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Integrating curimba culture during the grow-out phase of tambaqui affects overall productivity, water quality, and fish health

Adriana Ferreira Lima[1,2] | **André Silvério Pereira**[1] | **Luciana Nakaghi Ganeco-Kirschnik**[1] | **Patricia Oliveira Maciel-Honda**[1] | **Wagner C. Valenti**[2]

[1]Brazilian Agricultural Research Corporation (EMBRAPA), Fisheries and Aquaculture Center, Tocantins, Brazil

[2]São Paulo State University - UNESP, Aquaculture Center – CAUNESP, São Paulo, Brazil

Correspondence
Adriana Ferreira Lima, Brazilian Agricultural Research Corporation (EMBRAPA), Fisheries and Aquaculture Center, Palmas, 77008-900, Tocantins, Brazil.
Email: adriana.lima@embrapa.br

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Abstract

The efficiency of feed use in aquaculture may be improved by integrating the culture of extractive species into fed-species systems. This study assessed the impact of including curimba (*Prochilodus lineatus*) in tambaqui (*Colossoma macropomum*) production during the grow-out phase in earthen ponds. A completely randomized experiment with two treatments (production systems) and three replications of each was conducted over 7 months. Tambaqui monoculture and tambaqui with curimba-integrated culture were compared. The addition of curimba did not affect tambaqui performance, which reached a final weight of ~1.7 kg, survival rate of ~60%, and feed conversion ratio of ~1.73 in both systems; annual productivity reached about 7.1 t ha^{-1}. Curimba grew to ~144 g, with a survival rate of 97% and annual production of ~1.0 t ha^{-1}. Data indicated that total fish production (tambaqui + curimba) may be higher (~25%) in the integrated culture system. The presence of curimba was associated with lower morning dissolved oxygen and

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afternoon pH, and higher levels of chlorophyll *a*, turbidity, and total dissolved and suspended solids in the water. Phytoplankton, zooplankton, and monogenean parasites in tambaqui tended to be higher in the integrated culture system, possibly related to the resuspension of nutrients induced by bioturbation caused by the curimba. Implementing the integrated culture increased net profit by approximately US$ 1.5 thousand per hectare per year. Curimba appears to be compatible with and complementary to tambaqui, making them suitable for co-culture. Therefore, tambaqui can be effectively farmed in an integrated culture with curimba (and possibly other benthic species), enhancing aquaculture production efficiency and aligning with the principles of the circular economy.

KEYWORDS

Colossoma macropomum, economic analysis, integrated multitrophic aquaculture, monogenea, polyculture, *Prochilodus*

1 | INTRODUCTION

Tambaqui or cachama, *Colossoma macropomum*, is the most widely farmed native species in South America (Hilsdorf et al., 2022). This is a low-trophic pelagic species that consumes plankton and allochthonous vegetation in natural habitats (Goulding & Carvalho, 1982; Silva et al., 2000) and has a remarkable capacity to consume natural food in rearing ponds during all life stages (Gomes & Silva, 2009; Lima, dos Reis, et al., 2024; Lima, Pereira, et al., 2024; Sipaúba-Tavares & Braga, 2007). Generally, tambaqui is farmed in semi-intensive monoculture systems in earthen ponds or barrages (Valenti et al., 2021). Brazil is the leading producer, but production has declined each year because of low profits. This trend could be reversed by improving production technology and mainly increasing feed efficiency, which is the most expensive input.

The monocultures of fed fish are usually inefficient in using natural resources and feed (Boyd et al., 2020; FAO, 2024). In general, only a small portion of the nutrients from the feed supplied are assimilated by fish, while most are retained in the pond sediments or released in the effluents (Barbosa et al., 2024; David et al., 2017; Fan et al., 2004; Flickinger, 2019; Flickinger, 2020a; Flickinger, 2020b; Sahu et al., 2015). The integrated culture of species with complementary ecological traits that occupy different niches within ponds may be more efficient (Lecocq et al., 2024; Troell et al., 2009). This approach is often referred to as integrated multi-trophic aquaculture (IMTA). It creates balanced systems that promote environmental and economic sustainability and share feed costs among multiple commercial crops (Boyd et al., 2020).

