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Article

Evaluation of Growth and Phytochemical Profile of Trapoeraba (*Commelina erecta*) and Jambu (*Acmella oleracea*) and Performance of Nile Tilapia (*Oreochromis niloticus*) in an Aquaponic System

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RESUMO

O estudo avaliou o desenvolvimento e o perfil fitoquímico das Plantas Alimentícias Não Convencionais (PANC) Jambu (*Acmella oleracea*) e Trapoeraba (*Commelina erecta*), além do desempenho de Tilápias (*Oreochromis niloticus*), em um sistema aquapônico sob duas densidades de estocagem de peixes: 150 (T1) e 300 peixes/m³ (T2). Os resultados zootécnicos indicaram que a menor densidade (T1) favoreceu o crescimento e o peso das tilápias. O adensamento excessivo no T2 resultou em menor ganho de biomassa e comprimento, justificando-se pela maior competição alimentar e pelo estresse crônico associado a altas taxas de estocagem. No aspecto vegetal, as espécies responderam de formas opostas. O jambu apresentou crescimento significativamente maior nos tratamentos com peixes (T1 e T2) em comparação ao controle (T0), beneficiando-se do aporte de nitrogênio proveniente das excretas. Não houve diferenças significativas entre T1 e T2 para o jambu, sugerindo que a densidade menor já supria plenamente suas necessidades nutricionais. Em contrapartida, a trapoeraba demonstrou baixa adaptação ao sistema, manifestando clorose e podridão radicular devido à provável sensibilidade ao excesso de umidade e à toxicidade por amônia. As análises fitoquímicas focaram-se exclusivamente no jambu, dado o estado deficitário das amostras de trapoeraba. Saponinas e alcaloides foram identificados em todas as repetições, refletindo características intrínsecas da espécie. Os taninos catéquicos foram escassos devido à priorização do crescimento vegetal em ambientes ricos em nitrogênio. Por fim, os teores de fenólicos totais e a atividade antioxidante mantiveram-se semelhantes entre T1 e T2.

Palavras-chave: Atividade antioxidante; Compostos fenólicos; Espécies negligenciadas e subutilizadas; Hortaliças.

ABSTRACT

The study evaluated the growth and phytochemical profile of Non-Conventional Food Plants (PANC) Jambu (*Acmella oleracea*) and Trapoeraba (*Commelina erecta*), as well as the performance of tilapia (*Oreochromis niloticus*), in an aquaponic system under two fish stocking densities: 150 (T1) and 300 fish/m³ (T2). The zootechnical results indicated that the lower stocking density (T1) favored the growth and weight of the tilapia. Overcrowding in T2 resulted in lower biomass and length gains, which can be explained by increased competition for food and chronic stress associated with high stocking rates. Regarding the plants, the species responded in opposite ways. Jambu exhibited significantly greater growth in the treatments with fish (T1 and T2) compared to the control (T0), benefiting from the nitrogen supply from excreta. There were no significant differences between T1 and T2 for jambu, suggesting that the lower density already fully met its nutritional needs. In contrast, the trapoeraba showed poor adaptation to the system, exhibiting chlorosis and root rot due to probable sensitivity to excess moisture and ammonia toxicity. Phytochemical analyses focused exclusively on the jambu, given the poor condition of the trapoeraba samples. Saponins and alkaloids were identified in all replicates, reflecting intrinsic

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characteristics of the species. Catechin tannins were scarce due to the prioritization of plant growth in nitrogen-rich environments. Finally, total phenolic content and antioxidant activity remained similar between T1 and T2.
Keywords: Antioxidant activity; Phenolic compounds; Neglected and underutilized species; Vegetables.

Introduction

The increase in the world's population brings numerous challenges, such as water resource management, soil degradation, climate change, salinization, food production, and others. With regard to food production, livestock farming and conventional agriculture (mechanized and based on monocultures and large landholdings) contribute to soil degradation, food insecurity, biodiversity loss, and global environmental changes. This occurs due to several factors, such as changes in land use and occupation, suppression of native vegetation, extensive use of pesticides and synthetic fertilizers, and dietary standardization (Raulier et al. 2023; Verma et al. 2023).

