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Aquaponics as a Sustainable Approach for Producing Mahogany (*Swietenia macrophylla*) Seedlings with Effluent from Tambaqui (*Colossoma macropomum*) Farming

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Abstract

Aquaculture in the Amazon region has considerable potential to promote the sustainable use of natural resources. The integration of fish farming and forest has emerged as a resource-efficient strategy for sustainable production. This study aimed to evaluate the growth of mahogany (*Swietenia macrophylla*) seedlings in integrated systems with tambaqui (*Colossoma macropomum*), using different spacings (5, 10, 15, 20 and 25 cm) between seedlings. After 56 days of cultivation, dissolved oxygen, conductivity, total ammonia, and nitrate were significantly affected in the systems ($p < 0.05$). Tambaqui growth performance differed significantly between the aquaponic systems ($p < 0.05$). Regarding mahogany seedlings, root fresh mass, collar diameter, and the Dickson quality index were also significantly affected by the treatments ($p < 0.05$). The results demonstrate that aquaculture–forestry integration, using tambaqui effluent as a nutrient source for mahogany seedlings, is a technically viable and environmentally promising production strategy. Among the treatments evaluated, the 25 cm spacing produced seedlings with superior quality attributes, suggesting that wider spacing may promote seedling development under aquaponic conditions. These findings highlight the potential of integrated aquaponic systems for the sustainable production of both forestry and aquatic resources in the Amazon region.

Keywords: aquaculture; aquaponics; fish farming; forestry; sustainability

Academic Editors: Panagiotis Berillis and Nikolaos Vlahos

Received: 8 May 2026
Revised: 5 June 2026
Accepted: 10 June 2026
Published: 11 June 2026

1. Introduction

Aquaculture in the Amazon region has considerable potential to enhance food security, generate income, and promote the sustainable use of natural resources [1]. This is particularly evident through the cultivation of native species such as tambaqui (*Colossoma macropomum*) and other local species in integrated systems and polycultures, which can increase productivity and environmental efficiency [2–4]. However, the expansion of aquaculture in the Amazon region is constrained by technical and structural challenges [1].

The integration of aquaculture and forest has emerged as a resource-efficient strategy for sustainable production [5], particularly when implemented in ecologically sensitive tropical regions such as the Amazon region. In this context, effluents derived from the cultivation of tambaqui represent a relevant source of nutrients for plant growth, particularly due to their high concentrations of dissolved nitrogen compounds originating from fish metabolism [6–8]. During fish cultivation, metabolic waste is primarily excreted as ammonia, which is subsequently converted into nitrite and nitrate by nitrifying bacteria [9]. These forms are readily assimilated by plants, thereby enhancing nutrient availability and promoting efficient nutrient cycling within integrated systems such as aquaponics [6,10]. Such processes contribute to improved system sustainability and productivity.

Currently, in the Amazon region, the integration of aquaculture and agriculture through aquaponics has demonstrated the potential to reduce costs and recycle nutrients by using fish-farming effluent to fertilise plants such as Jambu (*Acmella oleracea*), thereby strengthening the local bioeconomy [11]. This approach is gaining attention, and sustainable aquaculture in the Amazon should focus on increasing production while addressing environmental concerns such as greenhouse gas emissions and land-use change, as well as promoting social equity for local communities [1]. Diversifying species through polyculture systems involving native species can help to reduce pressure on wild stocks and contribute to sustainable regional development [3,4].

Integrated systems also enhance environmental sustainability by reducing the discharge of nutrient-rich effluent into aquatic ecosystems, thereby lowering the risk of eutrophication [12]. Moreover, these systems improve production efficiency by combining aquaculture and plant cultivation within a circular resource-use framework [13,14]. The reuse of aquaculture wastewater in plant production may help reduce dependence on synthetic fertilisers and decrease water consumption compared with conventional farming methods [5]. This approach promotes nutrient recycling and mitigates environmental impacts [8,10], particularly in regions where water availability and input costs are limiting factors.

Among tropical forest species, mahogany (*Swietenia macrophylla*) is of particular interest due to its high commercial value and ecological importance. However, overexploitation has led to a decline in natural populations [15], reinforcing the need for efficient seedling production systems to support reforestation and sustainable forest management [16]. Seed germination and early seedling development are strongly influenced by nutrient and water availability [17–19]. In this regard, tambaqui effluents may provide favourable conditions for seedling establishment, as they supply essential nutrients that support root development and biomass accumulation.

Despite these advances, aquaculture in the Amazon continues to face challenges related to technology and waste management, which must be addressed for its full potential to be realised [1,20]. Studies evaluating the use of aquaculture effluents for the production of forest tree seedlings remain limited. Accordingly, this study aimed to evaluate the growth of mahogany seedlings in integrated systems with tambaqui fish, using different spacings (5, 10, 15, 20 and 25 cm) between seedlings and employing effluents from fish farming tanks as a nutrient source for the mahogany. It is expected that this approach will contribute to the development of sustainable, integrated production systems in the Amazon region.