The fishes of the genus *Prochilodus*, known as curimba, curimbatá, or curimatã, may serve as suitable complementary species to farm alongside tambaqui. This genus includes large detritivore species that are among the most prominent, abundant, and widely spread freshwater fishes in South American rivers. (Sivasundar et al., 2001). They are largely exploited by artisanal fisheries, and farming technology is well known (Valenti et al., 2021). As demersal fishes that feed on dead organic matter (Kalous et al., 2012), they have a complementary feeding habit relative to tambaqui, which is a crucial characteristic for selecting secondary species in integrated systems (Lecocq et al., 2024).

No research focusing on the co-culture of tambaqui and curimba was found in the literature. However, two studies have examined the inclusion of curimba alongside other species in tambaqui ponds. Hancz (1993) assessed the polyculture of tambaqui with curimba (*Prochilodus marggravii*) and grass carp (*Ctenopharyngodon idella*) over 164 days, demonstrating that co-cultivation of these species is feasible. Another study integrated tambaqui with curimba (*Prochilodus lineatus*) and Amazon River prawn (*Macrobrachium amazonicum*) during 53 days of juvenile production, finding no negative impact on tambaqui and an increase in overall yield and a decrease in feed conversion ratio (FCR). However, they were conducted during the initial production phase and did not compare performance to monoculture. Therefore, the present study aims to evaluate the effect of including curimba in tambaqui production during the grow-out phase in earthen ponds, focusing on fish performance, water quality, plankton community, fish health, and economics.

2 | MATERIALS AND METHODS

2.1 | Experimental design and fish culture

The study was conducted at the Aquaculture Experimental Center of Brazilian Agricultural Research Corporation in Palmas, Tocantins, Brazil (10°8′1.33″S, 48°19′9.86″W). A completely randomized experiment was designed with two production systems and three replicates each: (T) tambaqui *Colossoma macropomum* monoculture (0.4 fish m^{-2}) and (TC) tambaqui (0.4 fish m^{-2}) integrated with curimba *Prochilodus lineatus* (0.3 fish m^{-2}). Tambaqui stocking density followed commercial grow-out practices (Valenti et al., 2021), while curimba stocking density was based on a previous IMTA study (Franchini et al., 2020). The experiment duration was planned to obtain the commercial size of the target species, tambaqui. Thus, the experiment lasted seven months.

2.2 | Fish origin and pond preparation

Tambaqui (2.0 ± 0.8 g) and curimba (3.2 ± 2.1 g) fingerlings were purchased from a commercial hatchery in Tocantins, Brazil. They were stocked in separate nursery ponds and fed commercial extruded feed (1–2.6 mm; 45% crude protein; Archer Daniels Midland Company-ADM, Brazil) to apparent satiation four times daily for 60 days. Then, they were stocked in the grow-out ponds. Prior to the stocking, ponds were drained, disinfected with quicklime (200 g m^{-2}), limed (200 g limestock m^{-2}), fertilized (5 g urea m^{-2}, 3 g simple superphosphate m^{-2}, and 10 g rice bran m^{-2}), and filled with water from a local dam. After preparation, six earthen ponds (600 m^2, 1.3 m deep) were stocked with tambaqui (*Colossoma macropomum*) (29 ± 4 g). Three ponds were randomly assigned to the integrated treatment and additionally stocked with curimba juveniles (15.5 ± 8.7 g).

