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Growth and nutritional composition of *Scenedesmus acuminatus* (Lagerheim) (Chodat, 1902) in an alternative culture medium

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ABSTRACT

This study evaluated the biomass production of the microalga *Scenedesmus acuminatus* using aquaculture effluent as an alternative culture medium. The experiment was conducted in a controlled laboratory environment comparing two treatments: cultivation in aquaculture effluent and in a commercial NPK medium. Population growth, biomass production, nutrient removal efficiency, and the nutritional composition of the produced biomass were analyzed. The results demonstrated that *S. acuminatus* exhibited comparable growth in aquaculture wastewater and the NPK medium, with specific growth rates of 0.20 and 0.34·day^{-1}, respectively, and no significant differences between treatments (p = 0.49). Biomass productivity was also statistically similar between the two culture media. Additionally, *S. acuminatus* efficiently removed ammonia (95.3%) and nitrate (99.4%) from aquaculture wastewater, highlighting its potential as a sustainable biological approach for nitrogen bioremediation. The biomass produced maintained a rich nutritional profile of proteins, lipids, and minerals, indicating its applicability across various industrial sectors. Thus, this study demonstrated that aquaculture wastewater can successfully replace a conventional culture medium for *S. acuminatus*, enabling comparable biomass production and efficient nitrogen removal. These findings provide new evidence supporting the integration of microalgae cultivation with intensive aquaculture as a sustainable strategy for resource recovery and circular bioeconomy.

Keywords: aquaculture effluent; bioremediation; circular economy; microalgae; sustainable.

Crescimento e composição nutricional de *Scenedesmus acuminatus* (Lagerheim) (Chodat, 1902) em meio de cultura alternativo

RESUMO

Este estudo avaliou a produção de biomassa da microalga *Scenedesmus acuminatus* utilizando efluente de aquicultura como meio de cultivo alternativo. O experimento foi conduzido em ambiente laboratorial controlado por meio da comparação de dois tratamentos: cultivo em efluente de aquicultura e em meio comercial NPK. Foram analisados o crescimento populacional, a produção de biomassa, a eficiência de remoção de nutrientes e a composição nutricional da biomassa produzida. Os resultados demonstraram que a *S. acuminatus* apresentou crescimento comparável no efluente de aquicultura e no meio NPK, com taxas de crescimento específico de 0,20 e 0,34·dia^{-1}, respectivamente, sem diferenças significativas entre os tratamentos (p = 0,49). A produtividade de biomassa também foi estatisticamente semelhante entre os dois meios de cultivo. Além disso, a *S. acuminatus* removeu eficientemente amônia (95,3%) e nitrato (99,4%) do efluente de aquicultura, destacando seu potencial como uma abordagem biológica sustentável para a biorremediação de nitrogênio. A biomassa produzida apresentou um perfil nutricional rico em proteínas, lipídios e minerais, indicando sua aplicabilidade em diversos setores industriais. Assim, este estudo demonstrou que o efluente de aquicultura pode substituir com sucesso o meio de cultivo convencional para a *S. acuminatus*, permitindo uma produção de biomassa comparável e uma remoção eficiente de nitrogênio. Essas descobertas fornecem novas evidências que apoiam a integração do cultivo de microalgas à aquicultura intensiva como estratégia sustentável para a recuperação de recursos e a bioeconomia circular.

Palavras-chave: biorremediação; economia circular; efluente da aquicultura; microalgas; sustentabilidade.

