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Scientific Paper

Phycoremediation: assessment of the efficiency in removing organic compounds and nutrients commonly found in domestic effluents

Ficorremediação: avaliação da eficiência na remoção de compostos orgânicos e nutrientes comumente encontrados em efluentes domésticos

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ABSTRACT

Phycoremediation is emerging as a promising alternative for treating effluents, receiving significant attention in recent years. The microalgae's ability to efficiently remove contaminants from wastewater and survive in adverse conditions makes them excellent candidates for tertiary wastewater treatment. The main objective was to evaluate three species in monocultures of photosynthetic microalgae (*Chlorella vulgaris*, *Desmodesmus subspicatus,* and *Raphidocelis subcapitata*) in relation to the removal of organic compounds and nutrients generally present in domestic effluents. The effluent utilized was characterized by a chemical oxygen demand (COD) of 600 mg·L^{-1}, total nitrogen concentration of 24 mg·L^{-1}, and phosphate concentration of 10 mg·L^{-1}, prepared in mineral water and evaluated at two distinct microalgal densities (10^5 and 10^7 algae·mL^{-1}). After 96 hours, the species showed an increase in dry biomass production, with an increase of 17.3 and 11.4 times in the initial densities of 10^5 algae·mL^{-1} and 10^7 algae·mL^{-1}, respectively. Controls using mineral water, which provided essential minerals for microalgal growth, and culture medium demonstrated biomass production increases of 2-fold and 8.7-fold, respectively. The reduction in COD was directly related to algae density, with greater reductions observed in bioassays with 10^7 algae mL^{-1}. However, the COD reduction exceeded 78% in all bioassays. The highest nitrogen removal (80%) was recorded in the bioassay with *C. vulgaris* (10^7 algae mL^{-1}), while *D. subspicatus* demonstrated higher phosphate removal (34%). On average, nitrogen and phosphate removal across all bioassays reached 68% and 21%, respectively. These results highlight the potential of microalgae as a polishing step in decentralized wastewater treatment systems.

Keywords: microalgae; tertiary wastewater treatment; organic load; phosphate; total nitrogen.

RESUMO

A ficorremediação apresenta-se como uma alternativa promissora para tratar efluentes, recebendo significativa atenção nos últimos anos. A capacidade das microalgas de remover eficientemente contaminantes de efluentes e de sobreviver em condições adversas as torna excelentes candidatas para o tratamento terciário de efluentes. O principal objetivo foi avaliar três espécies em monoculturas de microalgas fotossintéticas (*Chlorella vulgaris*, *Desmodesmus subspicatus* e *Raphidocelis subcapitata*) em relação à remoção de compostos orgânicos e inorgânicos geralmente presentes em efluentes domésticos. O efluente utilizado foi caracterizado por uma demanda química de oxigênio (DQO) de 600 mg•L^{-1}, concentração de nitrogênio total de 24 mg•L^{-1} e concentração de fosfato de 10 mg•L^{-1}, preparado em água mineral e avaliado em duas densidades distintas de microalgas (10^5 e 10^7 algas•mL^{-1}). Após 96 horas, as espécies apresentaram aumento na produção de biomassa seca de 17,3 e 11,4 vezes nas densidades iniciais de 10^5 e 10^7 algas•mL^{-1}, respectivamente. Os controles utilizando água mineral, que forneceram minerais essenciais para o crescimento de microalgas, e o meio de cultivo demonstraram aumentos na produção de biomassa de duas e 8,7 vezes, respectivamente. A redução na DQO foi diretamente relacionada à densidade de algas, com maiores reduções observadas nos bioensaios com 10^7 algas•mL^{-1}, no entanto a redução da DQO excedeu 78% em todos os bioensaios. A maior remoção de nitrogênio (80%) foi registrada no bioensaio com *C. vulgaris* (10^7 algas•mL^{-1}), enquanto *D. subspicatus* demonstrou a maior remoção de fosfato (34%). Em média, a remoção de nitrogênio e fosfato em todos os bioensaios atingiu 68 e 21%, respectivamente. Esses resultados destacam o potencial das microalgas como uma etapa de polimento em sistemas de tratamento descentralizados de efluentes.

Palavras-chave: microalgas; tratamento terciário de efluentes; carga orgânica; fosfato; nitrogênio total.