Aquaculture has become a growing food production sector in recent years, representing an option for ensuring food security worldwide in response to population growth and the search for healthier and health-promoting foods. However, unsustainable management also generates environmental impacts, such as eutrophication, effluent discharge, introduction of exotic species into natural ecosystems, and changes in biodiversity, among others (Raulier et al. 2023; Verma et al. 2023; Amorim & Tosta 2020; Silva et al. 2018; Silva et al. 2023).

Sustainable agricultural practices are alternatives for mitigating the aforementioned socio-environmental impacts. Aquaponics is a sustainable integrated food production technology that combines recirculating aquaculture and soilless horticulture. In this system, nutrient-rich effluent (fish excreta and uneaten feed) is recirculated and used by plants as a nutrient source (fertilizer) in hydroponics and subsequently returns to the aquaculture tank with improved water quality parameters. Thus, aquaponics provides the benefits of low effluent discharge, efficient water use, minimal use of chemical additives, antibiotic-free production, maximization of plant biomass production, and food safety, in addition to having considerable economic potential (Raulier et al. 2023; Verma et al. 2023).

Tilapia is commonly used as a model species in aquaponics. However, crustaceans, carp, and catfish can also be used. Regarding plants, herbaceous species such as lettuce, herbs, leafy vegetables, and other species with rapid growth and low nutritional requirements are generally cultivated. Nevertheless, fruit-bearing species such as tomatoes, flowering species such as calendula, and non-leafy vegetables such as okra and peppers can also be produced (Verma et al. 2023).

This research incorporated non-conventional vegetables into an aquaponic system and evaluated their effects on the phytochemical profile, considering that the benefits generated by sustainable agroecosystems extend beyond improvements in biodiversity, soil quality, safe food production, and ecosystem regeneration and recovery. Diversification of land use in agroecological agricultural systems alters the phytochemical profile of foods, which may affect the flavor, aroma, and biological activities of plant secondary metabolites in the human body (Oliveira et al. 2022).

Non-conventional vegetables are native, exotic, or naturalized species that are not part of the conventional production chain, but represent foods with unexplored socioeconomic, cultural, nutritional, and even pharmacological potential. They fall within the concept of Non-Conventional Food Plants (PANC), which are species neglected or underutilized by the population and are not produced through conventional agriculture (Madeira et al. 2013; Tuler et al. 2019). Incorporating PANC into aquaponic systems may have positive effects on food and nutritional security, dietary diversification, floristic biodiversity, reduction of the impacts of conventional aquaculture and agriculture, and safe food production. However, studies evaluating the effects of this combination on plant development, phytochemical profile, and antioxidant capacity remain scarce.

Additionally, the popularization of sustainable technology involving the cultivation of traditional vegetables may contribute to the achievement of the Sustainable Development Goals, including Goal 1 (end poverty in all its forms everywhere); Goal 2 (end hunger, achieve food security and improved nutrition, and promote sustainable agriculture); Goal 6 (ensure availability and sustainable management of water and sanitation for all); Goal 8 (promote sustained, inclusive and sustainable economic growth, full and productive employment, and decent work for all); and Goal 12 (ensure sustainable consumption and production patterns) (United Nations 2015).

The following PANC species were used in this research: *Commelina erecta* (trapoeraba) and *Acmella oleracea* (jambu), which were cultivated in an aquaponic system with *Oreochromis niloticus* (tilapia) under two treatments: stocking densities of 150 and 300 fish/m³. The general objective of this research was to investigate the effect

of different fish stocking densities (150 and 300 fish/m³) in an aquaponic system on plant development, antioxidant capacity, and total phenolic content of PANC.