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INTRODUCTION

Microalgae play a critical role in the bio-based economy due to their ability to produce renewable biomass that can be converted into high-value products for the food, feed, pharmaceutical, and cosmetic sectors (Brandão et al., 2023; Sutherland et al., 2021). However, commercial-scale biomass production remains insufficient to meet the growing global demand (Acién et al., 2012; Kusmayadi et al., 2021; Nour et al., 2024). This limitation arises primarily from the high production costs associated with large-scale cultivation (Acién et al., 2012). A significant portion of these costs is attributed to the use of commercial culture media and freshwater (Acién et al., 2017; Nour et al., 2024). The cost of producing microalgae is different from one region to another. In Brazil, aquaculture is growing, but high prices for freshwater and co-fermentation media make it difficult for small and medium producers to use microalgae technologies at scale (Pereira et al., 2024). Even in developed countries, these costs keep microalgal biomass from competing with traditional products. This underscores the importance of finding cheaper ways to grow microalgae, such as using aquaculture wastewater as a nutrient source (Dias et al., 2025; Guieysse & Plouviez, 2024).

Given the challenge of increasing microalgae biomass production in a sustainable and economically viable manner, numerous studies have sought to develop cost-reduction strategies that yield positive environmental impacts, such as reduced reliance on natural resources, including potable water and synthetic fertilizers (Goh et al., 2022; Mendonça et al., 2021). One such promising approach involves the use of effluents from various sources (*e.g.*, industrial, domestic, agricultural, and aquaculture) as culture media, given their high nutrient content (*e.g.*, nitrogen and phosphorus), thereby replacing commercial culture media such as BG11, Bold, and BBM (Brandão et al., 2023; He et al., 2023).

Among the various types of effluents employed as alternative culture media, aquaculture effluents offer distinct advantages due to the absence of heavy metals and pharmaceutical residues, which are commonly present in industrial and domestic effluents and may restrict the application of the resulting biomass. The northern region of Brazil is one of the country's leading producers of native fish, but the expansion of aquaculture is constrained by environmental regulations and limited land availability. In the Brazilian Amazon, the requirement to maintain 80% of forested rural properties as legal reserve under the Brazilian Forest Code limits the area available for agricultural production (Brasil, 2012). Consequently, technologies that increase production efficiency through nutrient recycling and resource recovery are particularly important for the sustainable development of aquaculture in the region. Intensive aquaculture systems, such as bioflocs, have demonstrated promising results (Santos et al., 2024). Biofloc technology is characterized by minimal water renewal and high organic matter inputs, including uneaten feed, fertilizers, and excretory products, resulting in effluents that are nutrient-rich and have a significantly high nutrient load (Alonso-Rodriguez and Paez-Osuna, 2003; Santos et al., 2024).

Thus, the integrated generation of microalgae biomass and the bioremediation of effluents from intensive aquaculture systems represent a viable approach to developing more productive and environmentally sustainable systems while fostering the creation of novel products derived from microalgae biomass, which is rich in lipids, proteins, carbohydrates, and other value-added compounds with different applications (nutraceuticals, pet food) (Ansari et al., 2017; Vuppaladadiyam et al., 2018). In this context, the present study utilized a wild strain isolated from the Amazon region to evaluate its biomass production potential using effluent from an intensive matrinxã (*Brycon amazonicus*) breeding system.

Therefore, the general objective of this study was to evaluate the feasibility of using aquaculture effluent as an alternative culture medium for *Scenedesmus acuminatus*. Specifically, the study aimed to:

- Compare the growth performance and biomass production of *S. acuminatus* cultivated in aquaculture effluent and a conventional NPK medium;
- Determine the nutritional composition of the biomass produced in aquaculture effluent;
- Evaluate the nutrient removal efficiency of *S. acuminatus* during cultivation in aquaculture effluent.

MATERIAL AND METHODS

To evaluate the effects of aquaculture effluent on the growth and biomass production of *S. acuminatus*, as well as the nutritional composition of the resulting biomass and its nutrient removal efficiency, a laboratory experiment was conducted under controlled conditions for 10 days using inocula standardized to the same initial cell density. The cultivation period was selected because preliminary growth monitoring indicated that *S. acuminatus* reached the stationary phase within this timeframe, allowing reliable comparisons of growth performance, biomass production, nutrient removal, and biomass composition between treatments.

We utilized water from a super-intensive matrinxã (*B. amazonicus* production system, maintained in a circular suspended tank constructed from PVC laminate (total volume of 9,740 L).

