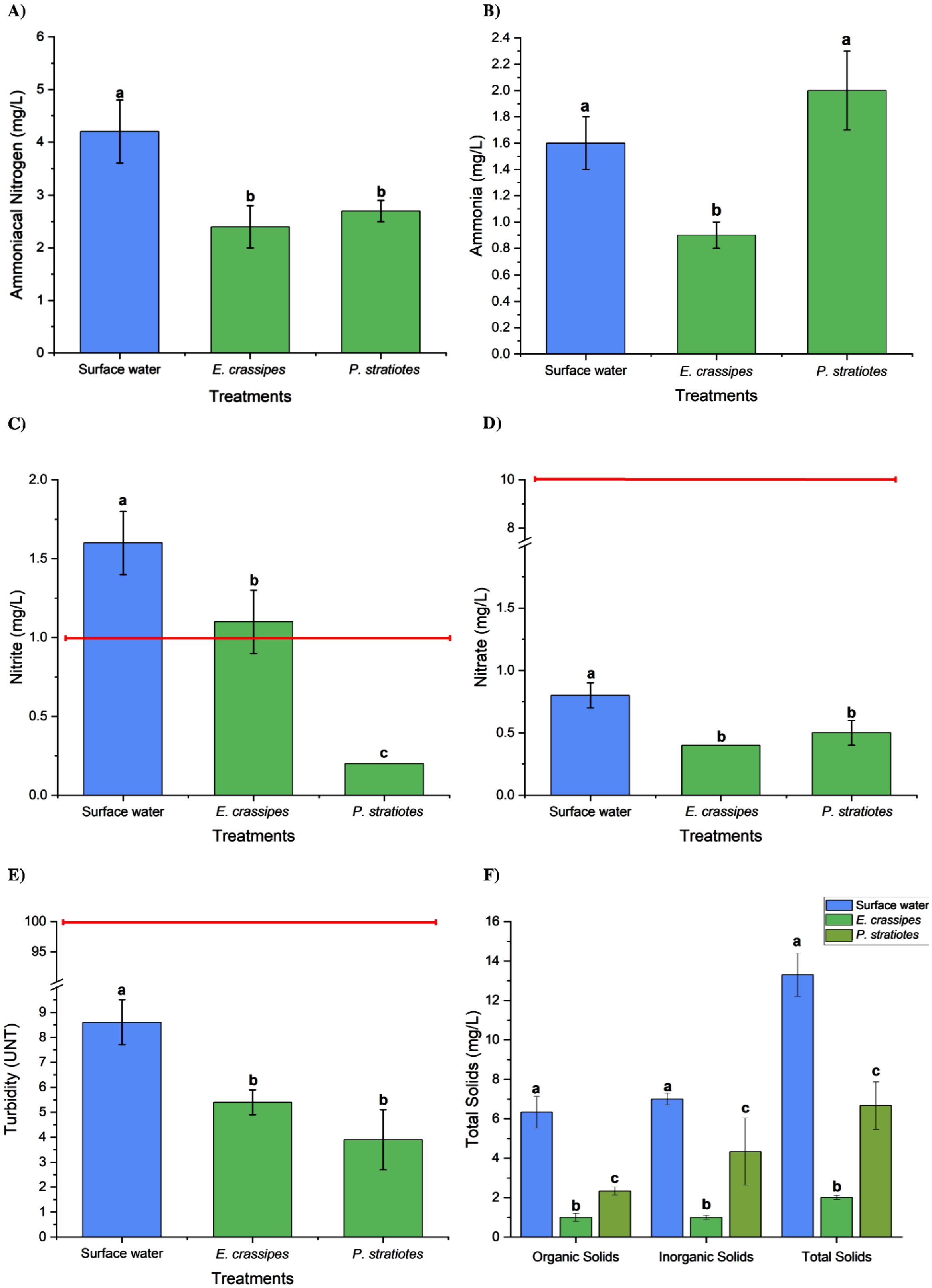

Figure 7 – Limnological variables analyzed for the Galinha Stream in surface waters before and after treatments with both macrophytes.
The red line indicates the limits established by Brazilian guidelines. Different letters indicate differences between treatments before and after treatment with macrophytes (compared to surface water) ($p<0.05$).