2.3 | Feed management and productive indicators

The target species was tambaqui, which was fed twice a day (8:00 and 16:00) with commercial extruded feed (Archer Daniels Midland Company-ADM, Brazil). Fish were fed according to the average body weight of the pond population. When the average weight of fish ranged from 30 to 230 g, 230 to 410 g, and 410 to 700 g, they were fed a diet containing 32% crude protein, at feeding rates of 4.5%, 3%, and 2% of body weight per day, respectively. For fish weighing between 700 and 1130 g, and those exceeding 1130 g, a feed containing 28% crude protein was provided at feeding rates of 2% and 1.5% of body weight per day, respectively (Oliveira et al., 2013). Feeding ended when the fish ceased eating or when the daily dose, computed from the feed rate, was reached. Each month, 30 tambaqui and 30 curimba were randomly sampled from each pond, weighed to monitor the growth, and then returned to their respective ponds. Only tambaqui biomass was considered when adjusting the amount of feed offered. Uneaten feed that floated on the pond surface was negligible, so the feed supplied was used as a proxy for actual feed intake.

The apparent FCR was determined for tambaqui and for the system, that is, considering total fish biomass produced by the two species. The FCR was calculated as the total feed supplied divided by the total harvested biomass minus the total stocked biomass. At the end of the experiment, ponds were drained, all fish were harvested and weighed in batches of five fish, and the total yield was recorded. Survival was determined as the percentage of the initial number of fish that survived to the end of the experiment. Annual productivity was calculated as the ratio of final biomass to pond area, expressed in t ha^{-1} $year^{-1}$, assuming year-round culture.

2.4 | Water quality parameters

Water variables were monitored regularly. Temperature, dissolved oxygen, pH, and conductivity were measured three times a week at 08:00 and 16:00 using a YSI Professional Plus probe (Yellow Springs Instruments Company, Yellow Springs, USA). Transparency was recorded three times a week with a Secchi disk. Each pond was sampled monthly at 08:00 for the analysis of total and dissolved phosphorus, chlorophyll *a*, total suspended solids, dissolved solids, and turbidity. These parameters were measured following the APHA methodology (APHA, 2017), except for total nitrogen, which was determined by catalytic combustion oxidation using an Elementar Vario TOC-N Select analyzer (Langenselbold, Germany), and turbidity, which was analyzed with a turbidimeter (Hach 2100Q, Loveland, CO, USA). For statistical analyses, all measurements were averaged monthly, resulting in one monthly value per pond for each variable. Whenever dissolved oxygen levels fell below 3 mg L^{-1}, supplemental aeration was applied using fountain-type aerators (1.5 HP), operating from 18:00 to 08:00, 14 h per day.

2.5 | Plankton availability

The availability of phyto- and zooplankton in the ponds was analyzed on months 0, 2, 4, 6, and 7, by sampling phyto- and zooplankton using phyto- and zooplankton nets (20 and 68 μm mesh, respectively). The nets were dragged for 10 m in the earthen ponds, with a total volume of 709 L for phytoplankton and 1075 L for zooplankton analysis. Phytoplankton was preserved in 2% formaldehyde neutralized with sodium bicarbonate (5 g L^{-1}). The zooplankton samples were preserved in 4% formaldehyde neutralized with sodium bicarbonate (5 g L^{-1}) and 0.1% rose Bengal dye. Phyto- and zooplankton samples were quantitatively analyzed using Neubauer and Sedgwick Rafter chambers, respectively.

2.6 | Parasitic analysis

Five tambaqui from each pond were sampled in months 5 and 7. The fish were euthanized by severing the spinal cord, and gill samples were collected and fixed in a 4% buffered formalin solution until analysis. The first branchial arch from the right side of each fish was examined for total monogenean parasite counts using a stereo microscope (Stemi305S, Zeiss, Germany). Prevalence, mean intensity, and abundance indexes were calculated according to Bush et al. (1997). For monogenean species identification, 60 parasites from each treatment group were treated in Hoyer's medium, and microscope slides were prepared to visualize identification structures (haptor and copulatory organ) (Eiras et al., 2006). Monogenean identification followed the methods outlined by Cohen et al. (2013).