The tank was stocked with fish weighing 15–20 grams at a density of 400 organisms·m^{-3}. The organisms were reared for two months, achieving a productivity of 21 kg·m^{-3} without water replacement. As a control, we used agricultural NPK fertilizer (Sipaúba-Tavares & Rocha, 2003), since the strain was already adapted to this formulation.

Initial inoculum and effluent disinfection

The inoculum of *S. acuminatus* was obtained from the microalgae bank of the Plankton Laboratory at the National Institute for Amazonian Research (INPA). The *S. acuminatus* strain was cultivated in transparent 1 L containers using an NPK culture medium formulated with 3.024 g·L^{-1} of urea, 0.24 g·L^{-1} of triple superphosphate, and 0.363 g·L^{-1} of potassium chloride. The cultivation conditions were maintained at 28 ± 0.5°C, with a 12/12-hour photoperiod, 1,600 lux illumination (provided by two 40W 6000K slim LED lamps), and constant aeration. These conditions were used considering that the strain is already adapted to them.

We collected a total of 60 L of effluent and stored it in a bucket to allow solids to settle for 30 minutes. We filtered the supernatant sequentially through a 55-µm mesh screen and then a 20-µm mesh screen. After filtration, the water was stored in a light-protected container and treated with 20 mg·L^{-1} of NaClO (Castro-Mendes et al., 2024). This container was aerated for 24 hours until the experiment was initiated. The effluent composition included: nitrate (196.68 mg·L^{-1}), ammonia (12.7 mg·L^{-1}), total suspended solids (278.48 mg·L^{-1}), orthophosphate (0.35 mg·L^{-1}), alkalinity (83 mg·L^{-1} $CaCO_3$), and pH (7.37).

Experimental design

The experiment was conducted in a controlled indoor environment. The cultivation conditions for both treatments were maintained at 28 ± 0.5°C, with 1,600 lux illumination provided by white LED lamps (40W 6000K slim LED lamps) and a 12/12-hour photoperiod. Two treatments were established: aquaculture wastewater (AWW) and NPK culture medium (control treatment, identical to the inoculum formulation). Each treatment consisted of three rectangular transparent plastic containers with a working volume of 25 L.

In the AWW treatment, each container received 15 L of effluent and 5 L of initial inoculum. In the NPK treatment, each container received 15 L of filtered water (distilled water) supplemented with the concentrated NPK culture medium (identical to the inoculum formulation) and 5 L of initial inoculum. The initial inoculum density was 943 cells·mL^{-1} in both treatments. Each container was aerated using hoses connected to a 1.5-kW air blower, which ensured continuous homogenization of the culture. The experiment lasted 10 days, with 250-mL samples taken from each cultivation container every 48 hours to estimate algal cell density and quantify nutrient concentrations.

Growth of *Scenedesmus acuminatus*

We estimated cell abundance using a Sedgewick-Rafter chamber. Based on the density values obtained, growth curves, maximum cell density, and the specific growth rate (µ) were determined. The specific growth rate represents the cell growth rate during the exponential phase of the growth curve, expressed in day^{-1} (Eq. 1).

$$\mu = \frac{In\,(N\,(t)/N_0)}{(t - t_0)} \quad (1)$$

where: $N(t)$: the cell number (cells·mL^{-1}); N_0: the initial cell number (cells·mL^{-1}); t: the time (days); t_0: the initial day of incubation (days).

Dry biomass production

Dry biomass yield (g·L^{-1}) was determined from initial and final aliquots (100 mL each), with three replicates per treatment. Whatman GF/C glass microfiber filters (1.2 µm) were used. They were pre-dried in an oven at 60°C for 24 hours and weighed on an analytical balance (0.05 mg precision) until constant mass was achieved. Subsequently, 100 mL of the initial and final samples from each treatment were filtered using a vacuum pump. After filtration, the filters were placed in an oven (60°C for 24 hours) and reweighed on an analytical balance until constant mass was achieved.