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INTRODUCTION

The continuous release of untreated domestic sewage into aquatic environments remains a serious and chronic problem in Brazil, with direct impacts on human and environmental health. According to the National Sanitation Information System (SNIS, 2023), approximately 56% of the population in Brazilian municipalities have access to a basic sanitation network. Within this percentage, only 52.2% of the domestic sewage generated in the country undergoes any form of treatment before being released into the environment. Since the majority of conventional wastewater treatment plants (WWTPs) were not designed to remove emerging micropollutants, a portion of these contaminants remains in the effluent, mainly due to their persistence, continuous introduction into the sewer system, and the lack of specialized treatment (Rabello et al., 2019; de Almeida et al., 2020).

The increasing discharge of untreated sewage into receiving waters, mainly consisting of organic matter (and associated micropollutants) and nutrients, can impact environmental and human health in various ways, becoming a significant public concern (Gosset et al., 2021). Nitrogen and phosphorus are essential nutrients for the growth and maintenance of microorganisms and plants. However, the excessive presence of nutrients in aquatic environments can lead to serious eutrophication issues (Rani; Maróti, 2021).

Phycoremediation is the use of microalgae/algae to remove and/or biotransform substances that may pose risks to the environment (Rabello et al., 2019; Rajamanickam; Shanthakumar, 2022). Certain species of single-celled green microalgae, such as *Chlorella vulgaris*, *Desmodesmus subspicatus*, and *Raphidocelis subcapitata,* have been used either individually or in combinations in numerous studies involving the toxicity, removal, and biodegradation of pharmaceuticals and other chemical compounds, as well as in wastewater treatment (Salomão et al., 2014; Ji et al., 2018; Liu et al., 2018; de Almeida et al., 2020). Phycoremediation has garnered interest due to its cost-effectiveness (low input energy), high nutrient removal capacity, and high biomass production rates (for biofuel production) (Javed et al., 2019).

Another advantage of phycoremediation is the possibility of establishing consortia with other microorganisms, such as bacteria, to enhance the efficiency of nutrient, organic matter, drug, and other chemical compound removal and biotransformation (Shen; Gao; Li, 2017; Ji et al., 2018). Integrating conventional effluent treatment processes with phycoremediation can not only improve treatment effectiveness but also yield biomass containing commercially valuable biocompounds, offering an economically and environmentally sustainable process (Kandasamy et al., 2021). The main objective of the present study was to evaluate three species of single-celled photosynthetic microalgae (*C. vulgaris, D. subspicatus,* and *R. subcapitata*) in monocultures regarding the removal of organic compounds and nutrients typically found in domestic effluents. This study highlights the innovative potential of algae-based systems for small Brazilian municipalities lacking basic sanitation. With ample land availability and high solar incidence, Brazil offers ideal conditions for implementing decentralized wastewater treatment systems (DWWTS). These systems efficiently remove and transform organic compounds and nutrients while producing high-value biomass, contributing to decarbonization by capturing CO_2. This biomass can be converted into bioproducts such as biofertilizers, biofuels, and bioactive compounds, offering economic, social, and environmental benefits. Additionally, this approach supports multiple UN Sustainable Development Goals (SDGs), including clean water and sanitation (SDG 6), affordable energy (SDG 7), and sustainable cities (SDG 11), offering a sustainable solution adaptable to local needs.

MATERIALS AND METHODS

Microalgae and culture conditions

The unicellular microalgae *C. vulgaris, D. subspicatus,* and *R. subcapitata* were cultivated and maintained in incubators with controlled photoperiod and temperature, following Standard ISO 8692 (ISO, 2012). The microalgae species cultivated at Universidade do Estado do Rio de Janeiro (UERJ) were purchased from the algae bank of Linnaeus University, Sweden. Cultures were replicated monthly, and the growth and development of the cultures were monitored biweekly by microscopic counting using a Neubauer counting chamber.