2. Materials and Methods

The study on Brazilian mahogany was conducted at the Laboratory of Amazonian Aquaculture Biosystems (BIOAQUAM) at the Federal Rural University of the Amazon (UFRA), Belém, Pará, Brazil (1°27′30″ S; 48°28′12″ W). The experiment was carried out between October and December 2024, corresponding to the species' natural seed dispersal period. The study was approved in August 2023 by the Animal Ethics Committee of UFRA (CEUA/UFRA) under protocol number 8598010323.

2.1. Experimental Design

The experiment was conducted using Brazilian mahogany seedlings, arranged into five treatments corresponding to different spacings (5, 10, 15, 20, and 25 cm) between seedlings. Each group comprised eight replicates. In this study, a spacing of 15 cm was adopted as the control treatment, as it represents a value within the range commonly used in mahogany nurseries [21] and is associated with lower levels of competition among seedlings, being frequently used as a reference in studies on seedling density and quality [22,23]. Each treatment, comprising eight seedlings, was connected to an independent aquaponic unit for tambaqui cultivation. The limited number of seedlings in each treatment was due to restrictions on the use of seeds from endangered tree species in Brazil, imposed by stringent environmental protection legislation for species such as Brazilian mahogany.

The aquaponic systems, based on the nutrient film technique (NFT), were installed in a protected greenhouse constructed with a wooden frame and covered with transparent low-density polyethylene (0.150 mm thickness). The structure had a total area of 96.0 m^2 (8.0 m × 12.0 m) and a height of 3.0 m. The sides of the greenhouse were left open to allow air circulation. Each aquaponic unit consisted of a recirculating system comprising a 1000 L polyethylene fish tank (Fortlev® residential water tank, Araquari, SC, Brazil), from which water flowed into a 100 L decanter connected to a 100 L biofilter, both constructed from high-density polyethylene (HDPE) drums. The biofilter was filled with PET bottle caps as low-cost biological support media. Water was then directed to a 150 L hydroponic bed used for mahogany cultivation. A submersible pump with a flow rate of 3000 L h^{-1} recirculated the water from the lowest to the highest point of the system. Water flow rates were maintained at 2.5 L min^{-1} in the fish tanks and 3.0 L min^{-1} in the hydroponic beds. Aeration was provided by a 0.38 hp radial blower (maximum airflow: 85.2 m^3 h^{-1}) (Asten & Cia Ltda., Valinhos, SP, Brazil), connected to a porous stone diffuser installed in the fish tank, following the methodology described by Guimarães et al. [13] and Natividade et al. [14] (Figure 1).

The fish were obtained from a commercial fish farm in the state of Pará, Brazil, and acclimatised at the BIOAQUAM laboratory prior to the experimental period. A total of 40 juvenile tambaqui, with a mean weight of 196.08 ± 0.30 g and a mean total length of 23.40 ± 0.50 cm, were randomly distributed among the five aquaponic systems, with eight individuals per system. The fish were fed three times daily (08:00, 12:00, and 16:30) with commercial extruded feed (Guabitec®, 36% protein and 7% lipid—Guabi Nutrição e Saúde Animal S.A., Campinas, SP, Brazil) at a rate equivalent to 3% of the fish biomass in each aquaponic system, divided into three equal portions. The fish cultivation period lasted 60 days.

2.2. Water Monitoring and Greenhouse Environmental Parameters

Water quality parameters in the aquaponic systems, including temperature, dissolved oxygen, electrical conductivity, and pH, were monitored daily. For oxygenation of the fish tanks, air stones connected to a 1.0 hp radial air compressor (Asten & Cia Ltda., Valinhos, SP, Brazil) were used. Dissolved oxygen measurements were taken using a YSI ProODO oximeter (Yellow Springs Instruments, Yellow Springs, OH, USA; accuracy ±0.01 mg L^{-1}), calibrated at the saturation point. pH was measured using a digital pH meter (AKSO®, Porto Alegre, RS, Brazil; accuracy ± 0.01), and electrical conductivity was measured using a TDS&EC conductivity meter (São Paulo, SP, Brazil; accuracy ± 2% FS), calibrated with a 1413 µS cm^{-1} standard solution (AKSO®).