2.7 | Partial budget analysis

A partial budget is an analytical technique used to evaluate how income and expenses would change if a proposed modification were made to the current farm plan (Engle, 2010). It is more suitable than the complete budget for analyzing the impact of small changes in the production process. A partial budget focuses only on the income and expense items affected by the proposed modification. Thus, in the present study, we considered the production costs associated with curimba juveniles and the additional labor required for stocking and harvesting curimba. For curimba stocking, an additional 5.5 h of labor per hectare was considered. For curimba harvesting, the extra time was estimated in proportion to the harvested biomass, based on the time required to harvest only tambaqui. We assume that harvesting 250 kg of tambaqui (~1 pond of 600 m^2) requires 2 h per worker, with a team of four workers. This time includes 20 min for material preparation, 30 min for the first net drag, 40 min for handling and removing fish from the net, and an additional 30 min for a second net drag, if necessary. The unit cost of curimba juveniles was US$ 0.04, the selling price of 1 kg of harvested curimba was US$ 1.85, and the monthly labor cost for a worker employed 22 days per month, 8 h per day, was US$ 369.58. Both values were obtained in Palmas, Tocantins, Brazil, in June 2024. All monetary values are presented in US dollars (US$ 1.00 = R$ 5.41, exchange rate from August 2024).

2.8 | Statistical analysis

Data were subjected to tests of normality (Shapiro–Wilk test) and homogeneity (Bartlett test) of residues, and transformed (Box & Cox, 1964) when they did not meet the premises. Data for fish weight, survival, yield, and FCR were subjected to Student's *t*-test. Water quality parameters, phytoplankton, zooplankton, rotifers, copepods, and cladocerans density and parasites were analyzed using linear mixed-effects models with the lme function of the nlme package in R. Production system (treatment), culture period (month), and their interaction were considered as fixed effects. Experimental units were considered as random effects. When significant effects were detected, means were compared using Tukey-adjusted pairwise comparisons with the emmeans package. The data were presented as the mean ± standard deviation, and statistical significance was assumed as *p* was low (close to or lower than 0.05), and the differences are biologically consistent. This follows modern statistical practice, which emphasizes the use of the *p*-value as a continuous measure of evidence, rather than adherence to an arbitrary threshold. All statistical analyses were performed using the 4.2.3 R software (R Core Team, 2024).

2.9 | Legal and ethical aspects

The study complied with official Brazilian guidelines for the care and use of animals for scientific and educational purposes (Concea-CEUA protocol 76/2022) and with the National Management System for Genetic Heritage and Associated Traditional Knowledge (AB47B85).

3 | RESULTS

The inclusion of curimba in the tambaqui ponds did not affect tambaqui growth and survival (Table 1). The integrated system resulted in a higher fish yield by approximately 25%. The apparent FCR of tambaqui remained unaffected, while the system FCR of the integrated ponds decreased about 12%, indicating an improved feed efficiency (Table 1).

Severe cormorant (*Nannopterum brasilianum*, formerly *Phalacrocorax brasilianus*) predation was observed during the second and third months of the experiment. The number of fish predated was not counted because of technical issues, but observations indicated it was substantial. Predation ceased from the fourth month onward because tambaqui reached an invulnerable size. This predation pattern is common in commercial ponds.

The addition of curimba in the system was associated with lower morning dissolved oxygen and afternoon pH. Additionally, it was associated with higher levels of chlorophyll *a* and nitrogen in the water, as well as turbidity

TABLE 1 Mean ± standard deviation of the productive performance of tambaqui monoculture (T) and integrated culture of tambaqui and curimba (TC) in ponds.