Phycoremediation assays

The pre-cultivation of microalgae species was conducted for 5 days in LC Oligo medium at 25°C with continuous aeration and lighting (4,500 lux). The culture medium pH was measured at the beginning of pre-inoculum cultivation using a digital pH meter (Orion 3-Star, Thermo Fisher Scientific, USA) and required no adjustment, as it was within the standard range established by the Brazilian Association of Technical Standards (ABNT, 2023). The lighting regime, which differs from real-scale conditions, was used to enhance biomass production for more accurate comparison among samples. On the day of the bioassay, to minimize the influence of the culture medium as an additional source of carbon and nutrients, the inoculum was centrifuged at 2,000 rpm for 15 minutes at 4°C. The supernatant was then discarded, resulting in a reduced solution volume with a higher microalgal density. After centrifugation, the pellets were transferred to 250 mL Erlenmeyer flasks containing 200 mL of mineral water. Mineral water was used in the assay to provide essential micronutrients and minerals that are critical for microalgal growth, ensuring the availability of key nutrients required for optimal metabolic activity and enhancing the accuracy of the evaluation process.

The bioassays were conducted over 96 hours, following the ecotoxicity testing protocols established by the Brazilian Association of Technical Standards (ABNT, 2023). Two microalgal densities (10^5 and 10^7 algae·mL^{-1}) (Table 1) were selected based on the guidelines of ABNT (2023) and on previous studies conducted by our laboratory (de Almeida et al., 2020; de Sá Salomão; Hauser-Davis; Marques, 2020). The bioassays were carried out in triplicate (n = 3) at 25–27°C with continuous aeration and lighting (4,500 lux), as previously described.

The nominal concentrations of organic compounds and nutrients (nitrogen and phosphorus) were calculated based on the stoichiometric values of the following compounds (Table 1): ammonium chloride (NH_4Cl), potassium nitrate

Table 1 – Experimental setup of the 96-hour bioassay with three microalgae species in two different densities and initial concentrations of organic compounds and nutrients.

Microalgae species	Density (mg L^{-1})	COD (mg L^{-1})	Total nitrogen (mg L^{-1})	Phosphate (mg L^{-1})
R. subcapitata	10^5	600	24	10
	10^7	600	24	10
C. vulgaris	10^5	600	24	10
	10^7	600	24	10
D. subspicatus	10^5	600	24	10
	10^7	600	24	10

(KNO_3), anhydrous monobasic potassium phosphate (H_2KO_4P), and anhydrous glucose ($C_6H_{12}O_6$). Samples of 25 mL were collected every 24 hours (0, 24, 48, 72, and 96 h) to assess biomass production and quantify the free organic compounds and nutrients in the water (Figure 1). These organic compounds and nutrients were analyzed using the standard methods described in APHA, AWWA and WEF (2012): 4500-N C for total nitrogen, 4500-P E for phosphate, and 5220-COD for organic carbon.

The dry biomass was determined by filtering 25 mL through a 0.2–0.6 µm fiberglass membrane and weighing the material retained after drying in an oven at 50°C for 2 hours (or until a constant weight was achieved) (de Almeida et al., 2020). The toxic effect was determined by cell counting in a Neubauer chamber, comparing the growth inhibition of algae biomass with the negative control (algae and mineral water) under the same test conditions.

Statistical analyses were performed using GraphPad Prism (v. 5.02 for Windows, San Diego, USA). For pairwise comparisons, the t-test and its non-parametric counterpart, the Mann–Whitney U test, were employed. To evaluate the effects of densities and sampling time, a two-way analysis of variance (ANOVA) was conducted, followed by a Bonferroni post-test. Statistical significance was determined at a $p < 0.05$.

RESULTS AND DISCUSSION

Microalgae biomass production

Microalgae present a cost-effective approach for wastewater treatment and biomass-based resource recovery, leveraging their high photosynthetic efficiency and ability to thrive under diverse and challenging conditions. Cultivating microalgae in wastewater, where they utilize available nutrients, enables biomass production that can be converted into biofuels and other bioproducts. Algal growth in wastewater is influenced by several factors, including CO_2 concentration, temperature, inoculum density, pH, light intensity, photoperiod, and nutrient levels. The initial microalgal density is particularly critical for optimizing bioaccumulation and contaminants removal, thereby enhancing the efficiency of wastewater treatment (Chekroun; Sánchez; Baghour, 2014; Raheem et al., 2018; de Almeida et al., 2020; Zhang; Li; Ho, 2021).

In the present study, the phycoremediation ability of three microalgae species was evaluated at two initial densities over a 96-hour period. The hydraulic retention time (HRT) in a WWTP varies based on the bioaccumulation or biosorption capacity of a target compound by a microalgae species (Acién et al., 2016). Consequently, HRT influences the daily volume of effluent treated and the size of treatment units or algae tanks, which can be crucial for the project's feasibility (Morillas-España et al., 2021).