The temperature variation can be attributed to the on-site measurement of surface water temperature and treated effluent temperature within the treatment prototype.

Santa Rita Stream

The DO in the Santa Rita Stream (Figure 4A) complied with the limits established by Brazilian guidelines (>5 mg L^{-1}) (Brasil, 2005), and there was a decrease in DO in both treatments with macrophytes ($p<0.05$). The reduction in DO indicates its consumption by microorganisms or plants. Said et al. (2020) explain that lentic water environments promote oxygen consumption through plant metabolism and the oxidation of reduced substances, such as organic matter, by heterotrophic bacteria and oxygen transport through evapotranspiration. Consequently, the oxygen production by the plants could not surpass the amount consumed during microbial decomposition and plant respiration, decreasing its concentration. However, in larger-scale phytoremediation applications, low oxygen levels can be rectified using simple strategies, such as cascading discharge of the treated effluent. Additionally, the proliferation of algae in the *E. crassipes* prototypes might contribute to increased oxygen consumption.

BOD (Figure 4B) was significantly reduced in the two systems ($p<0.05$). Both macrophytes systems caused the decrease; however, *E. crassipes* system showed better results when exposed to water samples from the Santa Rita Stream, whereas *P. stratiotes* performed better in water from the Galinha Stream. Similar findings were reported by Mustafa and Hayder (2021) and Gusti Wibowo et al. (2023), who achieved BOD reductions of 82 and 85%, respectively, using the same species. These studies indicate that BOD reductions occur through microbial degradation processes involving aerobic and anaerobic pathways, targeting soluble organic compounds and the decomposition of settleable organic particles. The required oxygen for aerobic degradation is supplied through root release (rhizosphere) or atmospheric diffusion.

Both plants achieved different DS results ($p<0.05$), and the values decreased from 42.7 to 30.2 and 33.3 mg/L in the treatments with *E. crassipes* and *P. stratiotes*, respectively (Figure 5C). All dissolved solids (DS) values were within Brazilian guidelines (Brasil, 2005). The two macrophytes reduced the levels of DS in the Santa Rita Stream compared to the values before treatment. Md Sa'at and Qamaruz Zamana (2017) suggest that the decrease in DS can be attributed to physical factors such as sedimentation or biological processes involving the adsorption and degradation of solids facilitated by the interaction between plants and microorganisms. These reductions align with the changes observed in EC influenced by the ionization of solid particles in water (Figure 4D). The EC values also remained within the established limits, and both treatment systems with macrophytes decreased their values. Notably, the *E. crassipes* system showed a significant reduction in the variable from 79.7 to 50.3 µS cm^{-1}, representing a reduction of 36%.

A significant reduction was observed in all evaluated nutrients, including total phosphorus, ammoniacal nitrogen ($N\text{-}NH_4$), ammonia, nitrite ($N\text{-}NO_2$), and nitrate ($N\text{-}NO_3$) (Figures 4E and 5A to 5D). Total phosphorus (at 0.11 mg L^{-1}) exceeded the limits specified by the Brazilian guidelines (<0.1 mg L^{-1}) in surface water (Brasil, 2005). However, both treatment systems with macrophytes decreased total phosphorus, reaching 0.06 mg L^{-1} and 0.01 mg L^{-1} in the prototypes containing *E. crassipes* (1.8 times lower) and *P. stratiotes* (11 times lower), respectively. The phytoremediation potential of nutrients by these species has already been studied by several authors (Lu et al., 2010; Wickramasinghe and Jayawardana, 2018; Mustafa and Hayder, 2021; Gusti Wibowo et al., 2023). They explain that the reduction is attributed to the assimilation and storage of essential nutrients (phosphorus and nitrogen) required for plant growth. Among the two species, *P. stratiotes* system exhibited greater effectiveness, reducing phosphorus levels from 0.11 to 0.01 mg L^{-1} in water samples from the Santa Rita Stream.