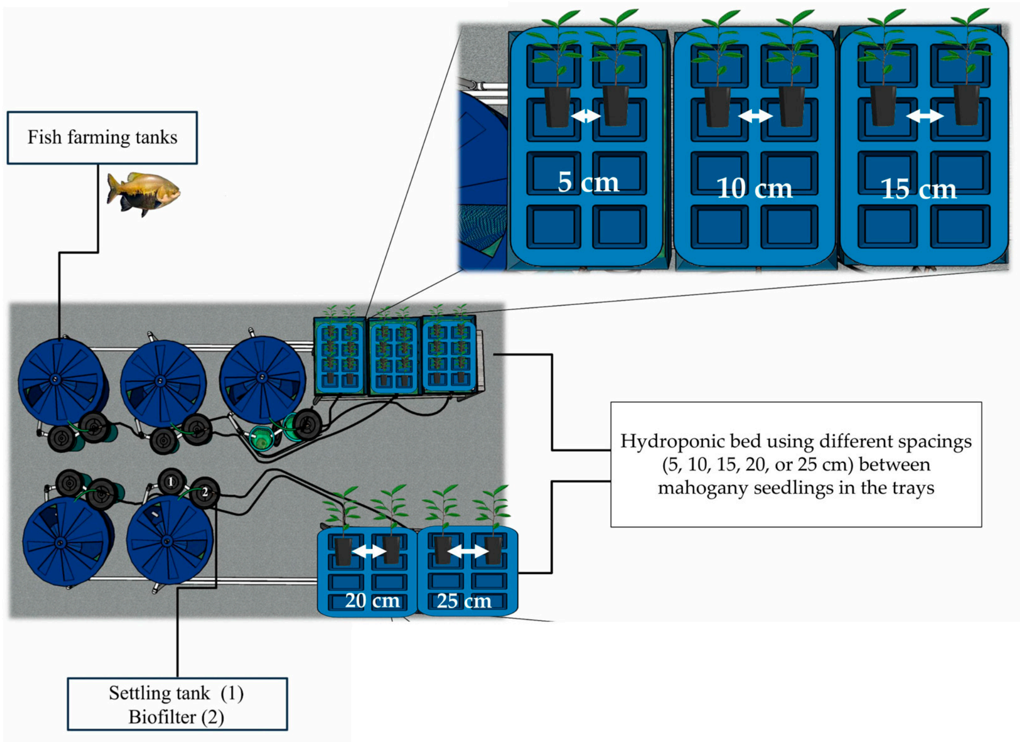

Figure 1. Aquaponic systems used for the production of mahogany (*Swietenia macrophylla*) seedlings with tambaqui (*Colossoma macropomum*) using different spacings (5, 10, 15, 20, or 25 cm) between seedlings in the trays.

Weekly water samples were collected from each system for the determination of total ammonia, nitrite, and nitrate using a commercial kit (LabconTest®, Alcon, Camboriú, SC, Brazil). Analyses were performed in duplicate using a Kasuaki IL-593 spectrophotometer (Kasuaki, São Paulo, SP, Brazil), at wavelengths of 630 nm for ammonia, 540 nm for nitrite, and 220–270 nm for nitrate.

To characterise environmental conditions within the greenhouse, air temperature, air quality, and light intensity were monitored daily throughout the experimental period. Air temperature and relative humidity were measured using a digital thermometer and hygrometer (WLXY® HF-2, Guangdong, China), and light intensity was measured using a photometer (TASI® TA8121 digital luxmeter, Jiangsu, China).

2.3. Mahogany and Tambaqui Growth Performance

At the beginning of the experiment (25 October 2024), the mahogany seedlings had an average stem length of 11.19 ± 0.49 cm, root length of 7.13 ± 0.63 cm, and total seedling length of 18.32 ± 1.11 cm. During the experiment, six phytotechnical evaluations were conducted in November 8, 14, 22, and 29, and December 6 and 13 (final), in which the following parameters were measured: stem length (cm), root length (cm), total length (cm), root fresh mass (g), leaf fresh mass (g), stem fresh mass (g), total fresh mass (g), collar diameter (mm), number of leaves, stem dry mass (g), root dry mass (g), leaf dry mass (g), total dry mass (g), Dickson quality index (DQI), and foliar area (mm^2). Stem length, collar diameter and number of leaves were recorded Weekly. The DQI of mahogany seedlings was evaluated at the end of the experimental period. The DQI is used to assess seedling quality and vigour, particularly in forest species, prior to field planting. It reflects the balance between shoot and root growth and is considered one of the most comprehensive quality indicators [24].

For all measurements, a centimetre-graduated ruler, a digital calliper graduated in millimetres (Mitutoyo® 200 mm 500-197-30, Jundiaí, SP, Brazil), and an analytical balance (Shimadzu Unibloc® ATY224, Barueri, SP, Brazil) were used. Fresh and dry mass were determined for mahogany seedlings. For dry mass determination, fresh samples were dried in an oven at 65 °C for 48 h.

For leaf area, each leaf blade was detached, labelled and placed on an A4 sheet of paper containing a 3 × 15 cm black rectangle (45 cm^2), used as a reference for image calibration. The leaves were scanned to determine leaf area using ImageJ® software (Version 1.54p).

To evaluate the growth performance of tambaqui, eight fish from each aquaponic treatment were assessed. The fish were fasted for 24 h prior to biometric measurements and individually anaesthetised with 50 ppm eugenol, according to Natividade et al. [14] to minimise handling stress. Growth performance was assessed based on initial length (cm) and weight (g), final weight (g) and final length (cm), weight gain (WG), specific growth rate (SGR), and weekly growth (WG).

$$Wg\ (\mathrm{g}) = Final\ average\ weight - Average\ initial\ weight \quad (1)$$

$$SGR\ (\%\ \mathrm{day}^{-1}) = \frac{ln(final\ weight) - ln(initial\ weight)}{(cultivation\ days)} \times 100 \quad (2)$$

$$WG\ (\mathrm{g\ week}^{-1}) = \left[\frac{(average\ final\ weight - average\ initial\ weight)}{cultivation\ weeks}\right] \quad (3)$$

2.4. Statistical Analysis

The experiment followed a completely randomised design, in which treatments were allocated to experimental units in a fully random manner. The data were tested for homoscedasticity and normality using the Shapiro–Wilk test. After confirming that the assumptions were met, a one-way ANOVA was performed, followed by Tukey's test for multiple comparisons of means. All statistical analyses were conducted at a 5% significance level using GraphPad Prism software (version 10).