The literature highlights the correlation between microalgal inoculum density, biomass production, and nutrient removal rate. A high inoculation rate can help microalgae species acclimate to adverse conditions in wastewater, such as the presence of toxic compounds. The high density supports a rapid growth rate and efficient removal of nutrients and organic compounds in a short period, reducing the lag phase duration (Guo et al., 2019). However, in some cases, a higher initial density of algae inoculum may lead to mutual shading within the algae population, reducing light penetration in the crop and consequently decreasing microalgae growth rates (Bohutskyi et al., 2016).

Figure 2 demonstrates that the presence of organic compounds and nutrients in the medium enhanced biomass production across all three microalgal species and their respective densities ($p < 0.05$), as evidenced by the dry biomass data, while also confirming that the tested concentrations of these compounds did not induce any toxic effects under the evaluated conditions ($p < 0.05$).

The bioassay with an initial density of 10^7 algae·mL^{-1} exhibited the highest algal biomass production by *C. vulgaris* (an increase of 1,181% and a biomass production of 328 mg·L^{-1}), followed by *D. subspicatus* (1182% and 260 mg·L^{-1}), and *R. subcapitata* (757% and 106 mg·L^{-1}). Similarly, in the bioassay with an initial density of 10^5 algae·mL^{-1}, the highest biomass production was also by *C. vulgaris* (an increase of 1,825% and a biomass production of 146 mg·L^{-1}), followed by *D. subspicatus* (1,175% and 94 mg·L^{-1}) and *R. subcapitata* (1,900% and 76 mg·L^{-1}). Although at the initial density of 10^5 algae·mL^{-1}, *R. subcapitata* showed a higher growth rate (%), *C. vulgaris* exhibited higher biomass production (mg·L^{-1}). Based on the dry biomass results obtained for the three species

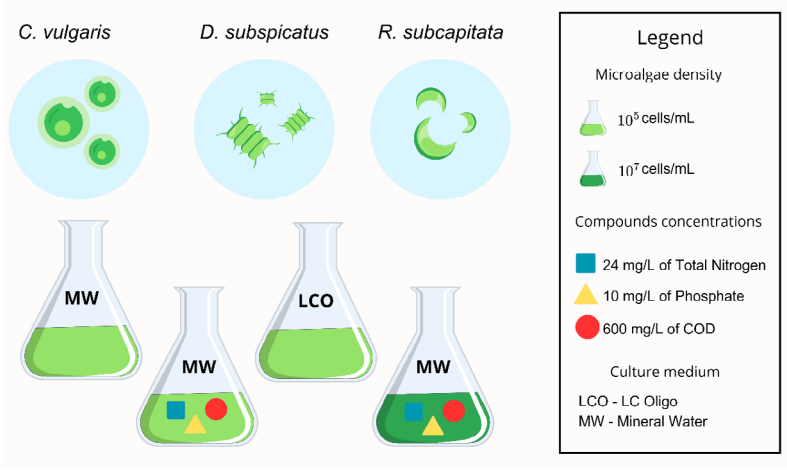


Figure 1 – Schematic of the experimental groups for phycoremediation analyses of organic compounds (COD) and nutrients (total nitrogen and phosphate), conducted separately for each species at two cell densities (10^5 algae·mL^{-1} and 10^7 algae·mL^{-1}) in LC Oligo culture medium (LCO) and mineral water (MW).

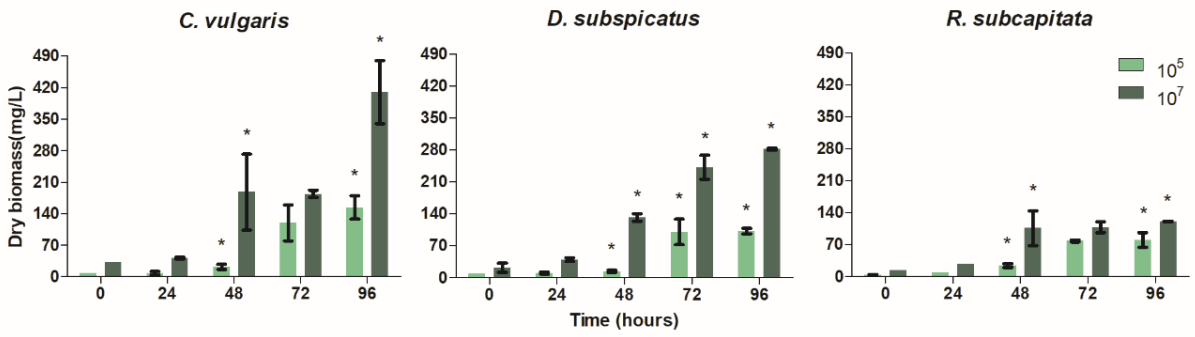


Figure 2 - Biomass production of three microalgae species at two initial densities (10^5 algae·mL^{-1} and 10^7 algae·mL^{-1}) exposed to organic compounds and nutrients over 96 hours.