Nutrient analysis of the culture medium

For dissolved nutrient analysis, we filtered 100 mL of the samples using Whatman GF/C glass microfiber filters (1.2 µm) with a vacuum pump. To measure orthophosphate (PO_4^{3-}) and nitrate (NO_3^-) concentrations, we followed the method described by Golterman et al. (1978), while ammonia (NH_4^+) was analyzed according to Koroleff (1970). In both cases, we used spectrophotometric techniques and generated calibration curves with specific standards for each nutrient. Nutrient removal efficiency (RE%) was determined using Eq. 2:

$$RE = \frac{S_0 - S_f}{S_0} \times 100\% \quad (2)$$

Where: S_0: the initial concentration of a given nutrient at time t_0; S_f: the final concentration at time t_f.

Proximate composition

To evaluate the nutritional composition of the biomass, we collected biomass from each treatment separately at the end of the experiment using a centrifuge (2,500 rpm, 578 g for 10 min). The samples were then frozen at -80°C and lyophilized (model L101, Liobras, Brazil) at -55°C and 0.13 mbar for 48 hours.

Moisture, ash, and crude protein contents were determined according to the official methods of the Association of Official Analytical Chemists (AOAC, 2016), using Method 934.01 for moisture, Method 942.05 for ash, and Method 978.04 (Kjeldahl method) for crude protein. Total lipids were extracted and quantified following the method of Bligh and Dyer (1959).

Mineral composition analysis

The mineral composition of the freeze-dried biomass was determined according to the methodology described by Zenebon et al. (2008). Samples were subjected to microwave-assisted acid digestion using concentrated nitric acid in a closed-vessel digestion system (MARS Xpress, CEM Corporation, United States of America). After complete mineralization of the organic matrix, the digests were cooled, diluted with deionized water, and analyzed by flame atomic absorption spectrometry (SpectrAA 220 FS, Agilent Technologies, Australia) using element-specific hollow cathode lamps. Calcium (Ca), potassium (K), sodium (Na), magnesium (Mg), iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu) were quantified according to the analytical procedures established by Zenebon et al. (2008).

Determination of fatty acids

Fatty acid methyl esters were analyzed by gas chromatography coupled to mass spectrometry (GCMS-QP2010 Plus, Shimadzu, Kyoto, Japan). Compounds were separated using a fused silica capillary column (RTX-5, 30 m × 0.25 mm i.d., 0.25 µm film thickness). The oven temperature was programmed from 80 to 220°C at a rate of 5°C·min^{-1}. The injector temperature was maintained at 230°C, and helium was used as the carrier gas at a linear velocity of 40 cm·s^{-1}. Samples were injected using a split ratio of 1:50. Fatty acids were identified by comparing the retention times and mass spectra with those of authentic fatty acid methyl ester standards. Quantification was performed using chromatographic peak area normalization, as described in AOAC International (2016).

Data analysis

To characterize the population growth and nutritional composition of *S. acuminatus*, growth curves were constructed using the mean cell density values recorded throughout the cultivation period, and descriptive statistics were calculated for biomass composition. Prior to statistical analyses, data normality was assessed using the Shapiro–Wilk's test. Since the experiment consisted of two independent treatments (AWW and NPK) and the data satisfied the assumption of normality, differences between treatments were evaluated using Student's *t*-test for independent samples. Statistical significance was established at $p < 0.05$. All statistical analyses were performed using Jamovi software (version 2.3.28, 2022).

RESULTS

The growth curve of *S. acuminatus* in the AWW treatment exhibited a lag phase of only one day. Exponential growth commenced 48 hours after the initiation of cultivation and continued until the eighth day, when the maximum cell density ($3x10^4$ cells·mL^{-1}) was reached. This was followed by the senescence phase from the ninth day onwards (Fig. 1). In the NPK control treatment, the lag phase lasted for two days. The exponential growth phase was shorter compared to the AWW treatment, lasting only two days and reaching maximum cell density on the sixth day (Fig. 1). The specific growth rate was 0.20·day^{-1} in the AWW treatment and 0.34·day^{-1} in the NPK treatment, but this difference was not statistically significant ($p = 0.49$).