3. Results

3.1. Greenhouse Environmental Parameters and System Water Quality

During the experimental period, the environmental conditions within the greenhouse were as follows: air temperature, 33.60 ± 3.08 °C; relative humidity, 52.49 ± 10.37%; and light intensity, 1061.51 ± 911.05 lux (Figure 2).

Water quality was significantly affected ($p < 0.05$) during the production of mahogany seedlings in aquaponic systems with tambaqui using different spacings between seedlings in the trays. Dissolved oxygen concentration was significantly higher ($p < 0.001$) in the treatments with spacings of 10, 15, and 25 cm. The pH was significantly higher ($p < 0.001$) in the 25 cm treatment than in the other treatments, whereas the 20 cm treatment exhibited the lowest pH value. Similarly, electrical conductivity was significantly higher ($p < 0.001$) in the 25 cm treatment than in the other treatments, while the 5 cm treatment exhibited the lowest value for this parameter. Alkalinity did not differ significantly ($p > 0.05$) among treatments (Table 1).

https://doi.org/10.3390/w18121436

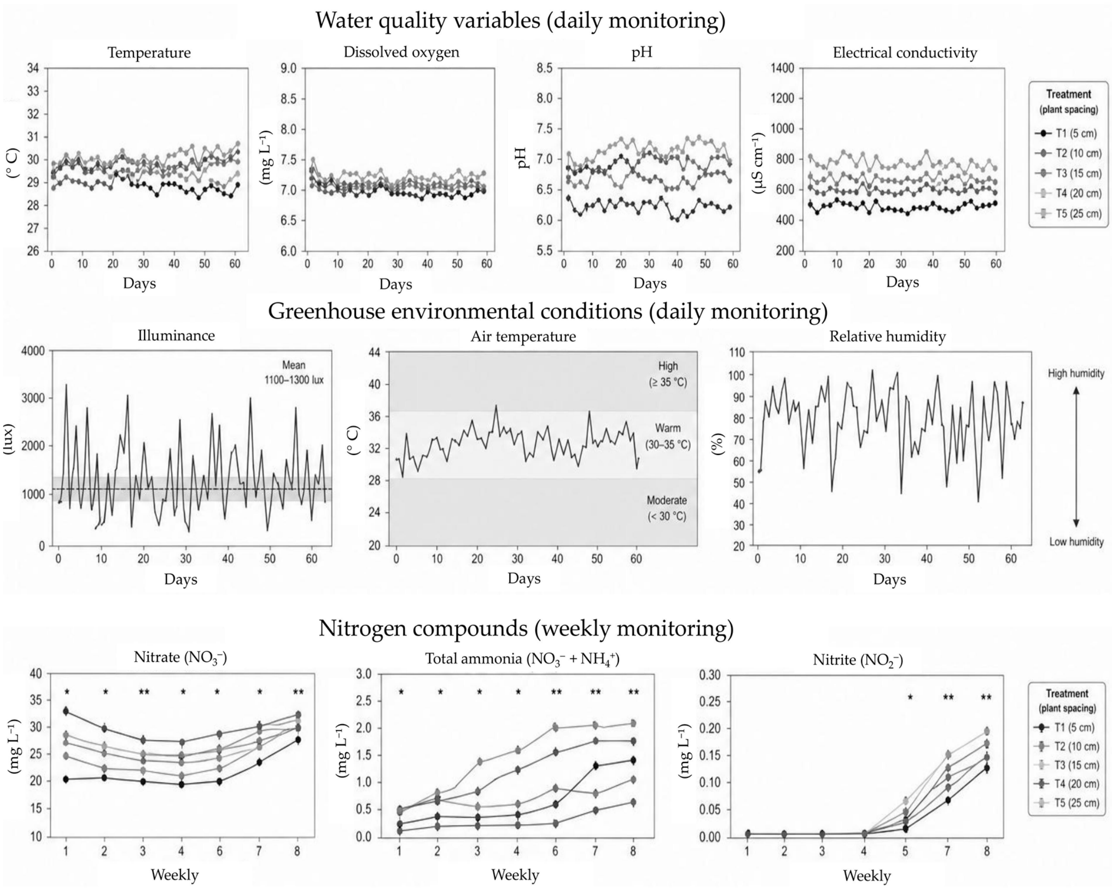

Figure 2. Water quality and environmental variables monitored throughout the experimental period during the production of mahogany (*Swietenia macrophylla*) seedlings in aquaponic systems with tambaqui (*Colossoma macropomum*) using different spacings (5, 10, 15, 20, or 25 cm) between seedlings in the trays. Water quality parameters, including temperature, dissolved oxygen, pH and electrical conductivity, as well as greenhouse environmental variables (air temperature and relative humidity), were measured daily. Nitrogen compounds were assessed weekly. Asterisks above the graphs (* $p < 0.05$; ** $p < 0.001$) indicate significant differences among treatments within each evaluation period.

Table 1. Water quality variables (mean ± standard deviation) recorded during the production of mahogany (*Swietenia macrophylla*) seedlings in aquaponic systems integrated with tambaqui (*Colossoma macropomum*) under different seedling spacings (5, 10, 15, 20 and 25 cm). Values represent the overall mean of each water quality parameter throughout the experimental period. Different lowercase letters within the same row indicate significant differences among treatments according to Tukey's test ($p < 0.05$).