and the two initial densities evaluated, the best outcome, considering the potential for subsequent biomass applications—such as bioproduct extraction, biodiesel production, or even from a decarbonization perspective—was achieved with *C. vulgaris* in the bioassay conducted at an initial density of 10^7 algae·mL^{-1} ($p < 0.05$), which produced the highest biomass yield (328 mg·L^{-1}) and demonstrated a substantial growth increase (1,181%).

Nutrients removal

The removal of phosphorus (P) and nitrogen (N) from wastewater is particularly important due to their role in promoting eutrophication of water bodies, including lakes, reservoirs, estuaries, and parts of the ocean (Smith; Joye; Howarth, 2006). Furthermore, the direct discharge of untreated or inadequately treated domestic wastewater is the primary source of non-point nutrient pollution in aquatic ecosystems, especially in developing countries (Morée et al., 2013), which poses threats to both ecological systems and public health.

According to the literature, domestic wastewater contributes approximately 6% and 50% of the total nitrogen (TN) and total phosphorus (TP) flux, respectively (Morée et al., 2013; Naden et al., 2016). In aquatic environments, nitrogen typically exists in the form of inorganic and organic nitrogen compounds. The main forms include organic nitrogen, ammonia (NH^{4+} or NH_3), nitrite (NO^{2-}), and nitrate (NO^{3-}). Microalgae absorb all forms of nitrogen as a nutrient, with ammonia and nitrate being the most assimilated forms (Chen; Wang, 2020).

In the present study, after 96 hours of experimentation (across all three microalgal species, $p < 0.05$), the algae density of 10^7 algae·mL^{-1} exhibited the highest efficiency in TN removal across the microalgal species ($p < 0.05$), except for *D. subcapitata* ($p = 0.66$). The bioassay with *C. vulgaris* achieved the highest removal rate of 80% (equivalent to 19.1 mg·L^{-1}), followed by *D. subcapitata* with 71% (16.9 mg·L^{-1}) and *R. subspicatus* with 67% (15.8 mg·L^{-1}). At the lower density of 10^5 algae·mL^{-1}, the reductions were as follows: *C. vulgaris* decreased 69% (equivalent to 18.1 mg·L^{-1}), *D. subcapitata* 63% (14.6 mg·L^{-1}), and *R. subspicatus* 58% (15.0 mg·L^{-1}) (Figure 3A).

Various microalgal species have proven effective in reducing nutrient concentrations in aquatic environments. Green microalgae, in particular, show superior ability in nitrogen removal compared to other species (Zhao et al., 2016). For example, Zhou et al. (2014) evaluated the removal of TN from wastewater using four species of freshwater green microalgae: *Chlamydomonas reinhardtii*, *Scenedesmus obliquus*, *Chlorella pyrenoidosa*, and *Chlorella vulgaris*. After 7 days of incubation, the nitrogen removal rates were 76.7, 88.9, 91.7, and 92.3%, respectively (initial concentration of 6.64 mg·L^{-1}).

The results of the present study align with previous studies, such as the one by Zhou et al. (2014), confirming the high nitrogen removal capacity of green microalgae. Specifically, in their study, *Chlorella vulgaris* achieved a nitrogen removal rate of 92.3%, slightly higher than the 80% observed in the present study after 96 hours. This highlights the efficiency of *C. vulgaris* in nitrogen uptake across both studies. Notably, the current study achieved substantial nitrogen removal within a shorter experimental period (4 days compared to 7 days in Zhou et al., 2014), indicating a faster nitrogen removal capacity. In addition to *C. vulgaris*, *D. subcapitata* and *R. subspicatus* also demonstrated effective nitrogen removal, with rates of 71% and 67%, respectively, at the higher density. These findings suggest that all three species are capable of contributing to nutrient removal, though *C. vulgaris* consistently outperformed the others in terms of TN removal.