The pH of the Santa Rita Stream did not exhibit significant variation, as ammonia is commonly found in its ionized form (Figure 4F). The slight fluctuations observed could be attributed to the decomposition of some specimens (leading to acidity) and the photosynthesis activity of the macrophytes (causing alkalinity). Another factor contributing to these minor variations is nitrification and the possible growth of periphyton, which can increase pH during the day due to the consumption of dissolved carbon dioxide (CO_2) (Mayo and Hanai, 2017). Despite these fluctuations, the pH values remained within the range established by regulations (Brasil, 2005).

Both species effectively reduced the levels of ammoniacal nitrogen ($N\text{-}NH_4$) and ammonia (Figures 5A and 5B). Notably, the treatment system with *E. crassipes* exhibited a 2-times reduction in the concentrations of both variables. Nitrogen plays a crucial role in the affluent as they are closely associated with pH levels and the eutrophication index of the water, particularly concerning phosphorus. Mustafa and Hayder (2021) explain that plants' reduction of nitrogen (in the form of NH_4^+ or NO_3^-) involves several steps, including assimilation, translocation, and absorption. In aerobic environments, ammoniacal nitrogen ($N\text{-}NH_4$) is oxidized to nitrite (NO_2) by *Nitrosomonas* bacteria and subsequently to nitrate (NO_3^-) by *Nitrobacter* bacteria; the process of nitrification is well-documented (Mayo and Hanai, 2017). When analyzing nitrogen levels, various biological processes influence nitrogen transformation, such as denitrification, mineralization, and volatilization. Several studies have reported excellent nitrogen removal efficiencies by *E. crassipes* and *P. stratiotes* species. Mayo and Hanai (2017) achieved 63.9% nitrogen removal using *E. crassipes*, while Mustafa and Hayder (2021) achieved 98% removal of ammoniacal nitrogen ($NH_4\text{-}N$) using *P. stratiotes*. These findings highlight the effectiveness of these plant species in removing nitrogen compounds from water bodies.

The concentration of nitrite ($N\text{-}NO_2$) in the surface waters of the Santa Rita Stream (1.9 mg L^{-1}) in Figure 5C, exceeded the Brazilian guidelines for surface water (<1 mg L^{-1}) (Brasil, 2005), but both species effectively reduced nitrite to levels within these limits. The treatment system with *E. crassipes* decreased the nitrite concentration by approximately 6.5 times (0.3 mg L^{-1}) compared to the surface water, while *P. stratiotes* system reduced it by 3.8 times (0.5 mg L^{-1}). The values for nitrate (N-NO_3) and turbidity (Figures 5D and 5E) were within the limits specified by guidelines (10 and 20 mg L^{-1}, respectively (Brasil, 2005), and both treatments with macrophyte species decreased their values after encountering the stream water (84.2 and 73.6% reductions for *E. crassipes* and *P. stratiotes*, respectively). Shafi et al. (2024) and Hernández-Vásquez et al. (2024) reported significant phytoremediation efficiencies using *E. crassipes* and *P. stratiotes* in contaminated aquatic systems. They observed a 69.7% reduction in turbidity for *E. crassipes* and a 20% reduction in nitrate (N-NO_3) concentrations for *P. stratiotes*. These results are attributed to plant and microbial absorption, as well as nitrification and denitrification processes.

Both water bodies exhibited turbid conditions, as expected in lotic environments characterized by suspended solids and water mixing. The turbidity results ranged between 7–9 nephelometric turbidity units (NTU), all within Brazilian guidelines (<100 NTU). In both samples with macrophytes, the turbidity values remained within acceptable limits. The lower turbidity values observed in the prototypes with macrophytes were anticipated, as these environments are known for their slower flow rates, which reduce water turbulence and facilitate the settling of suspended particles. However, plants also play a role in lowering turbidity, particularly in the case of *E. crassipes*, as explained by Johnston (1993). Colloidal particles (*e.g.*, suspended solids) adhere to the plant roots and are subsequently assimilated by the plant and microorganisms. This process gradually decreases turbidity and suspended solids in the water (Johnston, 1993). Farid et al. (2014) achieved a significant turbidity reduction of up to 33.7% for solid suspensions, while Lu et al. (2010) reported a turbidity decrease of over 60%, using *P. stratiotes*.