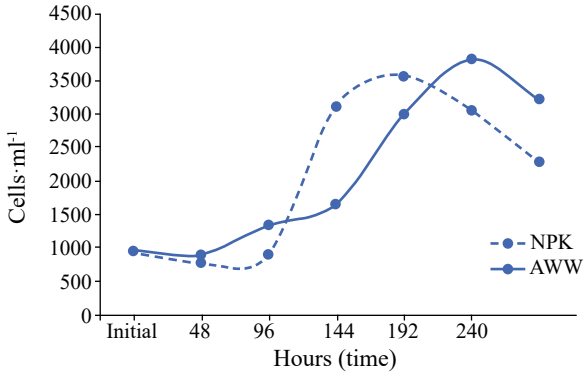


Figure 1. Growth curve of *Scenedesmus acuminatus* in aquaculture effluent and NPK culture medium.

The nutritional composition of the *S. acuminatus* biomass was comparable between treatments (Table 1).

Biomass production of *S. acuminatus* did not differ significantly between treatments ($p > 0.05$), with average yields of 0.47 g·L^{-1} in the AWW treatment and 0.53 g·L^{-1} in the NPK control treatment. The nutrient removal efficiency (RE%) in the AWW treatment was 95.3% for ammonia, 99.4% for nitrate, and

Table 1. Nutritional composition of *Scenedesmus acuminatus* biomass cultivated in aquaculture wastewater (AWW) effluent and NPK commercial culture medium.

Parameter	AWW	NPK
Proximate composition (%)		
Crude protein	16.54 ± 0.07	17.86 ± 0.05
Ash	15.88 ± 0.65	16.43 ± 0.02
Lipids	2.44 ± 0.05	1.98 ± 0.20
Fatty acid profile (%)		
Myristic acid (C14:0)	41.51 ± 0.04	38.13 ± 0.01
Palmitic acid (C16:0)	22.72 ± 0.03	23.06 ± 0.04
Oleic acid (C18:1)	27.13 ± 0.03	16.51 ± 0.02
Stearic acid (C18:0)	5.29 ± 0.13	9.65 ± 0.53
Mineral composition (mg·100 g^{-1})		
Calcium (Ca)	177.07 ± 2.01	144.27 ± 2.12
Magnesium (Mg)	444.07 ± 2.61	439.03 ± 1.63
Potassium (K)	284.10 ± 1.96	276.03 ± 4.02
Sodium (Na)	32.75 ± 0.97	30.58 ± 0.51
Manganese (Mn)	8.53 ± 0.09	7.01 ± 0.12
Copper (Cu)	0.38 ± 0.03	0.37 ± 0.02
Zinc (Zn)	13.78 ± 0.06	15.07 ± 0.65
Iron (Fe)	24.22 ± 1.06	23.29 ± 0.07

13.3% for orthophosphate. In the NPK treatment, the removal efficiencies for ammonia, nitrate, and orthophosphate were 96.4, 99.4, and 52.2, respectively (Table 2).

Table 2. Initial and final concentration of the culture media: aquaculture wastewater (AWW) culture medium and NPK culture medium.

Nutrient	Culture medium	Initial (mg·L^{-1})	Final (mg·L^{-1})
Ammonia (NH_4^+)	AWW	12.7 ± 0.12	0.6 ± 0.10
	NPK	16.9 ± 2.04	0.06 ± 0.07
Nitrate (NO_3^-)	AWW	196.68 ± 5.01	1.24 ± 0.98
	NPK	240.49 ± 3.04	0.25 ± 0.08
Orthophosphate (PO_4^{3-})	AWW	0.362 ± 2.15	0.314 ± 0.14
	NPK	0.484 ± 0.05	0.232 ± 0.02