Qin et al. (2021) demonstrated that the simultaneous supply of ammonium (NH^{4+}) and nitrate (NO^{3-}) in photobioreactors enhances microalgal nitrogen assimilation and supports biodiesel production, highlighting the benefits of mixed nitrogen sources for microalgal growth. The relationship between nitrogen uptake and growth is complex, with nitrogen availability affecting cellular components and biomass production (Giordano; Raven, 2014; Qin et al., 2021). As observed, species with higher growth rates tend to show more efficient nutrient uptake, reinforcing the connection between nitrogen assimilation, growth rate, and biomass production. Additionally, the results obtained at the higher density (10^7 algae·mL^{-1}) emphasize the importance of optimizing algae concentration for improved nutrient removal, which is a significant finding for practical applications in wastewater treatment.

Another nutrient evaluated in this context was phosphorus, a critical factor in water quality. Excess phosphorus in aquatic systems often leads to eutrophication, which can result in algal blooms, hypoxia, and ecological imbalances. Phosphorus exists in two primary forms in aquatic systems: dissolved and particulate. The dissolved phase includes inorganic and organic phosphorus, while the particulate phase comprises phosphorus adsorbed onto particles, precipitates, and amorphous forms. These particulate forms can undergo hydrolysis, releasing soluble orthophosphate, the only bioavailable form directly utilized by aquatic organisms (Rout et al., 2021).

As previously mentioned in the evaluation of nitrogen removal, the study by Zhou et al. (2014) also assessed phosphorus removal from wastewater using

