



Optimizing Stocking Density for Enhanced Tilapia and Lettuce Production in NFT Aquaponics

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Abstract: Water is an essential resource in arid regions; therefore, its management and use must be rational. Aquaponics, which integrates aquaculture and hydroponics, represents an innovative approach to efficient water use, particularly in arid environments. The objective of this study was to determine the effect of fish stocking density on the growth performance of lettuce (*Lactuca sativa*) and Nile tilapia (*Oreochromis niloticus*) in a nutrient film technique (NFT)-based aquaponic system under arid conditions. A randomized block design was adopted with three fish stocking densities (1.5, 3.0, and 4.5 kg m⁻³), expressed as Nile tilapia biomass per unit volume of water. Water temperature remained within the optimal range across all treatments and did not differ significantly among them. However, pH and dissolved oxygen (DO) concentrations were significantly influenced by stocking density, with DO concentrations decreasing as stocking density increased. Higher stocking densities also resulted in increased nitrate, nitrite, and total ammonia nitrogen concentrations, whereas potassium and soluble reactive phosphorus concentrations remained stable. Tilapia reared at the lowest stocking density (1.5 kg m⁻³) attained significantly greater final weight, weight gain, and specific growth rate, whereas survival rates did not differ significantly among treatments. In contrast, lettuce grown at the highest fish stocking density (4.5 kg m⁻³) had significantly greater biomass, head weight, and leaf and root lengths, possibly due to greater nutrient availability. These findings highlight the need to balance fish and plant production objectives to optimize the efficiency of NFT-based aquaponic systems.

Key words: Aquaponics, arid region, lettuce, nile tilapia, stocking density.

Aquaponics, a symbiotic system that combines aquaculture and hydroponics, has transformed food production in arid locations. These regions, marked by water shortage and severe weather conditions, have substantial obstacles in traditional agriculture. Aquaponics provides a sustainable, efficient, and resilient solution, considering technological, economic, environmental, and social aspects. Aquaponic systems utilize water with high efficiency, an essential consideration in arid areas. These systems perpetually recycle water, with research demonstrating water savings of up to 90% relative to conventional agricultural practices (Ibrahim *et al.*, 2023; Nishanth *et al.*, 2024). The use of sophisticated technologies, including IoT and automation, significantly improves efficiency. IoT-compatible technologies provide real-time monitoring and regulation of water quality, temperature, and nutrient levels, hence maintaining ideal conditions for aquatic life and vegetation (Abdilmouti *et al.*, 2025; Nagayo *et al.*, 2017). Aquaponics functions as a closed-loop system, wherein water is recycled repeatedly, hence reducing waste and conserving this vital resource (Abdilmouti *et al.*, 2025).

Aquaponic systems exhibit significant economic feasibility, especially in dry areas where conventional agriculture is difficult. The amalgamation of aquaculture with horticulture generates a dual income source, hence enhancing profitability. Research in areas like Saudi Arabia and Egypt underscores the economic viability of aquaponics, with systems realizing substantial net profits and cost recovery over a span of 2 to 3 years (Goada *et al.*, 2015; Memon *et al.*, 2022).

The nutrient film technique (NFT) aquaponic systems employ a water recirculation mechanism, wherein fish excrement supplies nutrients to the plants, hence diminishing the necessity for water and fertilizers (Goddard and Al-Abri, 2025; Joyce *et al.*, 2019). The utilization of alternate water sources, including agricultural drainage water, enhances water use efficiency, as evidenced by research indicating that lettuce production in NFT systems achieved substantial yields with minimum water input (Mohammed *et al.*, 2016). NFT aquaponic systems mitigate environmental effect by decreasing waste discharge and utilizing renewable energy sources, such as solar energy, for operation (Nagayo *et al.*, 2017). The amalgamation of

aquaponics with technologies like biofloc can enhance nutrient recovery and diminish pollution, rendering these systems ecologically sustainable (Goddard and Al-Abri, 2025).