Tilapia is a freshwater species widely used in aquaculture and is one of the most farmed fish species in the world, as it is resistant, has good feed conversion, and tolerates high stocking densities (Nivaldo et al. 2024; Gallo et al. 2023). Jambu is a herbaceous plant of the *Asteraceae* family that is widely distributed in northern Brazil and is used in culinary preparations. In several countries, it is also used in cosmetics, pharmacotherapy (with anti-inflammatory, diuretic, vasodilatory, antioxidant, and antimicrobial properties), and agricultural pest control. Its culinary use is quite diverse and is part of the cuisine of Indigenous peoples of Brazil. Its leaves and flowers are edible and provide pungency, an anesthetic effect, salivation, and a refreshing sensation. It is well adapted to tropical climates and grows in environments with high sun exposure and moist, well-drained soils rich in organic matter, especially nitrogen sources. In addition, it contains numerous secondary metabolites, such as alkaloids, flavonoids, saponins, steroid glycosides, and tannins (Spinozzi et al. 2022; Lee, 2026; Rodrigues et al. 2023).

Trapoeraba belongs to the *Commelinaceae* family and is widely distributed in Brazil. Like other plants of the genus *Commelina*, it is considered a pest (weed) in agriculture in several countries (Rocha et al. 2007). Its leaves and stems have food and medicinal uses and are used for infections, respiratory tract problems, diabetes, hypertension, etc. (Cavichi et al. 2023).Metodologia

Methodology

The experiment lasted 60 days and was conducted between May and July 2025 at the Sustainable Aquaculture Center, located at Fazenda Água Limpa (FAL), belonging to the University of Brasília, located in the Vargem Bonita Rural Nucleus, Park Way Mansions Sector, Brasília, Federal District. FAL comprises the Environmental Protection Area of the Gama and Cabeça do Veado Basins, in the Cerrado biome. The region's climate consists of tropical savanna and rainy temperate climate with dry winters, with average monthly temperatures always above 18°C, comprising a hot and rainy season from October to April, with annual rainfall of approximately 1,540 millimeters, and another cold and dry season from May to September (Telles 2020).

The aquaponic system used was the Media Based Systems, consisting of aquaponic units containing a 310-liter polypropylene fish production tank, 0.25-square-meter polypropylene boxes for vegetable cultivation filled with expanded clay, acting as a biological filter, a water pump (Grupo Sario®, Sariobetter SB1000C, Brazil), and an air compressor (Grupo Boyu®, ACQ-003, Guangdong, China).

The species *Oreochromis niloticus* was used in the fish tanks in two intensive system treatments, with a density of 150 (T1) or 300 fish per m³ (T2). Tilapia juveniles were introduced into the system and remained for 7 days for adaptation before the beginning of vegetable cultivation. The juveniles were fed commercial feed consisting of 40% crude protein, with a daily feeding rate of 5% of live weight, twice a day (Corrêa et al. 2018; Silva et al. 2020).

Two different densities (150 and 300 fish per cubic meter of water) and a negative control without fish (T0) were used, resulting in three treatments with four replicates each, with the treatments randomly distributed within the greenhouse. Thus, the sample consisted of 45 fish in each replicate in the treatment with 150 fish/m³ and 90 fish in the treatment with 300 fish/m³, totaling 540 individuals. Studies in fish farming seek to take into consideration different animal densities and zootechnical data for analyses of production systems through fish and plant biomass and productivity (Rahmatullah 2010; Araújo et al. 2010; Maeda et al. 2010; Ayroza et al. 2011; Costa 2014; Coelho et al. 2014).

Regarding vegetable cultivation, the species *Commelina erecta* (Trapoeraba) and *Acmella oleracea* (Jambu) were used. The PANC seedlings (cuttings) were acquired from Embrapa Vegetables, one of the decentralized units of the Brazilian Agricultural Research Corporation, linked to the Ministry of Agriculture, Livestock and Food Supply (Embrapa), with a focus on research and development for efficient and competitive vegetable production. Two units of each plant species, jambu and trapoeraba, were inserted into each aquaponic unit in the three treatments.