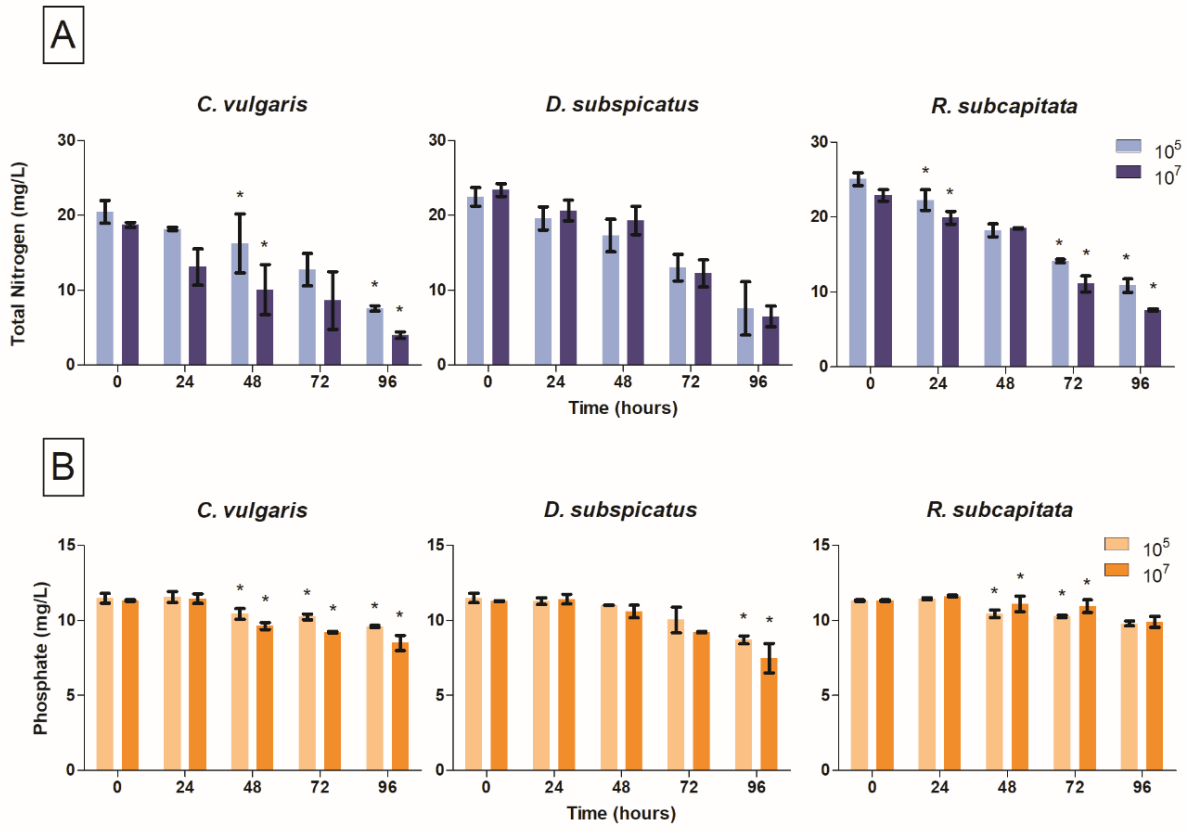


Figure 3 – (A) Total nitrogen and (B) phosphate concentration decay over 96 hours in bioassays with three microalgae species at two densities (10^5 and 10^7 algae·mL^{-1}).

the same four species of green microalgae (*C. reinhardtii*, *S. obliquus*, *C. pyrenoidosa*, and *C. vulgaris*). With an initial phosphorus concentration of 0.15 mg L^{-1}, the phosphorus removal rates after 7 days were 67.5% (equivalent to 0.10 mg·L^{-1}), 70.5% (0.11 mg·L^{-1}), 81.2% (0.12 mg·L^{-1}), and 82.2% (0.12 mg·L^{-1}), respectively, demonstrating the effectiveness of these species in reducing phosphorus concentrations in aquatic systems. In contrast, phosphate removal averaged 21% (equivalent to 2.4 mg·L^{-1}), as shown in Figure 3B. In bioassays with 10^5 algae·mL^{-1}, phosphate reduction was 23% (2.6 mg·L^{-1}) for *D. subspicatus*, 15% (1.7 mg·L^{-1}) for *C. vulgaris*, and 13% (1.5 mg·L^{-1}) for *R. subcapitata*. In bioassays with higher densities (10^7 algae·mL^{-1}), the reduction in phosphate concentration was 34% (equivalent to 3.8 mg·L^{-1}) for *D. subspicatus*, 25% (2.8 mg·L^{-1}) for *C. vulgaris*, and 14% (1.6 mg·L^{-1}) for *R. subcapitata*.

The phosphorus removal efficiency in the present study was lower than in the study by Zhou et al. (2014), where *C. vulgaris* achieved up to 82.2% phosphorus removal (0.12 mg·L^{-1}). The limited phosphorus removal of 0.12 mg·L^{-1} after 7 days can be attributed to the initially low phosphorus availability in the bioassay (0.15 mg·L^{-1}). Most of the phosphorus was rapidly consumed within the first 48 hours, with minimal reduction observed thereafter. On the other hand, the highest removal in this study was 3.8 mg·L^{-1} for *D. subspicatus* at a higher algae density (10^7 algae·mL^{-1}, $p < 0.05$). However, other species in the present study also showed potential, with *C. vulgaris* removing 2.8 mg·L^{-1} ($p < 0.05$) and *R. subcapitata* removing 1.6 mg·L^{-1} ($p < 0.05$). Overall, *D. subspicatus* was the most efficient species in phosphorus removal, particularly at higher algae densities.

Organic matter removal

Mixotrophic cultivation of microalgae, using wastewater as a source of organic carbon, represents a sustainable strategy for wastewater treatment while simultaneously producing valuable bioproducts. Through the use of organic carbon present in wastewater, microalgae such as *Chlorella* sp. and *Scenedesmus* sp. have demonstrated high efficiency in reducing chemical oxygen demand (COD) levels (> 80%) (Chandra et al., 2014; Daneshvar et al., 2018). In addition, the generated biomass can be tailored for biodiesel production or converted into other commercially valuable bioproducts (Cuellar-Bermudez et al., 2017). This dual-purpose process not only enhances wastewater management but also contributes to carbon sequestration, supporting global decarbonization efforts.

The organic load removal efficiency, measured as COD reduction, was evaluated for a microalgae density of 10^5 algae·mL^{-1} after 96 hours. The results showed efficiencies of 85% (equivalent to 515 mg·L^{-1}) for *D. subspicatus*, 84% (507.5 mg·L^{-1}) for *C. vulgaris*, and 78% (472.5 mg·L^{-1}) for *R. subcapitata*. In bioassays conducted with the highest density (10^7 algae·mL^{-1}), the organic load reduction increased to 89% (538.7 mg·L^{-1}) for *C. vulgaris*, 86% (520.0 mg·L^{-1}) for *D. subspicatus*, and 81% (492.5 mg·L^{-1}) for *R. subcapitata*. Across all 96-hour bioassays, COD reductions consistently exceeded 78%, with the highest reductions observed in assays with a density of 10^7 algae·mL^{-1} (Figure 4).