DISCUSSION

Aquaculture generates large volumes of nutrient-rich effluents containing high concentrations of nitrogen and phosphorus, which represent both an environmental challenge and a valuable resource for nutrient recovery through phycoremediation (Gupta et al., 2024; Magnotti et al., 2016). By assimilating these nutrients, microalgae can simultaneously improve wastewater quality while converting residual nutrients into biomass with potential applications in animal feed, biofertilizers, bioenergy, and other bio-based products, thereby contributing to circular bioeconomy strategies (Brandão et al., 2023; Sutherland et al., 2021). Therefore, this study evaluated the potential of wastewater from a super-intensive matrinxã (*B. amazonicus*) production system as an alternative culture medium for *S. acuminatus*, with emphasis on growth performance, biomass productivity, nutritional composition, and nutrient removal efficiency.

The growth curves observed in both treatments followed the typical pattern expected for microalgal cultivation, encompassing the lag, exponential, and stationary phases. *Scenedesmus acuminatus* exhibited satisfactory adaptation to aquaculture wastewater after being transferred to larger cultivation volumes, achieving growth performance and biomass productivity comparable to those observed in the conventional NPK medium. Several factors intrinsic to the cultivation system may influence microalgal adaptation during scale-up, including light availability, cultivation system configuration (open or closed), temperature, and culture medium composition.

Among these factors, the only variable modified in the present study was the replacement of the conventional NPK medium with aquaculture wastewater. In addition to supplying nitrogen and phosphorus, the aquaculture effluent provided nitrogen in readily available inorganic forms, including ammonium (NH_4^+) and nitrate (NO_3^-), whereas the conventional medium supplied nitrogen primarily as urea. Although *Scenedesmus* spp. are capable of utilizing urea through urease-mediated hydrolysis, the immediate availability of inorganic nitrogen in the effluent may have favored nutrient uptake during the initial stages of cultivation, contributing to the satisfactory adaptation of the inoculum (Markou et al., 2014; Sanz-Luque et al., 2015). Furthermore, aquaculture wastewater is a chemically complex medium that contains dissolved organic matter, micronutrients, and indigenous microbial communities, which may further support microalgal growth and nutrient recycling (Gupta et al., 2024). Therefore, comprehensive physicochemical and microbiological characterization of wastewater is essential to evaluate its suitability as an alternative culture medium for microalgae.

Algal biomass production is a critical factor when considering strategies to reduce production costs while maintaining productivity (Brandão et al., 2023). Our findings suggest that the use of aquaculture effluent did not negatively impact the biomass production of the local *S. acuminatus* strain cultivated in the AWW treatment, as the difference in biomass yield compared to the NPK treatment was only 0.06 $g \cdot L^{-1}$. The biomass production values obtained were consistent with those reported in the literature for species of the same genus cultivated in polluted waters from different sources (Table 3). These results support the feasibility of sustaining algal biomass production solely using aquaculture effluents, thereby reducing production costs by eliminating the need for commercial culture media and decreasing dependence on chemical fertilizers. This approach contributes to the development of circular and more sustainable production systems (Moraes et al., 2022). Moreover, the effluent did not require dilution before because it reduces the demand for clean water and promotes the reuse of this vital natural resource.

One of the key advantages of using microalgae for nutrient recovery from polluted water is the accumulation of bioactive compounds in the biomass during growth. These compounds include proteins, fatty acids, vitamins, and minerals, which have applications in various industries, such as pharmaceuticals, biofuels, biofertilizers, and both human and animal nutrition (Brandão et al., 2023). As shown in Table 1, the elemental composition of the biomass was similar between treatments, suggesting that aquaculture effluent can serve as a viable alternative culture medium for *S. acuminatus* without compromising its nutritional quality. This biomass could be applied in multiple industrial sectors, including the extraction of high-value substances or the direct production of live feed for fish larvae, mollusks, and shrimp (Fioresi and Sipaúba-Tavares, 2008; Magnotti et al., 2016).