Animal growth was evaluated by measuring weight (g) and total length (cm) at the beginning and end of the experiment, using a precision digital electronic scale (B-max – SF-400) and a measuring tape, respectively. The same instruments were used to evaluate plant development through the parameters of weight (g), height (cm), and number of leaves (Silva et al. 2020).

To determine the phytochemical profile (phytochemical screening, total phenolics, and antioxidant activity), ethanolic extracts were obtained from the dry matter of the plants. After 60 days of the experiment,

fresh samples (leaves) were collected, sanitized in a 2% sodium hypochlorite solution, placed in an oven for 72 h at 60°C, ground in a Willey-type mill, and stored in amber bottles (Carvalho et al. 2008).

In the phytochemical screening, tests were performed for the qualitative identification of foaming saponins, phenols, tannins, flavonoids, alkaloids (Bouchardat and Mayer reagents), catechins, steroids, and triterpenoids (Barbosa et al. 2004). The determination of total phenolic content was based on the Folin-Ciocalteu method, with results expressed in milligrams of gallic acid equivalents (Alu'datt et al. 2019; Mlcek et al. 2021). Antioxidant activity was evaluated using DPPH (2,2-diphenyl-1-picrylhydrazyl), and the results were expressed as IC50, which represents the exact concentration of an extract, compound, or antioxidant required to reduce (or inhibit) 50% of the free radicals generated in the assay. The data obtained were subjected to analysis of variance, and the means were compared using Tukey's test ($p \leq 0.05$) (Oliveira et al. 2013; Araújo 2011; Kuskoski et al. 2005; Rufino et al. 2007).

Results

Plants

Table 1 shows that there were no differences in the parameters measured at the beginning of the experiment, since the seedlings were standardized. At the end of the experiment, a statistically significant difference was observed for Jambu between T0 and Treatments 1 and 2, both with fish. Among the treatments with fish (T1 and T2), no statistically significant differences were found for the parameters measured for Jambu. For Trapoeraba, as with Jambu, the initial measurements showed no differences, since standardized seedlings were used. In the final measurements, a statistically significant difference was found only for the weight parameter, with no difference between T0 and T1, while both differed from T2.

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Table 1. Parameters of the two different plant species according to treatment and experimental phase. Different letters in the same row indicate statistical differences according to Tukey's test, $p < 0.01$.

Parameter/Species/Stage	***Jambu***					
Treatment	Baseline T0	Baseline T1	Baseline T2	Final T0	Final T1	Final T2
Weight	***4.63 ± 0.15***	***4.62 ± 0.14***	***4.67 ± 0.13***	$12.17^{a} \pm 10.69$	$695.78^{b} \pm 400.55$	$805.15^{b} \pm 409.72$
Height	**15**	**15**	**15**	$40.62^{a} \pm 10.26$	$96.37^{b} \pm 11.43$	$97.68^{b} \pm 7.77$
Nº of Pages	**4**	**4**	**4**	$37.25^{a} \pm 24.64$	$1322.62^{b} \pm 452.08$	$1624.87^{b} \pm 710.85$
Parameter/Species/Stage	***Trapoeraba***					
Treatment	Baseline T0	Baseline T1	Baseline T2	Final T0	Final T1	Final T2
Weight	**7**	**7**	**7**	$15.46^{a} \pm 9.1$	$18.71^{a} \pm 13.72$	$57.15^{b} \pm 53.98$
Height	***18.125***	**18**	***17.5833***	$20.81^{a} \pm 5.07$	$18.42^{a} \pm 5.82$	$24.41^{a} \pm 6.66$
Nº of Pages	**4**	**4**	**4**	$33.25^{a} \pm 17.11$	$28.85^{a} \pm 24.6$	$74.33^{a} \pm 70.36$

Source: Original work.

Fish

No significant differences were found in the parameters measured for the initial assessment of the fish. However, at the final stage of the experiment, statistically significant differences were observed between T1 and T2, with the fish in T1 showing greater growth and weight than those in T2. No differences were found among the treatments in water temperature, only statistically significant differences between the measurement times, with higher temperatures in the afternoon.