Furthermore, the values of total solids (TS)—organic and inorganic—were also measured (Figure 5F), revealing a decrease in solids in all cases ($p<0.05$). The treatment system with *E. crassipes* showed a reduction of approximately 1.5 times in total solids, lowering the concentration from 9.7 to 7.2 mg L^{-1} when compared to the surface water of the stream, and exhibited superior performance in total and inorganic solids. Sekar and Siraj Ansari (2018) also demonstrated high removal efficiencies using *E. crassipes*, achieving a 55.6% reduction in TS after ten days.

Galinha Stream

As can be observed in Figure 6A, all DO concentrations were within the limits established by Brazilian guidelines (>5 mg L^{-1}) (Brazil, 2005). However, there was an increase in DO with macrophytes, particularly notable in the results of the treatment systems with *E. crassipes* which increased the DO from 8.3 to 16 mg L^{-1}. The prototypes with *P. stratiotes* exhibited DO values of 12.2 mg L^{-1}. This rise in oxygen levels for both plants can be primarily attributed to the proliferation of algae. The increase in O_2 can also be attributed to oxygen exchange at the air-water interface, as the plants occupied approximately 70% of the surface area (Abubakar et al., 2023).

All BOD values (Figure 6B) exceeded the legal limit (<5 mg L^{-1}), but there was a reduction in the levels of the treatment systems with *E. crassipes* (8.7 mg L^{-1}) and *P. stratiotes* (5.4 mg L^{-1}) compared to the initial value (8.8 mg L^{-1}). The limited efficiency of *E. crassipes* in samples from the Galinha Stream can be attributed to the presence of algae. The observed oxygen production and low efficiency in reducing BOD can also be attributed to the proliferation of algae in the *P. stratiotes* system. Initially, algae contribute to high oxygen production, however, during decomposition they utilize the available nutrients, leading to an increase in algal biomass that subsequently decomposes and negatively impacts BOD levels (Abubakar et al., 2023).

The results obtained for DS and EC variables were consistent as they are interrelated. Neither met the minimum values specified by guidelines (<50 and <100 µS cm^{-1}, respectively) before and after the phytoremediation process (Brasil, 2005). However, macrophytes significantly reduced the values of these variables by more than 50% compared to the surface waters of the stream ($p<0.05$). The DS concentration in the Galinha Stream (Figure 6C) is nearly 5-times higher than that of the Santa Rita Stream, significantly exceeding the limits set by guidelines (50 mg L^{-1}) (Brasil, 2005). These high levels of DS in the Galinha Stream can be attributed to various factors, including the absence of riparian forests, direct pollution from human activities, and the collection of samples during the rainy season. Furthermore, the Galinha Stream is situated downstream of arid soil composed of sand and earth, which is prone to erosion during periods of rainfall.

Both macrophytes effectively lowered phosphorus levels by more than 50%, with the treatment system using *P. stratiotes* demonstrating a remarkable 71% reduction in concentrations (Figure 6E). In the Galinha Stream, although a decrease occurred, the variable still did not meet the limits. Between the two species, the *P. stratiotes* system exhibited greater effectiveness, reducing phosphorus levels from 0.7 to 0.2 mg L^{-1}. Several factors may influence the data, including saturation of absorption by plants, binding of phosphorus to sediment particles, and external conditions affecting phytoremediation. High pH values in the treatment system with *P. stratiotes* likely affected the solubility and availability of phosphorus for plants (Figure 6F) (Magdziak et al., 2015). Although exceeding the limits specified by guidelines (between 6–9) (Brasil, 2005), the lower pH value was expected considering the experimental conditions. Despite these fluctuations, the pH values remained within the range established by regulations, except for the effluent treated with *P. stratiotes* in the Galinha Stream, which had an average pH of 9.4±0.2.