Aquaponic systems provide a sustainable method for food production in dry areas by combining aquaculture with hydroponics, thereby establishing a closed-loop system that optimizes resource utilization (Joyce *et al.*, 2019). These systems can be deployed in urban environments with constrained space, such as rooftops, to supply fresh produce near population centres, hence minimizing transportation expenses and carbon emissions (Joyce *et al.*, 2019). The capacity to cultivate both fish and vegetables inside a unified system provides economic benefits and enhances food security in areas with restricted arable land (Goddard and Al-Abri, 2025; Khanjani *et al.*, 2023).

Finding the perfect stocking density for an aquaponic system can help to maximize the performance of crops and fish while still maintaining uncompromised water quality. This is a crucial issue since another important aspect to take into account is keeping the system economically viable. Though fish stocking density and feed volume play a major influence on the performance of aquaponic systems, little study has been done on how these elements affect lettuce growth in these systems. The present work sought to assess in dry zone conditions in the southeast of Algeria the effect of Nile tilapia (*Oreochromis niloticus*) stocking density on the growth performance of lettuce (*Lactuca sativa*) and the fish in an NFT aquaponic system.

Materials and methods

Study area and experimental description

This experiment was done from November 22, 2024, to January 17, 2025, under greenhouse conditions at the Department of Agricultural Science, University of Biskra. The research area, Biskra, is an arid region situated in southeastern Algeria, positioned between latitudes 33°19' - 35°17' N and longitudes 4°07' - 6°48' E, at an elevation of 120 m altitude. This region experiences a temperature range of 12°C to 34°C and receives an average yearly precipitation of approximately 155 mm. The experiment was conducted using a completely randomized

approach. Nine independent aquaponic systems were established, comprising three fish stocking densities, with three independent replicates per treatment. The fish were stocked at densities of 1.5, 3, and 4.5 kg m⁻³ for treatments T1, T2, and T3, respectively. Each was linked to a hydroponic system. This resulted in a total of nine hydroponic units, each comprising 10 PVC tubes arranged in five vertically aligned pairs, as described below. Each autonomous system comprised a plastic fish-rearing tank with a capacity of 1000 L, operated with 800 L of water and continuously aerated using an air stone. This tank was linked to a mechanical filter (300 L) engineered to eliminate solid particles and reduce floating debris, which was subsequently connected to a bio-filter container (300 L) containing plastic bio-rings that facilitated biological processes, particularly nitrification. A hydroponic Nutrient Film Technique (NFT) unit was incorporated to facilitate plant growth (Fig. 1). The system comprised two water storage tanks, strategically positioned to enhance water flow efficiency. Each of the two water-storage tanks was fitted with a submersible water pump (18-watt capacity, rated flow rate of 2500 L h⁻¹, maximum head of 2.5 m); the pump output was regulated with a control valve to deliver the target NFT flow rate. The initial tank, positioned prior to the hydroponic unit, gathers the effluent from the bio-filter and employs the submerged water pump to convey the water into the hydroponic system. The secondary tank, situated subsequent to the hydroponic unit, gathers the effluent from the

hydroponics, and its submerged water pump recirculates the water to the fish tank, therefore completing the closed water cycle (Fig. 1).

The hydroponics system employing NFT technology consists of 10 PVC tubes, each measuring 4 meters in length and 11 centimeters in width. The tubes are organized in pairs, with five levels vertically aligned, and each pair is separated by a distance of 40 cm. The nutrient-rich aquaculture effluent (no externally prepared fertilizer solution was used) is supplied at the upper end of the top trough and flows consecutively through each trough before returning to the reservoir. The flow rate was established at 5 L min⁻¹. Weekly adjustments were made to compensate for water loss from the tanks due to evaporation by adding groundwater.