Table 2. Fish parameters according to treatment and experimental phase. Different letters in the same row indicate statistical differences according to Tukey's test, $p < 0.01$.

Parameter/Phase	***Fishes***			
Treatment	Initial T1	Initial T2	Final T1	Final T2
Weight	$1.3^{a} \pm 0.35$	$1.23^{a} \pm 0.38$	$18.58^{b} \pm 5.18$	$12.03^{c} \pm 3.57$
Total Length	$4.13^{a} \pm 0.45$	$4.27^{a} \pm 0.44$	$10.32^{b} \pm 0.99$	$9.02^{c} \pm 0.88$

Source: Original work.

Table 3. Water temperature according to treatment and measurement time. Different letters in the same row indicate statistical differences according to Tukey's test, $p < 0.01$.

Temperature/Treatment/Schedule	T0 7:00	T1 7:00	T2 7:00	T0 14:00	T1 14:00	T2 14:00
Temperature (°C)	$28.39^{a} \pm 1.16$	$28.34^{a} \pm 1.22$	$28.39^{a} \pm 1.24$	$32.48^{b} \pm 1.68$	$32.39^{b} \pm 1.68$	$32.36^{b} \pm 1.62$

Source: Original work.

Phytochemical profile

Trapoeraba showed low productivity in the aquaponic system at the end of the study, and the plants showed signs of rot and chlorosis, making it impossible to obtain a sufficient number of samples with adequate weight and quality for the analyses of the phytochemical profile, total phenolics, and antioxidant activity. The leaves would need to be healthy to ensure the scientific validity of the study. Therefore, the data below are only from Jambu.

Table 4. Phytochemical screening in Treatment 1.

Tests		**Density of 150 fish/m³**							
		1st repetition		**2nd repetition**		**3rd repetition**		**4th repetition**	
		Jambu 1	Jambu 2	Jambu 1	Jambu 2	Jambu 1	Jambu 2	Jambu 1	Jambu 2
Saponins		+	+	+	+	+	+	+	+
Alkaloids	Bouchardat	+	+	+	+	+	+	+	+
	Mayer	+	+	+	+	+	+	+	+
Flavonoids		+	+	-	-	-	-	-	-
Catechins		-	-	-	-	-	-	-	-
Phenols and tannins		-	+ Catechin tannins	-	-	-	-	-	-
Steroids		-	-	-	-	-	-	-	-

Source: Original work.

Table 5. Phytochemical screening in Treatment 2.

Tests		**Density of 300 fish/m³**							
		1st repetition		**2nd repetition**		**3rd repetition**		**4th repetition**	
		Jambu 1	Jambu 2	Jambu 1	Jambu 2	Jambu 1	Jambu 2	Jambu 1	Jambu 2
Saponins		+	+	+	+	+	+	+	+
Alkaloids	Bouchardat	+	+	+	+	+	+	+	+
	Mayer	+	+	+	+	+	+	+	+
Flavonoids		+	+	-	-	-	-	-	-
Catechins		-	-	-	-	-	-	-	-
Phenols and tannins		+ Catechin tannins	-	-	-	-	-	-	-
Steroids		-	-	-	-	-	-	-	-

Source: Original work.

Discussion

In the aquaponic system, fish are the main source of nutrients for plants through their excreta. The feed provided is rich in protein, and the nitrogen from this feed is excreted by fish in the form of ammonia (Hu et al. 2015). Nitrifying bacteria, such as *Nitrosomonas* and *Nitrobacter*, present in the biofilter and plant roots convert ammonia first into nitrite (NO_2^-) and then into nitrate (NO_3^-), which is the form of nitrogen preferentially

absorbed by most cultivated plants (Maucieri et al. 2019; Hu et al. 2015). Thus, the more fish there are and the more feed is provided, the more nutrients become available in the water for the plants. This explains the greater development of jambu in both treatments compared with the control group, in which the only source of nutrients was the water itself, which is poor in nitrogen and other essential elements.