Both treatment systems reduced the ammoniacal nitrogen values, decreasing from 4.2 mg L^{-1} in the surface waters to 2.4 mg L^{-1} with *E. crassipes* and 2.7 mg L^{-1} with *P. stratiotes* (Figure 7A). The increase in ammonia concentrations in the Galinha Stream for *E. cras-*

sipes can be attributed to a shift in the medium's balance, resulting from a significant increase in pH (Figure 7B). Although ammonia concentrations are not regulated by Brazilian guidelines (Brazil, 2005), other guidelines exist, including from the European Commission. The U.S. Environmental Protection Agency, for instance, establishes 0.021 mg L^{-1} for non-ionized ammonia and 0.78 mg L^{-1} for total ammonia (EPA, 2013).

Substantial reductions of nitrite (Figure 7C) were observed with *P. stratiotes* (0.2 mg L^{-1}) compared to surface water (1.6 mg L^{-1}), meeting the Brazilian guidelines (Brazil, 2005). The *E. crassipes* system also reduced the values to 1.1 mg L^{-1}. All values were within the limits specified by Brazilian guidelines (<10 mg L^{-1}) (Brazil, 2005). Moreover, both treatment systems with macrophyte species decreased the nitrate values in the surface water from 0.8 to 0.4 mg L^{-1} with *E. crassipes* and 0.5 mg L^{-1} with *P. stratiotes*. There was a notable improvement in nitrite concentrations in the Galinha Stream, with *P. stratiotes* exhibiting the highest efficiency with a removal rate of 87.5% (Figure 7D). This outcome can be attributed to the plants' assimilation of ions from the water, as nitrite is an ionic form that readily dissolves in water and is quickly taken up by plants (Lamichhane et al., 2021). The authors explain that in aerobic environments, nitrite can be oxidized to nitrate by nitrifying bacteria present in plant roots. Both plants had significant variations in the Galinha Stream, underscoring the species' potential to reduce excessive nutrient concentrations in the medium. The measured nitrite levels in the surface waters of both streams (Figures 5D and 7D) exceeded the limits established by Brazilian guidelines (maximum allowed concentration of 1.0 mg L^{-1}) (Brazil, 2005).

The same trend was observed for turbidity (Figure 7E), with values falling within the limits set by law (<100 NTU). Both treatment systems with macrophyte species successfully remediated the water, reducing the turbidity from 8.6 NTU in the surface waters to 5.4 NTU with *E. crassipes*, and 3.9 NTU with *P. stratiotes*. TS values were lower in all samples (Figure 7F). Both macrophytes had positive results in significantly reducing the TS values compared to the prototypes with samples from the Galinha Stream. The *E. crassipes* system eliminated over 80% of TS, while *P. stratiotes* system reduced the values of total, organic, and inorganic solids, by 30–60% in the prototype with samples from the Galinha Stream after the phytoremediation period. Similar trends were observed for the samples from Galinha Stream, with *E. crassipes* demonstrating effectiveness across all solids. The high concentrations of suspended solids found in the surface waters of the streams can be attributed to the previously discussed variables. Mechanisms such as phytodegradation and the absorption of dissolved ions by plants can reduce TS concentrations, as described by Johnston (1993).

Phytoremediation potential of machophytes in the Santa Rita and Galinha streams

Table 1 shows the phytoremediation potential of each macrophyte species for the analyzed variables. Asterisks (*) indicate statistically significant differences ($p<0.05$). The treatment system with *E. crassipes* outperformed *P. stratiotes* in both streams. For the Santa Rita Stream, *E. crassipes* system exhibited significant results in BOD, nitrite, ammonia, and nitrogen, while *P. stratiotes* system showed significant reductions in the variables turbidity, phosphorus, and organic suspended solids. The phytoremediation efficiency ranged from 12 to 84.2% for *E. crassipes* and 16 to 90.9% for *P. stratiotes*. For the Galinha Stream, similar results were observed, with *E. crassipes* yielding better outcomes in DO, DS, TSS, organic suspended solids (OSS), inorganic suspended solids (ISS), nitrate ($N\text{-}NO_3$), ammonia, and nitrogen, while the treatment system with *P. stratiotes* significantly reduced turbidity, EC, BOD, phosphorus, and nitrite ($N\text{-}NO_2$). The significant values ranged from 42.8 to 93.6% for *E. crassipes*, while the treatment system with *P. stratiotes* exhibited a variation from 38 to 90.1%. These responses demonstrate satisfactory results concerning the influence of both plants on the water quality.