Water Quality Variables	**Treatments**					***p*-Value**
	5 cm	**10 cm**	**15 cm**	**20 cm**	**25 cm**	
Temperature (°C)	29.06 ± 0.79	28.95 ± 0.74	29.18 ± 0.79	29.96 ± 2.48	29.28 ± 0.76	0.061
Dissolved oxygen (mg L^{-1})	7.08 ± 0.34 ^{b}	7.31 ± 0.28 ^{a}	7.37 ± 0.27 ^{a}	7.12 ± 0.31 ^{b}	7.29 ± 0.25 ^{a}	<0.001
Alkalinity (mg $CaCO_3{}^{-1}$)	9.22 ± 1.91	11.27 ± 1.31	10.05 ± 2.24	9.58 ± 1.45	13.82 ± 1.71	0.561
Total ammonia (mg L^{-1})	0.17 ± 0.18 ^{b}	0.74 ± 0.91 ^{a}	0.39 ± 0.42 ^{ab}	0.73 ± 0.68 ^{a}	0.22 ± 0.24 ^{b}	0.031
Nitrite (mg L^{-1})	0.04 ± 0.07	0.06 ± 0.10	0.05 ± 0.08	0.05 ± 0.08	0.04 ± 0.07	0.228
Nitrate (mg L^{-1})	25.31 ± 3.82 ^{c}	30.75 ± 2.11 ^{b}	30.07 ± 2.23 ^{b}	32.34 ± 1.89 ^{a}	30.44 ± 2.01 ^{b}	<0.001
pH	6.76 ± 0.52 ^{b}	6.55 ± 0.69 ^{b}	6.84 ± 0.39 ^{b}	5.92 ± 0.56 ^{c}	7.34 ± 0.28 ^{a}	<0.001
Conductivity (µS cm^{-1})	518.2 ± 189.40 ^{c}	676.5 ± 221.80 ^{b}	634.7 ± 204.20 ^{b}	702.1 ± 196.70 ^{b}	785.3 ± 210.50 ^{a}	<0.001

Regarding nitrogen compounds, total ammonia concentration was significantly higher ($p = 0.031$) in the 10 and 20 cm treatments than in the 5 and 25 cm treatments, which did not differ significantly ($p > 0.05$) from the 15 cm treatment. Nitrate concentration was significantly lower ($p < 0.001$) in the 5 cm treatment than in the other treatments, whereas the 20 cm treatment showed significantly higher nitrate concentrations. Temperature and nitrite concentration did not differ significantly ($p > 0.05$) among treatments (Figure 2 and Table 1).

3.2. Tambaqui Growth Performance

The growth of tambaqui was statistically significant ($p < 0.05$) among the different aquaponic systems. The final weight of tambaqui was significantly higher ($p = 0.019$) in the 5 and 25 cm treatments than in the other treatments. The treatment with a 10 cm spacing between seedlings exhibited the lowest final fish weight. Weight gain was significantly higher ($p < 0.001$) in fish from the 25 cm treatment than in those from the other treatments, whereas weight gain was significantly lower in fish from the 10 cm treatment. Weekly growth was significantly higher ($p < 0.001$) in fish from the 25 cm treatment than in those from the other treatments, with the lowest weekly growth values observed in the 10 cm treatment. The 5, 15, and 20 cm treatments did not differ significantly from one another. Similarly, the specific growth rate was significantly higher ($p < 0.001$) in fish from the 25 cm treatment than in those from the other treatments, which did not differ significantly from one another (Table 2).

3.3. Mahogany Growth Performance

The different spacings between seedlings in the trays for the production of mahogany seedlings with tambaqui in aquaponic systems significantly affected ($p < 0.05$) some plant growth parameters. Root fresh mass was significantly higher ($p = 0.005$) in plants from the 10 cm treatment than in those from the 15 and 20 cm treatments, which did not differ significantly ($p > 0.05$) from the 5 and 25 cm treatments. Collar diameter was significantly larger ($p = 0.012$) in plants from the 25 cm treatment. The DQI, used to evaluate overall robustness, survival potential, and seedling quality, was significantly higher ($p = 0.019$) in plants from the 5 and 25 cm treatments than in those from the 15 cm treatment, which did not differ from the 10 and 20 cm treatments. The other mahogany growth performance indicators did not differ significantly (Table 3).

Table 2. Growth performance (mean ± standard deviation) of tambaqui (*Colossoma macropomum*) during the production of mahogany (*Swietenia macrophylla*) seedlings in aquaponic systems using different spacings (5, 10, 15, 20, or 25 cm) between seedlings in the trays. Different lowercase letters within the same row indicate significant differences among treatments according to Tukey's test ($p < 0.05$).