	T	TC	*p*-Value
Tambaqui			
Initial individual weight (g)	29 ± 4	29 ± 4	NA
Final individual weight (g)	1693 ± 307	1776 ± 194	0.7136
Survival (%)	58 ± 14	60 ± 14	0.8397
Yield (kg ha^{-1} $year^{-1}$)	6485 ± 657	7056 ± 943	0.4258
FCR tambaqui	1.73 ± 0.16	1.73 ± 0.25	0.9851
Curimba			
Initial individual weight (g)	-	15 ± 9	-
Final individual weight (g)	-	144 ± 44	-
Survival (%)	-	97 ± 6	-
Yield (kg ha^{-1} $year^{-1}$)	-	962 ± 307	-
System FCR	1.73 ± 0.16	1.52 ± 0.23	0.2698
System yield (kg ha^{-1} $year^{-1}$)	**6485 ± 657**	**8028 ± 943**	**0.0831**

Note: Bold values indicate significant differences between systems using the *t*-test.
Abbreviation: FCR, feed conversion ratio.

and total dissolved and suspended solids. Dissolved oxygen levels fell below 3 mg L^{-1} in some ponds between the fourth and fifth months, requiring the use of supplemental aeration. The average number of days the aerator was used ranged from 0 to 53 days in tambaqui ponds and from 0 to 78 days in integrated culture ponds, showing no clear difference between both production systems ($p = 0.9319$). Although most water quality parameters varied over time (Table 2), no clear temporal trend was observed. An interaction between treatment and culture period was observed only for morning pH, suggesting a synergistic effect. Higher pH values were recorded in the tambaqui monoculture during the second and third months. Phytoplankton and zooplankton densities showed no significant variation during the culture. Phytoplankton density was about 40% higher in the integrated system; however, this difference has 27% of being obtained by chance ($p = 0.2734$). Rotifer densities were higher in ponds with curimba (Table 3), while cladoceran and copepod densities were similar between the two culture systems.

Three species of monogenean parasites were identified in the gills of tambaqui: *Anacanthorus spathulatus*, *Notozothecium janauachensis*, and *Mymarothecium boegeri* (Monogenoidea). The prevalence, regardless of the species, was 100% in tambaqui in both monoculture and integrated systems at 5 and 7 months. The mean abundance of monogenean parasites was lower in tambaqui monoculture (287 ± 164 individuals) compared to integrated culture (472 ± 148) ($p = 0.0002$). Additionally, the evaluation time (5 or 7 months after stocking) showed no clear effect on parasite intensity ($p = 0.5027$).

The integrated system produced, on average, 962 kg ha^{-1} $year^{-1}$ of curimba biomass, resulting in additional revenue of US$1777.42 per hectare per year (Table 4). Production costs also increased by US$ 296.28 per hectare per year, mainly because of the purchase of curimba juveniles. Overall, the integration of curimba increased net profits by US$ 1481.14 per hectare per year, reflecting the financial gain from adopting the integrated system (Table 4).

4 | DISCUSSION

The inclusion of curimba in tambaqui ponds did not appear to negatively affect tambaqui growth, survival, productivity, or FCR. Although the current study had only three replicates per treatment, which limits the power of the *t*-test

TABLE 2 Mean ± standard deviation of the water quality parameters measured in tambaqui monoculture (T) and integrated culture of tambaqui and curimba (TC) in ponds.