Table 1 – Phytoremediation potential of both macrophytes.

Limnological variables	Santa Rita Stream		Galinha Stream	
	E. crassipes	*P. stratiotes*	*E. crassipes*	*P. stratiotes*
	% Phytoremediation		% Phytoremediation	
Turbidity	15.8	*16.7	37.6	*54.7
Electrical Conductivity	*36.8	8.9	48.1	*48.5
Biochemical Oxygen Demand	*44	24.4	0.8	*38
Total Phosphorus	45.4	*90.9	61.9	*76.2
Total Nitrogen	*57.4	36.1	*42.8	35
Nitrite	*84.2	73.6	34	*90.1
Nitrate	25	25	*50	37.5
Ammonia	*50	0	*55.9	-11.1

* Indicates statistically significant differences ($p<0.05$).

Various factors should be considered when assessing the potential of each studied plant, including luminosity, seasonality, and contact time, which play significant roles in the system's dynamic balance and provide optimal conditions for achieving water quality improvements. Seasonality also plays a role in the effectiveness of *in situ* phytoremediation for polluted water bodies. Lima et al. (2022) explain that the metabolic activity and growth of phytoremediation plants can change according to variations in temperature, precipitation, and light availability. Warmer months and higher temperatures generally increase plant growth and contaminant uptake, while colder seasons can reduce these activities, potentially slowing down remediation. The implementation of *in situ* phytoremediation techniques requires careful planning and detailed studies on the characteristics of each specific environment, as discussed by several authors, such as Ali et al., (2020), Churko et al., (2023) and Chatterjee (2024). These authors emphasize that the selection of plants, planting/insertion of species, maintenance, monitoring, harvesting, and disposal of the utilized specimens are crucial factors for ensuring the effectiveness and success of decontamination. The absence of water quality data after the exposure period in control systems without macrophytes was a limitation of our study. As a result, the findings reflect the influence of plants on water quality and do not account for other factors such as plankton activity, chemical reactions, and sedimentation that could change water quality even in the absence of macrophytes. Future research may benefit from exploring diverse exposure times, synergistic effects of multiple plant species, large-scale implementation (wetlands), cost-benefit analysis, integrating physical and chemical analyses, biological assessments such as chlorophyll-a measurements, and the quantification of the uptake of chemicals within plant tissues. Such comprehensive approaches will contribute to a deeper understanding of the mechanisms underlying phytoremediation and facilitate the development of more efficient and holistic strategies for water remediation in polluted environments.

Conclusions

The phytoremediation of water bodies contaminated with domestic sewage holds significant promise, presenting a sustainable and environmentally friendly solution to pollution. The treatment systems with *E. crassipes* and *P. stratiotes* emerged as highly effective agents in treating polluted water by domestic sewage in urban streams. Their efficacy resulted in tangible enhancements in the quality of both water samples (based on the estimated phytoremediation efficiency), marked by notable improvements across several variables known to detrimentally affect water quality in urban streams, such as nutrient levels. Phytoremediation is an alternative to address water pollution but also fosters sustainable development and advances environmental science research. This method contributes to nature-based ecosystem restoration and reduces reliance on chemical interventions.

Authors' contributions

Alexandre, D.S.: conceptualization, methodology, formal analysis, investigation, writing – original draft, project administration; **Ogura**, A.P.: investigation, writing – reviewing and editing. **Mohedano**, R.A.: writing – reviewing and editing; **Thiba**u, L.B.G.: conceptualization, methodology, writing – reviewing and editing, supervision, resources.

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