Specific studies on jambu show that nitrogen is a determining factor for its growth. Aviz et al. (2019) tested different nitrogen rates (0 to 150 kg/ha) in jambu cultivated in soil and found that the best productivity was obtained with approximately 79 kg of N per hectare and that fresh shoot mass increased significantly with nitrogen fertilization, up to a certain point. Jambu is a leafy vegetable with a high nitrogen requirement, as are lettuce, kale, and other Brassicas. However, the simple presence of fish in the system, even at the lower density of 150 fish/m³, already provided sufficient nitrogen and other nutrients for jambu to express its full growth potential.

Studies in aquaponics show that even moderate fish densities can provide nitrate concentrations that satisfactorily meet plant requirements. For example, a study with lettuce in aquaponics using tilapia at densities ranging from 10 to 25 kg/m³ showed that the nitrate concentration in the water reached 105 mg/L even at the highest density, and that plant fresh weight increased with density, but differences between intermediate and high densities were not always significant for all parameters (Pineda-Pineda et al. 2015).

The density of 300 fish/m³, although doubling the number of fish and, therefore, the amount of feed provided and excreta produced, may have generated an excess of nutrients that exceeded the plants' absorption capacity, or because their growth rate had already reached a plateau under the system conditions (light, temperature, space), or because the higher concentration of ammonia in the water at higher densities may have slightly inhibited growth, offsetting the greater nutrient supply.

Commelina erecta (trapoeraba) showed a distinct behavior. Unlike jambu, which is a leafy vegetable selected for biomass production, trapoeraba is a more prostrate-growing plant, frequently considered a "weed" in many agricultural systems. Trapoeraba showed no differences in height or number of leaves among the treatments at the end of the study. In addition, it showed leaf yellowing (chlorosis) and stem and root rot, suggesting some type of stress in the aquaponic system.

It can be hypothesized that trapoeraba suffered from ammonia toxicity. In aquaponic systems, especially during the first days of operation or when fish density is high, ammonia may accumulate before nitrifying bacteria are fully established. Ammonia at high concentrations is toxic to many plants, causing chlorosis, smaller leaves, reduced growth, inhibition of root growth, and, in severe cases, root rot. The mechanisms include: (1) competition between ammonium and other cations (K^+, Ca^{2+}, Mg^{2+}), leading to mineral deficiencies; (2) acidification of the root environment; (3) changes in intracellular pH and osmotic balance; and (4) accumulation of reactive oxygen species that damage cell membranes (Gerendás et al. 1997; Li et al. 2022).

It is important to point out that there are enormous differences among plant species in their tolerance to ammonium. While some plants (such as onion and maize) are relatively tolerant, others (such as tomato, beans, and cucurbits) are very sensitive (Gerendás et al. 1997). Trapoeraba, having never been selected for cultivation in aquaponic systems, probably falls within the group of species sensitive to excess ammonium in the root zone.

Despite these results, trapoeraba showed greater weight in T2 compared with treatments T0 and T1. One possible explanation comes from studies on invasive plants and their response to nitrogen. Research shows that some plants classified as "ruderal" or "weedy" (such as many Commelinaceae) may allocate more biomass to the aboveground part when nutrients are abundant, even under stressful conditions (Liu et al. 2019).

Trapoeraba in T2 may have had access to such a large amount of nutrients that, despite the stress caused by ammonia, it was able to accumulate more biomass despite the visual symptoms of deterioration. Stem and root rot suggests that the root system was compromised, possibly by opportunistic pathogens that proliferate under conditions of high humidity and stress in the host plant.

In addition, competition for light, nutrients, and root space among plant species in the same cultivation area may have reflected in the less expressive results for trapoeraba, considering that jambu showed more vigorous growth. Studies on competition among plant species show that when one species grows faster and reaches a larger size, it can shade and suppress the neighboring species, drastically reducing its access to light for photosynthesis (Ramseier & Weiner 2006; Gruntman et al. 2017). In addition, the more extensive root system of jambu may have captured most of the available nutrients before the roots of trapoeraba could absorb them.