Fish stocking and feeding

The Nile Tilapia (*Oreochromis niloticus*) utilized in this study were obtained from an aquaculture facility in Biskra, where they were cultivated in a traditional aquaculture technique. Initially, fish were acclimatized for two weeks prior to operating the system to elevate ammonia levels and promote the proliferation of nitrifying bacteria. A total of 1,350 Nile tilapia fingerlings with an initial average weight of 20 grams were utilized. The fish were stocked at densities of 1.5 kg m⁻³ (75 fish m⁻³), 3 kg m⁻³ (150 fish m⁻³), and 4.5 kg m⁻³ (225 fish m⁻³), referred to as T1, T2, and T3, respectively. Each stocking density was

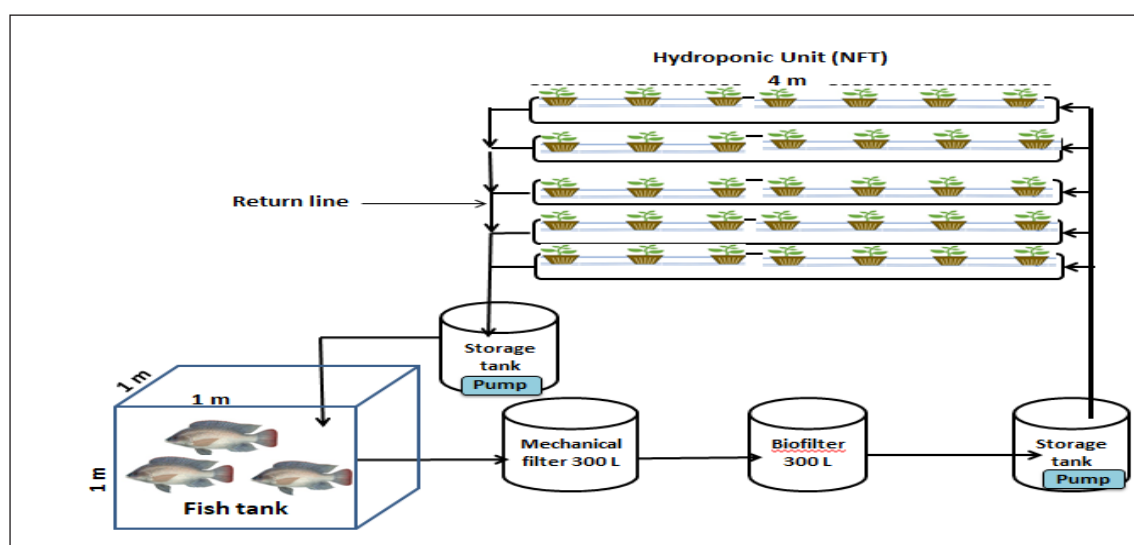


Fig. 1. Schematic representation of the experimental aquaponic unit showing the water flow directions.

replicated as thrice. The fish were administered up to 3% of their body weight in 3.5 mm commercial floating pellets sourced from DZira Ponc SPA, Biskra, Algeria. The immediate nutrient composition of the fish meal consisted of 47.47% protein, 11.87% fat, 5.48% ash, 5% fiber, and 15.26% moisture content. The fish were nourished bi-daily (Hadjeb *et al.*, 2023).

Establishment of a plantation

Lettuce (*Lactuca sativa*) seedlings were sown and nurtured in plastic trays within a greenhouse during the agricultural season (2024/2025) until they attained the appropriate size for transplantation. After 10 days, the germinated plants, at the third to fourth true leaf stages, were immediately transferred into plastic pots containing sawdust as the growth medium. This selection was decided because of its accessibility, lightweight characteristics, moisture retention capability, and economic efficiency (Depardieu *et al.*, 2016; González-Orozco *et al.*, 2018). Subsequently, these plants were relocated to nutrient film technique (NFT) hydroponic systems, sustaining a planting density of 25 lettuces per square meter and a spacing of 20 cm for all treatments. No external material, including fertilizers, were incorporated into the aquaponic system, as the nutrients were only derived from tilapia fish farming waste; also, both air and water temperatures were not regulated during the experiment.