The present study achieved COD reduction efficiencies comparable to those reported in the literature. For instance, reductions of over 78% were consistently

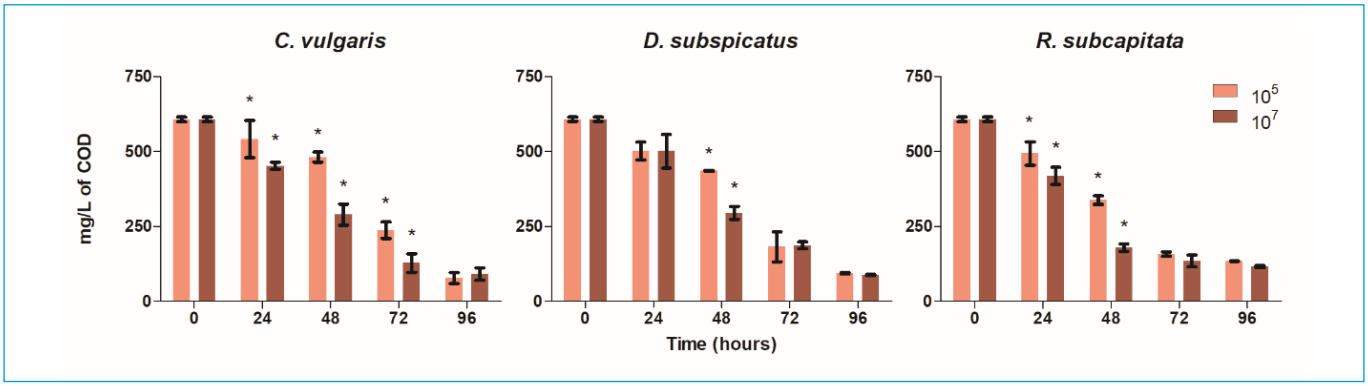


Figure 4 - Chemical oxygen demand (COD) concentration over 96 hours in bioassays with three microalgae species at two densities (10^5 and 10^7 algae·mL^{-1}).

observed in the present study, with peak values reaching 89% at both cell densities ($p > 0.05$), aligning with Chandra et al. (2014) and Daneshvar et al. (2018), who noted over 80% COD reduction in similar contexts. These results highlight the potential of microalgae such as *C. vulgaris* and *D. subspicatus* for effective wastewater treatment ($p = 0.003$).

CONCLUSIONS

The results of this study demonstrate the significant potential of phycoremediation as a sustainable and effective approach for wastewater treatment. Among the evaluated species, *C. vulgaris* at an initial density of 10^7 algae·mL^{-1} achieved the highest biomass production (410 mg·L^{-1}), the greatest TN removal (80%, equivalent to 19.1 mg·L^{-1}), and the most efficient degradation of organic matter (89%, equivalent to 538.7 mg·L^{-1}). Additionally, *D. subspicatus* excelled in phosphate removal, achieving the highest recorded reduction (3.8 mg·L^{-1}) under similar conditions.

In the context of small Brazilian municipalities (around 50,000 inhabitants) lacking basic sanitation, the implementation of decentralized wastewater treatment systems (DWWTS) leveraging phycoremediation is particularly promising. Brazil's abundant land availability and high solar incidence provide ideal conditions for these systems, enabling effective effluent treatment and resource recovery in areas with limited infrastructure. Given its capacity to efficiently treat wastewater, adapt to diverse environmental conditions, and support sustainable development, phycoremediation stands out as a practical and eco-friendly solution for advancing sanitation and environmental management in decentralized contexts.

AUTHORS' CONTRIBUTIONS

Rocha, G.A.C.: Conceptualization, Formal analysis, Methodology, Writing—original draft. Silva, G.C.M.: Conceptualization, Formal analysis, Visualization, Writing—original draft. Moraes, A.P.J.: Formal analysis, Visualization, Writing—original draft. Pinho, T.B.M.: Formal analysis, Writing—original draft. Salomão, A.L.S.: Conceptualization, Resources, Supervision, Writing—review and editing.

DATA AVAILABILITY STATEMENT

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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