Trapoeraba is a species that did not adapt well to the aquaponic system. The symptoms of chlorosis and root rot indicate sensitivity to the high-moisture environment and/or ammonium toxicity. The increase in

weight only in T2 probably reflects a forced accumulation of low-quality biomass under high nutrient availability, rather than healthy growth.

The lower fish density favored greater development of the tilapia. These results reflect lower competition for feed at lower stocking densities. Studies show that feed consumption rates decrease significantly with increasing stocking density. In a classic experiment, researchers observed that hybrid tilapia stocked at different densities showed reduced feed consumption as stocking density increased (Siddiqui & Al-Harbi 1999). This occurs because larger or more aggressive fish may monopolize the feed, leaving smaller fish with less access, a phenomenon well documented in tilapia, which form social dominance hierarchies (Mcginty 1985; Barcellos 1999a).

Ani et al. (2022) compared three densities (150, 300, and 450 fish/m³) in an aquaponic system with tilapia and lettuce and found that feed conversion was worse at higher densities: 1.86 and 1.66 for densities of 300 and 450, respectively, compared with 1.45 at the lowest density. This means that, at higher densities, each kilogram of feed yielded fewer kilograms of fish. The same study also reported lower survival at the highest density (93.85%, 89.73%, and 82.05% survival at 150, 300, and 450 fish/m³, respectively).

Another possibility is greater stress at higher densities, which increases cortisol levels in fish. In an experiment conducted by Barcellos et al. (1999a), Nile tilapia kept in larger groups (10 fish per tank) showed higher cortisol levels than fish raised alone or in pairs. These more stressed fish also gained less weight over 60 days. In tilapia subjected to chronic stress, researchers observed an approximately one-third reduction in weight gain compared with non-stressed fish (Barcellos 1999b).

Higher fish densities may also compromise water quality, especially water hardness, dissolved oxygen, nitrite, and nitrate, which increase as density increases. In an experiment with carp in aquaponics, the highest density (4.6 kg/m³) resulted in significantly lower dissolved oxygen and higher ammonia concentrations compared with the lowest density (2.5 kg/m³). This impaired both fish growth and vegetable production (Maucieri et al. 2019).

Furthermore, at high densities, reduced physical space itself may limit growth. A study with juvenile tilapia in cages showed that when density was increased from 250 to 350 fish/m³, the final weight of the fish decreased by 68.2%, and at 450 fish/m³, the reduction was 56% (Costa et al. 2017).

In the phytochemical screening, the presence of saponins and alkaloids was observed in all samples, regardless of treatment, which reflects the intrinsic chemical composition of jambu. The species *Acmella oleracea* is known to produce a wide variety of alkaloids and saponins as part of its secondary metabolism. The most well-known compound in jambu is spilanthol, an alkamide and an alkaloid responsible for the tingling sensation and local anesthetic effect caused by the plant. Studies on the chemical profile of jambu have identified dozens of alkaloids (mainly N-isobutyl-substituted alkamides) and several phenolic compounds, such as chlorogenic acids and glycosylated flavonoids (Nascimento et al. 2020). Triterpenoid saponins are also common metabolites in plants of the *Asteraceae* family. The production of these compounds is genetically determined but can be modulated by environmental factors. For example, studies with *Panax notoginseng* showed that saponins (such as ginsenosides) increase significantly under low-nitrogen conditions, whereas high nitrogen doses reduce their accumulation (Zhang et al. 2020). The fact that saponins and alkaloids were present in all plants from both treatments indicates that the ability to produce these metabolites is constitutive.

Regarding catechin tannins, they were identified in only a few samples from both treatments. Tannins are complex phenolic compounds formed by the polymerization of flavonoids (such as catechin and epicatechin). The production of tannins is influenced by several environmental factors, such as ultraviolet radiation, temperature, water availability, and nutrients (Gobbo-Neto et al. 2016). The review by Gobbo-Neto et al. (2016) highlights that the synthesis of these metabolites may vary seasonally and be affected by abiotic stresses.