Assessment of water quality

Daily measurements of dissolved oxygen (DO) concentration, pH, and temperature were conducted and documented in the recirculating fish rearing tanks and hydroponic tanks with a YSI 556 Multiparameter meter (YSI Inc. USA). Water samples from the two units were collected weekly for the analysis of total ammonia nitrogen (TAN), nitrates, nitrite, potassium, and soluble reactive phosphorus (SRP) utilizing an optical photometer, the YSI 9500 (YSI Incorporated, Yellow Springs, OH, USA), which boasts a precision of 1% (YSI, I. 2014).

Assessment of ichthyic growth efficacy: The health of the fish was assessed on a daily basis. A random sample of fish from each tank was collected for weight measurements at the trial's commencement and subsequently on a weekly

basis until the conclusion of the experimental period. The measurements were performed with an electronic balance (accuracy: 0.01 mg). The growth performance of tilapia was assessed using the following metrics: weight gain (WG), specific growth rate (SGR), survival rate (SR), and feed conversion ratio (FCR), as outlined by (Jimoh, 2020).

$$WG (g) = \text{Mean final weight (g)} - \text{Mean initial weight (g)} \quad \dots(1)$$

$$SGR (\% \text{ per day}) = [(LnW_{t1} - LnW_{t0}) / t] \times 100 \quad \dots(2)$$

where: W0 and W1 are initial and final weights respectively, t is time in days.

$$SR (\%) = \frac{\text{Final number of fish survived}}{\text{Final number of fish stocked}} \times 100 \quad \dots(3)$$

$$FCR = \frac{\text{Total weight of dry feed given (g)}}{\text{Total wet weight gain (g)}} \times 100 \quad \dots(4)$$

Assessment of plant growth performance

The lettuce plants were harvested on the 56th day. Data on plants were obtained at the conclusion of the experiment. The wet weight (g) of the lettuce harvest head was measured using an electronic balance (precision 0.01 mg). The root length was documented as well. The dimensions of each leaf were quantified using a leaf area meter (CI-202 Portable Laser) to determine the total leaf area at the time of harvest.

Statistical analysis: The data regarding water quality, fish growth, and plant growth across various stocking densities were computed as means $\pm$ SD utilizing MS Office Excel Professional Plus 2010 and subsequently analysed through a one-way ANOVA using XLSTAT by Addinsoft software (version 25.1.1408). The significance of mean differences was assessed using the Tukey HSD test at a significance level of 0.05. Box plots were employed to examine variations in the mean fresh weight of plants across varied stocking densities.

Results and Discussion

Water quality

The results related to the water quality parameters during the experiment show that there was no significant difference ($p > 0.05$) in the water temperature between the different treatments (1.5, 3, and 4.5 kg m⁻³) (Table 1).

Table 1. The aquaponics system's water quality characteristics (means $\pm$ SD) at various stocking densities (1.5, 3 and 4.5 kg m⁻³) using *O. niloticus* fingerlings