Tambaqui Growth Indices	Treatments					p-Value
	5 cm	10 cm	15 cm	20 cm	25 cm	
Initial weight (g)	214.75 ± 37.21^{a}	225.88 ± 42.76^{a}	214.75 ± 37.21^{a}	221.25 ± 28.44^{a}	103.75 ± 14.95^{b}	<0.001
Final weight (g)	464.38 ± 73.68^{a}	415.12 ± 57.67^{d}	449.50 ± 56.15^{b}	438.38 ± 82.92^{c}	464.38 ± 81.94^{a}	0.019
Weight gain (g)	249.62 ± 94.24^{b}	189.25 ± 39.60^{c}	234.75 ± 64.09^{b}	217.12 ± 89.14^{b}	360.62 ± 76.10^{a}	<0.001
Initial length (cm)	23.50 ± 1.41	23.50 ± 1.20	23.50 ± 1.41	23.12 ± 1.36	23.38 ± 1.19	0.973
Final length (cm)	27.15 ± 1.49	26.79 ± 1.22	27.01 ± 0.69	27.44 ± 2.09	27.50 ± 1.97	0.887
Weekly growth (g week^{-1})	32.36 ± 12.22^{b}	24.53 ± 5.13^{c}	30.43 ± 8.31^{b}	28.15 ± 11.55^{b}	46.75 ± 9.86^{a}	<0.001
Specific growth rate (% day^{-1})	1.43 ± 0.52^{b}	1.14 ± 0.26^{b}	1.38 ± 0.40^{b}	1.25 ± 0.42^{b}	2.77 ± 0.30^{a}	<0.001

Table 3. Growth indices (mean ± standard deviation) of mahogany (*Swietenia macrophylla*) in aquaponic systems with tambaqui (*Colossoma macropomum*) using different spacings (5, 10, 15, 20, or 25 cm) between seedlings in the trays. Different lowercase letters within the same row indicate significant differences among treatments according to Tukey's test ($p < 0.05$).

Mahogany Growth Indices	Treatments					*p*-Value
	5 cm	10 cm	15 cm	20 cm	25 cm	
Stem length (cm)	36.29 ± 4.64	35.97 ± 4.66	34.79 ± 6.84	35.29 ± 9.16	32.36 ± 4.63	0.783
Root length (cm)	20.57 ± 3.72	23.13 ± 5.26	21.23 ± 6.26	23.56 ± 7.25	18.66 ± 2.25	0.421
Total length (cm)	56.86 ± 5.04	59.10 ± 7.44	56.01 ± 9.02	58.84 ± 14.52	51.01 ± 5.24	0.459
Root fresh mass (g)	12.30 ± 4.84 [ab]	13.08 ± 3.16 [a]	6.73 ± 3.82 [b]	6.85 ± 3.21 [b]	11.12 ± 3.33 [ab]	0.005
Leaf fresh mass (g)	18.56 ± 3.90	17.60 ± 3.98	15.35 ± 5.64	17.35 ± 6.33	18.08 ± 3.03	0.755
Stem fresh mass (g)	11.84 ± 2.96	10.40 ± 2.18	9.35 ± 4.47	11.51 ± 8.23	11.61 ± 1.63	0.827
Total fresh mass (g)	42.70 ± 10.28	41.09 ± 8.10	31.43 ± 13.64	35.70 ± 16.89	40.81 ± 5.69	0.359
Collar diameter (mm)	5.43 ± 0.81 [b]	5.06 ± 0.64 [b]	4.43 ± 0.69 [b]	4.95 ± 0.95 [b]	6.00 ± 0.80 [a]	0.012
Number of leaves	35.43 ± 4.54	32.29 ± 3.04	29.57 ± 10.64	36.00 ± 12.78	33.14 ± 3.39	0.574
Stem dry mass (g)	2.84 ± 0.82	2.36 ± 0.64	2.20 ± 0.98	2.59 ± 1.40	2.83 ± 0.44	0.614
Root dry mass (g)	2.90 ± 1.49	2.62 ± 0.84	1.77 ± 0.97	2.32 ± 0.82	2.42 ± 0.62	0.315
Leaf dry mass (g)	4.94 ± 0.93	4.29 ± 0.89	3.98 ± 1.19	4.33 ± 1.41	4.84 ± 0.93	0.448
Total dry mass (g)	10.68 ± 2.92	9.27 ± 1.84	7.96 ± 2.84	9.24 ± 2.55	10.10 ± 1.44	0.291
Dickson quality index (DQI)	1.14 ± 0.43 [a]	0.95 ± 0.24 [ab]	0.70 ± 0.29 [b]	0.87 ± 0.13 [ab]	1.16 ± 0.20 [a]	0.019
Foliar area (mm^2)	231.22 ± 59.56	254.81 ± 65.17	235.54 ± 67.19	240.95 ± 80.96	214.22 ± 77.62	0.560

4. Discussion

This study investigated the feasibility of producing mahogany seedlings in an aquaponic system integrated with tambaqui farming. The integration of tambaqui farming and mahogany seedling production, using aquaculture effluents as a nutrient source, may be regarded as a sustainable intensification strategy based on the principles of the circular economy [25]. It is also important to emphasise that the primary objective of the present study was not to evaluate the effects of seedling spacing on fish growth, but rather to assess the performance of mahogany seedlings cultivated under different spacing arrangements within functional aquaponic systems. Fish were included as an integral component of the aquaponic system, serving as the source of nutrients for plant production. Consequently, fish growth was considered a complementary indicator of system performance rather than the main response variable of the experiment.