		Production system		*p*-Value		
Variables		**T**	**TC**	**System**	**Month**	**System*month**
Temperature (°C)	Morning	29.0 ± 1.8	28.9 ± 1.6	0.5486	<0.0001	0.6820
	Afternoon	32.2 ± 1.8	32.1 ± 1.6	0.0614	<0.0001	0.3053
Dissolved oxygen (mg L^{-1})	Morning	**6.0 ± 1.7**	**5.5 ± 1.6**	0.0280	0.0011	0.0890
	Afternoon	10.0 ± 2.3	9.9 ± 2.0	0.9255	0.1512	0.1114
Conductivity (µS cm^{-1})	Morning	92.4 ± 29.8	110.4 ± 24.8	0.2482	0.0001	0.9868
	Afternoon	103.5 ± 32.1	120.2 ± 23.2	0.2009	0.0006	0.9893
pH	Morning	8.0 ± 0.7	7.9 ± 0.7	0.2384	<0.0001	0.0312
	Afternoon	**8.8 ± 0.5**	**8.6 ± 0.4**	0.0183	0.0958	0.1065
Total nitrogen (mg L^{-1})	Morning	**1.02 ± 0.57**	**1.32 ± 0.62**	0.0838	0.2162	0.2292
Total phosphorus (µg L^{-1})	Morning	83.5 ± 44.5	93.5 ± 56.1	0.5123	<0.0001	0.3534
Total dissolved phosphorus (µg L^{-1})	Morning	32.5 ± 19.8	32.8 ± 18.3	0.8675	<0.0001	0.4562
Chlorophyll *a* (mg L^{-1})	Morning	**19.0 ± 27.4**	**34.5 ± 37.2**	0.0442	0.8384	0.1592
Total dissolved solids (mg L^{-1})	Morning	**86.6 ± 41.0**	**104.7 ± 55.6**	0.0216	<0.0001	0.4271
Total suspended solids (mg L^{-1})	Morning	**11.8 ± 10.9**	**25.6 ± 24.7**	0.0117	0.0001	0.4417
Transparency (cm)	Morning	**92.3 ± 32.7**	**65.8 ± 33.8**	0.0107	0.0992	0.3547
Turbidity (NTU)	Morning	**28.5 ± 29.3**	**49 ± 41.1**	0.0022	0.0482	0.7848

Note: Bold values indicate significant differences between systems using the *t*-test. Data on temporal variation are not shown in the table. *p*-Values refer to differences among culture systems (system), the means of the parameter by culture month (month), and interactions between systems and months (system*month).

TABLE 3 Mean ± standard deviation of plankton density measured in tambaqui monoculture (T) and integrated culture of tambaqui and curimba (TC) in ponds.

	Production system		*p* Value		
	T	**TC**	**System**	**Month**	**System*month**
Phytoplankton (individuals L^{-1})	2314 ± 2374	3203 ± 2854	0.2734	0.3520	0.2376
Zooplankton (individuals L^{-1})	**430 ± 352**	**806 ± 530**	0.0389	0.2541	0.9370
Rotifer (individuals L^{-1})	**109 ± 110**	**325 ± 374**	0.0325	0.5145	0.4911
Copepods (individuals L^{-1})	319 ± 299	409 ± 314	0.3004	0.0132	0.9255
Cladocerans (individuals L^{-1})	1.18 ± 2.43	1.14 ± 1.99	0.9132	0.1139	0.4536

Note: Bold values indicate significant differences between systems using the *t*-test. *p*-Values refer to differences among culture systems (system), the means of the parameter by culture month (month), and interactions between systems and months (system*month).

(Sokal & Rohlf, 2012), the numerical mean values were higher in the integrated culture than in the monoculture. In addition, the variability in tambaqui performance was relatively low (CV ranged from 11% to 24%), and the *t*-test *p*-values were high, ranging from 0.42 to 0.98. Therefore, it is reasonable to conclude that tambaqui performance was similar across both farming systems, indicating that curimba did not compete with tambaqui for space or food. This finding aligns with the results reported by Franchini et al. (2020) for tambaqui juvenile production. Conversely,

TABLE 4 Partial budget analysis of curimba inclusion in pond-based tambaqui (*Colossoma macropomum*) culture.

Category	Value (US\$ ha^{-1} $year^{-1}$)
Additional benefits	
Revenue	1777.42 ± 568.58
Additional costs	
Juvenile	209.14
Labor (stocking and harvesting)	87.14
Net benefit (Benefits − costs)	1481.14 ± 568.58

Note: Price data were obtained in Palmas, Tocantins, Brazil, in June 2024. Monetary values are expressed in US dollars (US\$ 1.00 = R\$ 5.41, exchange rate accessed in August 2024).

curimba influenced water quality and plankton communities, even though the parameters remained within ranges acceptable for freshwater aquaculture, according to Boyd (2020). The integrated system showed ∼25% higher total fish production (tambaqui plus curimba), without additional feed, suggesting a potential benefit of integration, thereby boosting farm revenue and profit.