Parameter	1.5 kg m ⁻³		3 kg m ⁻³		4.5 kg m ⁻³	
	(Fish Tank)	(Hydroponic)	(Fish Tank)	(Hydroponic)	(Fish Tank)	(Hydroponic)
Temperature (°C)	28.10 $\pm$ 0.50	28.70 $\pm$ 0.55	28.85 $\pm$ 0.50	28.30 $\pm$ 0.25	29.95 $\pm$ 0.60	29.35 $\pm$ 0.60
pH	7.80 $\pm$ 0.03 ^a	7.55 $\pm$ 0.03 ^a	7.35 $\pm$ 0.05 ^b	7.20 $\pm$ 0.03 ^b	6.75 $\pm$ 0.05 ^c	6.40 $\pm$ 0.05 ^c
Dissolved Oxygen (mg L ⁻¹)	5.60 $\pm$ 1.30 ^a	5.90 $\pm$ 1.20 ^a	4.70 $\pm$ 0.65 ^b	5.40 $\pm$ 0.80 ^b	3.95 $\pm$ 0.50 ^c	4.10 $\pm$ 0.15 ^c
Nitrate (mg L ⁻¹)	1.15 $\pm$ 0.035 ^c	0.95 $\pm$ 0.012 ^c	1.18 $\pm$ 0.014 ^b	1.10 $\pm$ 0.016 ^b	1.35 $\pm$ 0.024 ^a	1.30 $\pm$ 0.026 ^a
Nitrite (mg L ⁻¹)	0.011 $\pm$ 0.002 ^c	0.010 $\pm$ 0.001 ^c	0.038 $\pm$ 0.020 ^c	0.030 $\pm$ 0.003 ^b	0.075 $\pm$ 0.063 ^a	0.070 $\pm$ 0.007 ^a
SRP (mg L ⁻¹)	2.50 $\pm$ 0.020	2.30 $\pm$ 0.085	2.20 $\pm$ 0.035	2.10 $\pm$ 0.030	2.55 $\pm$ 0.015	2.15 $\pm$ 0.025
Potassium (mg L ⁻¹)	5.80 $\pm$ 0.06	5.70 $\pm$ 0.05	5.85 $\pm$ 0.07	5.40 $\pm$ 0.05	6.00 $\pm$ 0.05	5.20 $\pm$ 0.07
TAN (mg L ⁻¹)	0.034 $\pm$ 0.005	0.025 $\pm$ 0.003	0.036 $\pm$ 0.005	0.024 $\pm$ 0.004	0.037 $\pm$ 0.004	0.027 $\pm$ 0.005

SRP = Soluble Reactive Phosphorus; TAN = Total Ammonium-Nitrogen.

Values are mean $\pm$ standard deviation.

The temperature during the experiment indicated no significant variation in water temperature across the three stocking densities in the fish tanks. Water temperature ranged between 28.10 $\pm$ 0.50°C and 29.95 $\pm$ 0.60°C, remaining within the acceptable range for tilapia growth (27-30°C).

However, there is a significant difference ($p < 0.05$) in pH and dissolved oxygen (DO) across the treatments, with water pH levels being relatively neutral regardless of stocking density, ranging from 6.75 $\pm$ 0.05 to 7.80 $\pm$ 0.03 in the fish tank and from 6.40 $\pm$ 0.05 to 7.55 $\pm$ 0.03 in the hydroponic. Moreover, the average DO level in the fish tank ranged from 3.95 $\pm$ 0.50 to 5.60 $\pm$ 1.30 mg L⁻¹ at stocking densities of 4.5 kg m⁻³ and 1.5 kg m⁻³, respectively. Similarly, in the hydroponic, the dissolved oxygen levels ranged between 4.10 $\pm$ 0.15 and 5.90 $\pm$ 1.20 mg L⁻¹ at stocking densities of 4.5 kg m⁻³ and 1.5 kg m⁻³, respectively.

Nitrate concentrations tend to increase with higher stocking densities in fish tank and hydroponic. The highest nitrate concentration was observed at the storage density of 4.5 kg m⁻³, with an average of 1.35 $\pm$ 0.024 mg L⁻¹, while the lowest concentration was recorded at

the storage density of 1.5 kg m⁻³, averaging of 1.15 $\pm$ 0.035 mg L⁻¹. The highest concentration of nitrate was observed at the storage density of 4.5 kg m⁻³, averaging of 1.35 $\pm$ 0.024 mg L⁻¹, while the minimum concentration was recorded at the storage density of 1.5 kg m⁻³, averaging of 1.15 $\pm$ 0.035 mg L⁻¹. The storage density of 1.5 kg m⁻³ exhibited the lowest concentrations of nitrites and TAN, while the storage density of 4.5 kg m⁻³ showed the highest concentrations in the fish tank and hydroponic. The storage density of 1.5 kg m⁻³ exhibited the lowest concentrations of nitrites and TAN, while the storage density of 4.5 kg m⁻³ exhibited the highest concentrations in the fish tank and hydroponic. In contrast, potassium and soluble reactive phosphorus (SRP) were not affected by fish stocking density (Table 1).