Cultivation of *S. acuminatus* in aquaculture effluent produced biomass with biochemical characteristics comparable to those obtained in the conventional NPK medium, demonstrating that

Table 3. Comparison of *Scenedesmus acuminatus* biomass cultivated in different effluent types.

Species	Culture media/type of effluent	Yield ($g \cdot L^{-1}$)	Cultivation time	Reference
S. acuminatus	Aquaculture	0.47	10	Present study
S. obliquus	Domestic	1.44	11	He et al. (2023)
S. obliquus	Swine	0.83	11	He et al. (2023)
Scenedesmus sp.	Municipal	0.73	14	Silambarasan et al. (2021)
S. obliquus	Agriculture	0.47	14	Tan et al. (2023)
S. obliquus	Agriculture	2.92	14	Tan et al. (2023)
Scenedesmus sp.	Domestic	3.4	8	Devi et al. (2022)
Scenedesmus sp.	Agriculture	2.4	7	Yuan et al. (2021)
S. quadricauda	Biopharmaceuticals	0.35	10	Chen et al. (2023)

replacing the conventional culture medium did not compromise biomass quality. Similar studies have reported that *Scenedesmus* spp. cultivated in wastewater can maintain biochemical characteristics comparable to those obtained in conventional media, reinforcing the feasibility of wastewater as an alternative nutrient source while preserving the industrial value of the biomass (Devi et al., 2022; Gupta et al., 2024).

The biomass produced in the present study contained several compounds of industrial interest. Among the identified fatty acids, myristic, palmitic, oleic, and stearic acids are widely used in different industrial sectors. Myristic and stearic acids are important raw materials for the manufacture of cosmetics, soaps, surfactants, and pharmaceutical excipients, whereas palmitic and oleic acids have broad applications in the food, cosmetic, oleochemical, and biodiesel industries due to their functional and physicochemical properties (Chisti, 2007; Vyas et al., 2022). These findings indicate that cultivation in aquaculture effluent preserves the biochemical profile required to produce several value-added bioproducts.

In addition to its lipid composition, the biomass exhibited considerable concentrations of essential mineral nutrients, particularly magnesium (441.06 $mg \cdot 100\ g^{-1}$), potassium (281.84 $mg \cdot 100\ g^{-1}$), calcium (179.39 $mg \cdot 100\ g^{-1}$), iron (24.88 $mg \cdot 100\ g^{-1}$), and zinc (13.77 $mg \cdot 100\ g^{-1}$). These elements play fundamental roles in plant physiology, including chlorophyll biosynthesis, enzyme activation, osmotic regulation, photosynthesis, and cellular metabolism.

Therefore, the mineral composition quantified in the present study provides experimental evidence supporting the potential application of *S. acuminatus* biomass as a raw material for biofertilizer or biostimulant formulations, complementing its organic composition with the supply of essential macro- and micronutrients required for plant growth (Dagnaisser et al., 2022; Vuppaladadiyam et al., 2018).

Beyond producing biomass with industrial and agricultural potential, cultivation in aquaculture effluent promoted efficient nutrient recovery, removing 95.3% of ammonia and 99.4% of nitrate from the wastewater. This demonstrates the dual functionality of the proposed approach, which simultaneously generates value-added biomass and mitigates the environmental impacts associated with nutrient-rich aquaculture effluents. Collectively, these findings demonstrated that aquaculture effluent can successfully replace conventional NPK medium without compromising the growth performance, biomass productivity, or nutritional quality of *S. acuminatus*. Furthermore, the integration of nutrient recovery, phycoremediation, and biomass production reinforces the potential of this cultivation strategy to support more sustainable and circular aquaculture production systems.