Tambaqui reached the commercial size of about 1700 g after seven months of culture, which was faster than typically expected. This weight is usually achieved in 10 months or more (Lima et al., 2025; Lima, dos Reis, et al., 2024; Valenti et al., 2021). This accelerated growth may be a result of high early-culture mortality caused by cormorant predation, which reduced pond density. Despite predation, the observed survival rate (∼60%) aligns with expectations for tambaqui production in ponds, where fish weighing 25–50 g typically achieve 60–80% survival (Woynárovich & Van Anrooy, 2019). Annual productivity observed in the present study (∼7 t ha^{-1} $year^{-1}$) was compatible with that observed in commercial farms, which range from 5 to 12 t ha^{-1} $year^{-1}$ (Valenti et al., 2021). The 30% reduction in culture duration allows 1.7 cycles per year instead of the usual 1.2, compensating for annual production. These findings indicate that lower stocking densities offer an opportunity for farmers who prioritize more frequent cycles over maximum yield per cycle, enabling higher financial turnover.

The final individual mean weight of curimba in our study was approximately 145 g, survival averaged 97% over 7 months of culture, and annual yield was 962 kg ha^{-1}. Curimba was not preyed upon by cormorants because it is a demersal fish that swims close to the bottom. Della Rosa et al. (2016) reared *Prochilodus lineatus* combined with pacu, *Piaractus mesopotamicus*, in ratios 1:3, 1:2, and 1:1, with a total density of 0.5 fish per m^2, harvesting curimba at an average weight of 425 g after 11 months, with a yield of 400 kg ha^{-1}. The growth was greater than that observed in the curimba monoculture fed a commercial diet (210 g), suggesting that pacu waste may be more effective in nourishing curimba. In our study, we completed the culture at a ratio of 5 curimba to 3 tambaqui, with a total density of approximately 0.5 fish per m^2. The higher ratio of curimba to tambaqui may have reduced the availability of tambaqui waste for curimba, thereby limiting their growth. This indicates that lower stocking densities or revised species ratios could allow curimba to reach larger marketable sizes within the intended culture period.

The integrated culture produced almost 1 t ha^{-1} $year^{-1}$ of curimba in tambaqui ponds without any additional diet. Tambaqui FCR showed similar values between systems, suggesting that curimba growth may have been supported by nutrients from aquatic biota, diet wastes, and tambaqui feces. The mean total fish harvested was ∼25% higher, indicating an enhancing nutrient recovery. This aligns with the principles of ecological intensification in restorative aquaculture (Alleway et al., 2021; Aubin et al., 2019). This outcome is consistent with the IMTA and circularity principles, where the by-products (organic and inorganic wastes) of one cultured species are inputs for others (Boyd et al., 2020; Checa et al., 2024; Knowler et al., 2020). The growth of the secondary species relies on nutrients that would otherwise be wasted in the ponds or released into the environment. By transforming these nutrients into fish biomass, potential pollutants are turned into valuable biomass, boosting fish production without needing extra input or expanding the farming area.

The inclusion of curimba in the integrated culture was associated with changes in nutrients and plankton dynamics. Increased turbidity and total dissolved and suspended solids, along with decreased water transparency observed in the integrated culture, may be related to sediment bioturbation resulting from the iliophagous behavior of curimba (Oliveira Junior et al., 2019). This bioturbation suspended nutrients that had accumulated on the pond bed, triggering a bottom-up trophic cascade, which boosted the phytoplankton community and affected the entire ecosystem through higher trophic levels. This was evident from the chlorophyll *a* concentration in the water column, which was about 80% higher in the integrated culture. Although the phytoplankton density was also higher, the high variability in the data and the small number of trials may have limited the statistical power to detect significant differences. Thus, only substantial differences between treatments will be statistically detectable (Smart et al., 1998). Additionally, phytoplankton biomass may be rapidly consumed by zooplankton, which were more abundant in ponds with curimba. Likely, cladocerans were quickly consumed by tambaqui, which strongly prefer this group (Lima, dos Reis, et al., 2024), while rotifers and copepods experienced less predation, allowing their populations to grow in the integrated culture. Thus, nutrients that were inactive on the bottom were recycled by the biota and partially incorporated by the tambaqui. Therefore, curimba plays a key role in making nutrients available in the water column, promoting nutrient recycling in pond systems, and making them accessible to animals at higher trophic levels through the food web.