The results of the growth parameters of tilapia fed under the three densities (1.5, 3, and 4.5 kg m⁻³) are presented in (Table 2).

The results from the statistical analysis using ANOVA showed that there are important differences in final weight, weight gain, SGR (specific growth rate), SR (survival rate), and FCR (feed conversion ratio) of tilapia based on the different stocking densities ($p < 0.05$). The

Table 2. Growth parameters of tilapia (*O. niloticus*) in the aquaponics system at different stocking densities

Growth parameters	Fish stocking densities (kg m ⁻³)		
	1.5 kg m ⁻³	3 kg m ⁻³	4.5 kg m ⁻³
Initial weight (g)	20,10 $\pm$ 0.02	20,25 $\pm$ 0.01	20,30 $\pm$ 0.02
Final weight (g)	57,20 $\pm$ 1.60 ^a	36,10 $\pm$ 2.00 ^b	29,00 $\pm$ 2.05 ^c
Weight gain (g)	37,10 $\pm$ 0.91 ^a	15,85 $\pm$ 1.55 ^b	8,70 $\pm$ 2.01 ^c
SGR (% day)	1.88 $\pm$ 0.18	1.00 $\pm$ 0.08	0,60 $\pm$ 0.05
SR (%)	97.79 $\pm$ 1.49 ^a	94.85% $\pm$ 1.80 ^b	93 $\pm$ 2.90 ^b
FCR	1,54	2,40	5,20

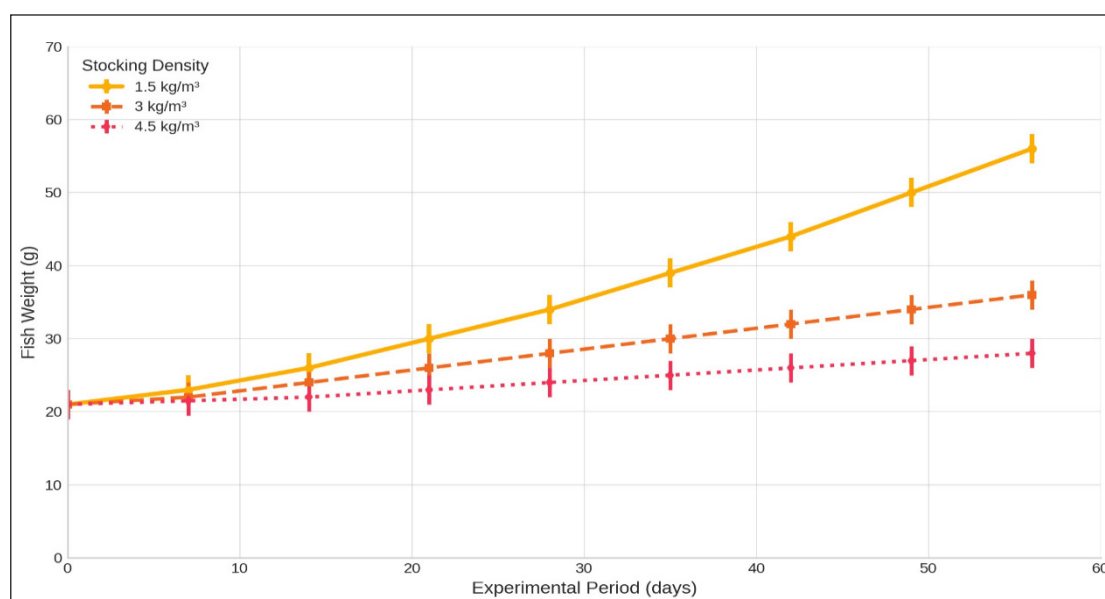


Fig. 2. Growth performance of *Tilapia* fingerlings co-cultivated with lettuce (*Lactuca sativa*) in an aquaponic system under different stocking densities (1.5, 3.0, and 4.5 kg m⁻³).