The relatively low orthophosphate removal observed in aquaculture wastewater (13.3%) is likely attributable to the low initial orthophosphate concentration (0.362 $mg \cdot L^{-1}$), which was substantially lower than the medium's orthophosphate concentration. Under phosphorus-limited conditions, phosphorus uptake is primarily constrained by nutrient availability rather than by microalgae's assimilative capacity (Markou et al., 2014). In contrast, the conventional NPK medium contained a higher initial orthophosphate concentration (0.484 $mg \cdot L^{-1}$), resulting in greater phosphorus removal (52.1%). This outcome aligns with the established positive relationship between phosphorus availability and microalgal uptake. Additionally, the limited phosphorus concentration in the aquaculture effluent likely inhibited luxury phosphorus uptake, a phenomenon in which microalgae accumulate phosphorus more than their immediate metabolic requirements when it is abundant (Powell et al., 2009).

Despite lower orthophosphate removal, *S. acuminatus* cultivated in aquaculture wastewater achieved growth performance, biomass productivity, and nutritional quality comparable to those observed in the conventional NPK medium. This result indicated efficient utilization of available phosphorus for biomass synthesis rather than intracellular phosphorus storage. These findings demonstrated that *S. acuminatus* can efficiently convert the limited phosphorus available in aquaculture wastewater into biomass while simultaneously removing 95.3% of ammonia and 99.4% of nitrate. This dual functionality underscores the potential of this species as a biological platform for integrated aquaculture wastewater treatment and biomass production, thereby contributing to nutrient recovery and supporting circular bioeconomy strategies (Markou et al., 2014).

CONCLUSION

This study demonstrated that AWW can successfully replace conventional NPK medium for the cultivation of *S. acuminatus* without compromising growth performance, biomass productivity, or overall nutritional quality. In addition to supporting efficient biomass production, cultivation in AWW removed 95.3% of ammonia and 99.4% of nitrate, demonstrating the dual functionality of this approach for wastewater treatment and biomass generation.

Although the proximate composition of the biomass was similar between treatments, cultivation in AWW resulted in biomass enriched in selected minerals and monounsaturated fatty acids, indicating that this alternative culture medium can preserve or even enhance the production of compounds with industrial and agricultural value. These findings demonstrated that aquaculture effluent represents a viable substitute for conventional culture media, reducing dependence on commercial fertilizers while promoting nutrient recovery and the valorization of aquaculture waste streams.

Overall, this study provides experimental evidence that integrating microalgal cultivation with aquaculture effluent management is a feasible strategy for simultaneously producing value-added biomass and recovering nutrients from wastewater. This integrated approach contributes to the development of more sustainable aquaculture systems and supports the implementation of circular bioeconomy principles through the reuse of residual resources and the reduction of environmental impacts.

CONFLICT OF INTEREST

Nothing to declare.

DATA AVAILABILITY STATEMENT

Data will be provided upon request.

AUTHORS' CONTRIBUTION

Conceptualization: Nascimento, R.G., Castro-Mendes, R., Santos-Silva, E.N.; **Formal Analysis:** Nascimento, R.G., Castro-Mendes, R.; **Investigation:** Nascimento, R.G.; **Resources:** Nascimento, R.G.; **Supervision:** Nascimento, R.G., Castro-Mendes,

R., Santos-Silva, E.N.; **Validation:** Nascimento, R.G., Castro-Mendes, R., Aguiar, J.P.L., Souza, F.C.A., Santos-Silva, E.N.; **Data curation:** Nascimento, R.G., Castro-Mendes, R., Aguiar, J.P.L., Souza, F.C.A., Santos-Silva, E.N.; **Writing – original draft:** Nascimento, R.G.; **Writing – review & editing:** Nascimento, R.G., Castro-Mendes, R., Aguiar, J.P.L., Souza, F.C.A., Santos-Silva, E.N.; **Final approval:** Nascimento, R.G., Castro-Mendes, R., Aguiar, J.P.L., Souza, F.C.A., Santos-Silva, E.N.

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DECLARATION OF USE OF ARTIFICIAL INTELLIGENCE TOOLS

Grammarly (version 1.2.300.1965) was used as a supporting tool for grammatical and linguistic revision to identify and correct potential grammatical, spelling, and punctuation errors and to improve the clarity and flow of the writing. The author remains responsible for the scientific content, interpretation of the results, and conclusions.

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