Integrated culture was associated with a higher mean abundance of monogeneans in tambaqui. As these monogeneans are stenoxenous, that is, parasitizing a single or very closely related species (Tavares-Dias et al., 2022), they do not parasitize curimba. We hypothesize that this increase may be because of changes in water quality and bioturbation-induced sediment disturbance. In general, parasitism intensity is strongly correlated with water quality factors, including organic matter and eutrophication levels (Blanar et al., 2009; Hosseini Aghuzbeni et al., 2016). Monogenean abundance is associated with eutrophic conditions (Gilbert & Avenant-Oldewage, 2021). Additionally, bioturbation by curimba may have facilitated the resuspension and dispersion of monogenean eggs in the water column. After being released, these eggs typically sink and accumulate in the bottom sediment. Bioturbation can resuspend them into the water column, increasing the likelihood that newly hatched oncomiracidia (infective larvae) encounter and infect tambaqui hosts. Further research should be conducted to assess the causes of higher tambaqui infection in the integrated culture.

The fundamental purpose of a partial budget is to assess the change in net benefit, which indicates whether net returns are expected to increase or decrease with the proposed modification and by how much (Engle, 2010). The addition of curimba in the monoculture of tambaqui leads to a net benefit gain of US$ 1481.14 per hectare per year. Production costs increased by US$ 296.28 per hectare per year, mainly as a result of the cost of purchasing curimba juveniles, which was largely compensated by their revenue. Although the curimba harvested in our study did not reach the typical market size of ~600 g, they were included in the revenue calculation because smaller curimba are commonly sold in Brazil as food, bait fish, juveniles for repopulating degraded areas, or for restocking in ponds for a second grow-out cycle (Valenti et al., 2021). In polyculture systems, cost increases are commonly linked to the acquisition of additional juveniles, as observed in our study, and, in some cases, to higher feed consumption (Bessa Junior et al., 2012; Engle, 2010; Mansour et al., 2021). An increase in income from IMTA systems relative to original monocultures has been observed for the tambaqui and Amazon River prawn (*Macrobrachium amazonicum*) (Dantas et al., 2022) and for some other species (Ibrahim & El Naggar, 2010; Knowler et al., 2020). Additionally, the IMTA system diversifies the products, thereby increasing the farm's sustainability (Valenti et al., 2018).

5 | CONCLUSIONS

Results indicate no negative effects of curimba inclusion on tambaqui growth, survival, productivity, or FCR. This suggests that an increase in harvested fish biomass with no additional feed is feasible. Besides potential improvements in feed utilization, the integrated culture may lead to changes in water quality, plankton, and parasite abundance, possibly related to sediment bioturbation by the curimba's feeding behavior. This bioturbation may release nutrients into the water column, stimulating a bottom-up trophic cascade and allowing the pond biota and farmed species to recover these nutrients. Implementing the integrated culture may also increase net profit by about US$ 1.5 thousand per hectare per year. Curimba appears to be compatible and complementary to tambaqui, making them suitable for co-production. Therefore, tambaqui can be successfully farmed in an integrated culture with curimba (and possibly other benthic species), enhancing aquaculture production efficiency and aligning with the principles of the circular economy. Further studies should explore alternative proportions and stocking densities of tambaqui and curimba to optimize curimba growth and total productivity. Results obtained in small experimental ponds should be validated in large commercial ponds. However, this study was conducted under conditions similar to those in the production sector, making the results more applicable to the production sector.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Adriana Ferreira Lima https://orcid.org/0000-0002-8828-6992

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