weight of the fry at 1.5 kg m⁻³ increased from 20.020 g to 57.20 g, that of the fish at 3 kg m⁻³ from 20.25 g to 36.10 g, and that of the fish at 4.5 kg m⁻³ from 20.030 g to 29.00 g. The final average weight was significantly higher in individuals with a density of 1.5 kg m⁻³ than in those with densities of 3 kg m⁻³ and 4.5 kg m⁻³, respectively (Fig. 2). The fish raised at 1.5 kg m⁻³ showed the highest average weight gain (37.10 ± 0.91) compared to those raised at 4.5 kg m⁻³ (8.70 ± 2.01). According to the results of the ANOVA test analysis, it is noted that there is a significant difference between the treatments.

The (SGR) also showed significant differences between the treatments. The same trend was observed for (SGR), with the fish at 1.5 kg m⁻³ achieving the highest SGR (1.88 ± 0.20), indicating a significant increase in growth compared to the other two stocking densities. On the other hand, the stocking density of 4.5 kg m⁻³ exhibited the lowest SGR (0.60 ± 0.05), indicating a slower growth rate (Table 2).

The survival rate (SR) was significantly influenced by stocking density. Fish reared at the lowest density (1.5 kg m⁻³) exhibited the highest survival rate (97.79 ± 1.49%), whereas those at higher densities showed lower survival rates (94.85 ± 1.80% and 93 ± 2.90% for 3 and 4.5 kg m⁻³ respectively). Concerning the (FCR), an inverse correlation with stocking density was observed. The highest (FCR) is found in fish cultivated at a density of 4.5 kg m⁻³, indicating a less efficient use of feed by the fish. In contrast, the density of 1.5 kg m⁻³ exhibited the lowest (FCR), suggesting a more efficient feed conversion (Table 2).

The growth rate of Nile tilapia fingerlings cultivated with lettuce in an aquaponic system distinctly decreased as the fish population increased. Figure 2 indicates that fish maintained at the lowest stocking density (1.5 kg m⁻³) exhibited the most rapid growth. Their mean body weight increased from approximately 21 g at the commencement of the trial to above 60 g by day 56. Fish stocked at 3.0 kg m⁻³ and

Table 3. Growth parameters of lettuce plants according the different tilapia stocking densities

Growth parameters	Fish stocking densities (kg m ⁻³)		
	1.5 kg m ⁻³	3 kg m ⁻³	4.5 kg m ⁻³
Biomass (g)	279.10 ± 6.85 ^c	286.25 ± 19.80 ^b	347.05 ± 22.65 ^a
final mean head weight (g)	195.83 ± 2.50 ^c	204.32 ± 11.90 ^b	249.60 ± 17.1 ^a
Leaf length (cm)	22.05 ± 10.10 ^c	24.65 ± 17.95 ^b	29.00 ± 29.20 ^a
Leaf width (cm)	17.30 ± 9.90 ^c	19.75 ± 13.20 ^b	23.20 ± 24.50 ^a
Root length (cm)	41.60 ± 1.05 ^b	45.90 ± 1.50 ^{ab}	54.20 ± 2.30 ^a

4.5 kg m⁻³ exhibited much slower growth, attaining weights of approximately 36 g and 30 g, respectively, in the end of experimentation.

A comparison of the growth characteristics of lettuce plants using different fish stocking densities (kg m⁻³) is presented in Table 3.

The findings indicated that augmenting the fish storage density in the system resulted in a notable enhancement in the majority of growth metrics for the examined plants. The biomass rose from (279.10 ± 6.85 g) at a density of 1.5 kg m⁻³ to (286.25 ± 19.80 g) at 3 kg m⁻³ and further to (347.05 ± 22.65 g) at a storage density of 4.5 kg m⁻³, exhibiting a statistically significant difference among the treatments ($p < 0.05$).

An elevation in the average final mean head weight was noted, with plants at the maximum density (4.5 kg m⁻³) exhibiting a weight of (249.60 ± 17.10 g, in contrast to (195.83 ± 2.50 g) at the lowest density of 1.5 kg m⁻³. For a density of 3 kg m⁻³, the average final mean head weight observed was (204.32 ± 11.90 g).