The carbon/nutrient balance hypothesis predicts that phenolic compounds such as tannins tend to accumulate when there is an excess of carbon relative to available nitrogen (Deng et al. 2019). Under adequate nitrogen supply, the plant preferentially allocates carbon to growth rather than to the production of these defense compounds, which would explain the low occurrence of catechin tannins. In addition, the meta-analysis by Sun et al. (2020) showed that nitrogen addition reduces the concentration of flavonoids and total tannins in plants by approximately 30%. This suggests that the nitrogen supplied through aquaponics may be actively suppressing the tannin biosynthetic pathway in jambu.

Therefore, catechin tannins may have been produced in very low quantities, below the detection limit of the method used in most samples. In the study by Nascimento et al. (2020), which conducted a detailed chemical mapping of jambu using mass spectrometry, the main compounds identified were phenolic acids, glycosylated flavonoids, and alkamides, but tannins were not mentioned as major components.

As observed in Figures 5 and 6, there was no significant difference in total phenolic content or antioxidant activity between the two treatments. This allows inferences to be made regarding the relationship between nitrogen availability and secondary metabolism in plants. According to the carbon/nutrient balance hypothesis, plants that grow in environments with low nitrogen availability tend to divert more carbon toward the production of phenolic compounds (which are rich in carbon and poor in nitrogen). Under conditions of abundant nitrogen, however, the plant prioritizes growth (protein production) and reduces the synthesis of these defense compounds (Deng et al. 2019; Sun et al. 2020).

The reduction in secondary metabolites is positively correlated with the plant's C/N ratio: the lower the C/N ratio (i.e., the greater the nitrogen availability), the lower the phenolic content (Sun et al. 2020). In tobacco, researchers demonstrated that nitrogen deficiency activates genes in the phenylpropanoid pathway (such as PAL — phenylalanine ammonia-lyase), increasing chlorogenic acid levels by 3 to 4 times and rutin levels (a flavonoid) by up to 10 times (Fritz et al. 2006).

In this study, the two fish densities possibly resulted in concentrations of nitrogen available to the plants that remained within a similar range, perhaps both adequately meeting the growth requirements of jambu, and therefore similar phenolic contents and antioxidant activity between the treatments would be expected. In addition, a specific study on jambu compared organic and conventional cultivation and showed that the type of fertilization influenced phenolic levels, but in a manner dependent on the cultivar and the plant part analyzed (Borges et al. 2016). Another study compared jambu cultivated in a hydroponic system and in a conventional soil system and observed that the leaves consistently had the highest levels of total phenolics, flavonoids, and antioxidant capacity, regardless of the cultivation system, but the absolute values varied according to the cultivation method. In addition, total phenolic content was higher in soil cultivation (probably as a response to environmental stresses) (Nascimento et al. 2020). This reinforces that jambu is a plant that responds subtly and specifically to nutritional conditions.

Final considerations

These results have an important practical implication: in aquaponic systems, the choice of plant species is crucial. Species such as jambu, which are "demanding" in nitrogen and tolerate the conditions of the system well, are excellent candidates. Species such as trapoeraba, on the other hand, may not be suitable for this type of cultivation unless grown separately or in systems with lower fish densities and greater control of water quality.

The two fish densities tested were not sufficiently different to create distinct nutritional environments for jambu. Aquaponic systems have considerable buffering capacity: even if the higher density generates more waste, much of the nitrogen may be lost through volatilization and denitrification, resulting in similar effective nutrient availability to plants. The presence of saponins and alkaloids in all samples confirms that jambu maintains its characteristic chemical identity, while the scarcity of tannins reflects the prioritization of growth over secondary metabolites.

To advance the understanding of these relationships, future studies should consider: increasing the difference between the fish densities tested; measuring the nitrogen contents and C/N ratio effectively available to the plants throughout the cycle; and analyzing not only the concentration but also the total metabolite content per plant, since the dilution effect caused by increased biomass may mask actual differences in compound production.

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