In integrated systems such as the aquaponic systems evaluated in the present study, effluents rich in nutrients such as nitrogen and phosphorus cease to be potential pollutants and are instead reused in seedling fertilisation, thereby reducing dependence on mineral inputs and increasing resource-use efficiency [8,10,13,26]. Recent studies have shown that the presence of lambari (*Astyanax bimaculatus*) was associated with lower concentrations of total ammoniacal nitrogen, toxic ammonia, and total suspended solids in aquaponic systems [26]. In addition, lettuce (*Lactuca sativa*) grown in treatments containing lambari exhibited greater final weight, leaf height, and total biomass, resulting in higher system productivity [26]. In mahogany cultivation, this condition may favour initial growth, seedling vigour, and potentially seedling quality for field establishment, particularly during the nursery phase, although the response may vary according to management practices and effluent quality. Although the available literature is largely restricted to herbaceous crops, these studies provide valuable insights into nutrient cycling and water quality dynamics in aquaponic systems. To the best of our knowledge, the present study is among the first to evaluate the production of a forest tree species, *S. macrophylla*, under aquaponic conditions. Consequently, direct comparisons with other woody species remain limited. Further research involving additional forest and woody species is needed to expand the scientific basis for comparison and to improve our understanding of the applicability of aquaponic systems to forest seedling production.

The effect of seedling spacing is also relevant in this context, as it influences competition for light and nutrients and may modulate the efficiency of resource utilisation [27,28]. However, despite its positive environmental potential, the system requires rigorous management, particularly regarding effluent composition; as nutritional imbalances or the presence of undesirable compounds may compromise plant development [6,13,29]. Thus, this approach represents a promising alternative for integrating aquaculture and forestry, with potential applications in forest restoration systems and the sustainable production of high-value timber in the Amazon.

In the present study, water quality results indicate that the effluent from the tambaqui farming systems exhibited characteristics compatible with its potential reuse in the production of mahogany seedlings, thereby reinforcing the environmental viability of integrating aquaculture and forestry. It is important to highlight that, in aquaponic systems, the main factors affecting nitrogen transformations are pH, dissolved oxygen, hydraulic loading rate, ammonia and nitrite concentrations, and the C:N ratio [30]. For example, nitrifying bacteria have an optimal range for bioaugmentation, in which ammonia-oxidising and nitrite-oxidising bacteria most effectively convert toxic nitrogen compounds at a pH of 7.0–8.0 and dissolved oxygen concentrations between 5 and 6 mg L^{-1} [31]. These conditions were observed in the present study, particularly in the treatments with a 25 cm spacing between mahogany seedlings.

In the present study, the elevated nitrate concentrations observed across the treatments, particularly at wider spacings, suggest a greater availability of nutrients essential for plant growth [13,26,30], which may favour early seedling development and reduce the need for supplementary mineral fertilisation. Similarly, although total ammonia concentrations varied among treatments, they remained relatively low, indicating the absence of potentially toxic conditions for fish [13]. The increase in electrical conductivity observed at wider spacings suggests a greater accumulation of dissolved ions in the effluent [13], reflecting the presence of nutrients derived from fish culture and reinforcing the fertilising potential of the reused water [32]. Furthermore, adequate dissolved oxygen concentrations and relatively stable temperatures indicate that the system maintained favourable environmental conditions for both fish production and the use of effluent for irrigation. Conversely, the reduction in pH observed in some treatments may indicate intensified biological activity and enhanced organic matter mineralisation [26], highlighting the need for continuous monitoring to prevent potential constraints on long-term seedling development. Although phosphorus and other mineral nutrients were not directly quantified in the present study, these elements are known to play a fundamental role in plant nutrition [33] and may influence nutrient-use efficiency in integrated aquaponic systems. The observed patterns in nitrate concentration and electrical conductivity suggest that nutrient availability was sufficient to support seedling growth. However, future studies should include a more comprehensive assessment of water nutrient composition, including phosphorus, potassium, calcium, magnesium and micronutrients, in order to improve our understanding of nutrient dynamics and their relationship with the growth and quality of forest seedlings cultivated in aquaponic systems.

In aquaponic systems, the hydraulic load applied to the aquaponic bed housing the plants may affect nitrogenous compounds, as well as fish and plant growth. For example, when hydraulic loading rates (HLRs) of 1.4, 5.4, 13.6, and 23.3 m^3 day^{-1} m^{-2} were evaluated, significant differences in water quality parameters were observed. The higher HLRs (13.6 and 23.3 m^3 day^{-1} m^{-2}) resulted in greater ammonia removal efficiency across the treatments. In contrast, the HLR of 1.4 m^3 day^{-1} m^{-2} reduced plant growth performance, whereas the HLR of 5.4 m^3 day^{-1} m^{-2} improved fish growth performance.

https://doi.org/10.3390/w18121436

Tambaqui cultivated in aquaponic systems with an HLR of 5.4 m^3 day^{-1} m^{-2} exhibited a significantly higher final weight (116.3 ± 5.77 g) [14].

Similarly, increasing plant density in hydroponic beds may alter the water quality of aquaponic systems without affecting fish performance [13]. A coriander (*Coriandrum sativum*) density of 512 cells m^{-2} reduced the electrical conductivity of the water (0.097 ± 0.001 dS m^{-1}), whereas pH, dissolved oxygen, and temperature remained similar across the different densities evaluated (32, 72, 128, and 512 cells m^{-2}). However, total ammoniacal nitrogen (28.81 ± 2.26 mg L^{-1}) and nitrate concentrations (51.07 ± 0.81 mg L^{-1}) were higher at the density of 32 cells m^{-2}. Nevertheless, this did not affect tambaqui growth [13]. In the present study, the highest values for final weight, weight gain, weekly growth, and specific growth rate of tambaqui were observed in the treatment with seedling spacing of 25 cm. Although fish reared in the 25 cm spacing treatment showed higher final weight, weight gain, weekly growth, and specific growth rate, these results should be interpreted with caution. Fish in this treatment started the experiment with a substantially lower initial body weight than those in the other treatments. In tambaqui, specific growth rate is typically higher in smaller individuals, and compensatory growth responses may occur during juvenile development [4,11,13,14]. Therefore, the superior growth performance observed in this treatment may be partially associated with differences in initial body size rather than solely with the spacing adopted for the seedlings. Because fish performance was not the primary objective of the study, these results are presented as complementary observations and should not be interpreted as direct evidence that seedling spacing affects tambaqui growth.

The growth performance of the mahogany seedlings indicated that the use of effluents from tambaqui farming was able to sustain plant development without causing significant negative effects on most of the morphological variables evaluated, highlighting the potential of the integrated system for forest seedling production. The highest values for fresh root mass observed in the 5, 10, and 25 cm spacing treatments indicate better root system development under these conditions, possibly associated with differences in nutrient availability and plant competition [13,26]. Stem diameter, which is directly related to robustness and post-planting survival [33], showed higher values in the 5, 20, and 25 cm spacings, suggesting the formation of structurally more vigorous seedlings in these treatments. Furthermore, the higher DQI values recorded at 5 and 25 cm reinforce this interpretation, since this index integrates biomass and morphological balance parameters and is widely used as an indicator of forest seedling quality [24]. Thus, the results suggest that the integrated system promoted mutual benefits between aquaculture and forestry, simultaneously enabling the environmentally appropriate reuse of effluents and the maintenance, or even optimisation of fish growth, reinforcing the sustainable potential of this production model under Amazonian conditions. Future studies should incorporate economic and cost–benefit analyses to support decision-making regarding commercial implementation.

5. Conclusions

The integration of fish farming and Brazilian mahogany seedling production enabled the reuse of nutrient-rich effluents, contributing to the circularity and resource efficiency of the aquaponic system. The findings demonstrate that this integrated approach represents a technically viable and environmentally promising production strategy. Under the conditions evaluated, a spacing of 25 cm between seedlings is recommended for aquaculture–forestry integration, as it resulted in superior phytotechnical performance and improved seedling quality. Nevertheless, the results should be interpreted in light of certain limitations. The study was conducted using a single aquaponic unit (fish tank) per treatment, and the concentrations of phosphorus and other mineral nutrients were not directly quantified. Therefore, future studies incorporating replicated systems and comprehensive nutrient profiling are needed to strengthen the understanding of nutrient dynamics and validate the applicability of these findings under a wider range of production conditions.

Author Contributions: P.C.A.L. Conceptualization, Methodology, Formal analysis, Validation, Investigation, Writing—Original Draft. F.C.S. Validation, Methodology, Conceptualization, Writing—Original Draft, Project administration. J.F.G.C.J. Formal analysis, Validation, Investigation. S.B.L.J. Investigation, Data curation. J.D.d.S.P. Investigation, Formal analysis. R.T. Funding acquisition, Project administration. M.S.O. Data curation, Manuscript review, Writing—Original Draft, Writing—Review & Editing. S.L.d.M.G. Investigation, Data curation. G.D.A.P. Funding acquisition, Data curation, Conceptualization, Project administration, Supervision, Writing—Original Draft, Writing—Review & Editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by the Coordination for the Improvement of Higher Level Personnel (CAPES Grant No. 001), PROCAD AMAZÔNIA 2018 (project no. 88887.200588/2018-00), and National Council for Scientific and Technological Development—CNPq Pro-Amazonia 444218/2024-6.

Institutional Review Board Statement: The authors conducted in vivo experiments on fish but performed only biometric sampling on the animals, and none of them underwent any suffering or surgical procedures. The experimental protocol was approved in August 2023 by the Ethics Committee (CEUA) of the Federal Rural University of the Amazon (UFRA) protocol number CEUA 8598010323, and all animal experiments were performed according to the Directive 2010/63/EU.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors would like to thank the Coordination for the Improvement of Higher Level Personnel (CAPES) and the Brazilian CNPq for supporting Fabio Carneiro Sterzelecki through the Pro-Amazônia Project (CNPq Grant No. 444218/2024-6), as well as the PDPG—Strategic Postdoctoral Programme No. 16/2022/CAPES for the postdoctoral fellowship awarded to Sávio Lucas de Matos Guerreiro (Process No. 88887.939510/2024-00). Declaration of Generative AI: During the preparation of this manuscript, the authors used Grammar Labs for language editing to ensure the readability of the work. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

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