The leaf length varies significantly among the plants. The treatment of 1.5 kg m⁻³ has an average of 22.05 cm, while the plants treated with 3 kg m⁻³ have an average of 24.65 cm. The 4.5 kg m⁻³ treatment results in an average of 29 cm. On the other hand, there is a significant difference in the average leaf width between the 4.5 kg m⁻³ and 3 kg m⁻³ treatments, with averages of 23.20 cm and 19.75 cm, respectively. However, the treatment of the 1.5 kg/m³ group resulted in an average of 17.30 cm. When it comes to root length, the two treatments (4.5 kg m⁻³ and 1.5 kg m⁻³) show differences with average values of 54.20 cm and 41.60 cm, respectively.

The average root length for plants treated with the stocking density of 3 kg m⁻³ is 45.90 cm, which is between the average length of plants treated with the stocking density of 4.5 kg m⁻³ and the stocking density of 1 kg m⁻³.

The effect of tilapia population density (*Oreochromis niloticus*) in an aquaponic system using the nutrient film technique (NFT) on water quality is an essential factor that influences fish health and plant growth. Diversified studies have investigated how different stocking densities impact water quality parameters such as pH, dissolved oxygen, ammonia, nitrites, and nitrate levels. These parameters

are fundamental for maintaining an aquaponic system that balances both aquatic life and vegetation. The results of these studies show that while higher fish densities could promote plant development due to the accumulated nutritional value, they can also affect water quality, thereby influencing the health and growth of the fish.

Higher stocking densities tend to reduce DO levels due to increased fish respiration and organic matter decomposition. In a study looking at densities of 3 kg m⁻³, 6 kg m⁻³, and 9 kg m⁻³, the dissolved oxygen (DO) levels were between 4.33 and 6.35 mg L⁻¹, with the lower densities having higher DO levels (Al-Zahrani *et al.*, 2023). Another study found that the average dissolved oxygen levels were 71 mg L⁻¹ in a simple recirculation system, showing that having enough oxygen is important when there are more fish (Hussein *et al.*, 2020).

Increased fish density typically results in heightened waste production, thereby elevating ammonia and nitrite concentrations. A study found that average nitrite levels of 0.004 mg L⁻¹ and ammonia levels between 0.010 to 0.120 mg L⁻¹ necessitate effective filtration and plant absorption to manage these by-products (Hussein *et al.*, 2020). Aquaponic systems typically maintain their pH at a range conducive to the growth of both plants and fish. The measured pH values in systems with varying fish densities ranged from 6.74 to 7.47, with higher densities potentially inducing slight pH fluctuations due to metabolic activity (Al-Zahrani *et al.*, 2023).

The management of water quality parameters, such as pH and nitrate levels, is crucial to avoid any negative impact on the health of fish and plants (Fabula *et al.*, 2023). Studies have shown that while higher densities can promote plant growth, they can also lead to difficulties in maintaining optimal water conditions, such as dissolved oxygen levels and ammonia concentration (Rayhan *et al.*, 2018). A study shown that water quality parameters remained within acceptable ranges throughout various stocking densities, hence providing a conducive environment for both lettuce and tilapia (Sabwa *et al.*, 2022).

For the growth performance of the fish; the initial weight of tilapia in aquaponic systems is typically affected by the stocking density.

Reduced stocking numbers frequently facilitate enhanced growth performance, as the fish benefit from increased space and resources. A study examining stocking densities of 3 kg m⁻³, 6 kg m⁻³, and 9 kg m⁻³ revealed that the ultimate body weight and weight gain were significantly greater in the lowest density treatment (Al-Zahrani *et al.*, 2023). The ultimate weight is directly correlated with stocking density; lower densities typically yield larger final weights (Rayhan *et al.*, 2018; Rahmatullah *et al.*, 2010; Tadeo and Malaya, 2021).

The SGR is a crucial metric for assessing the efficacy of fish growth. Elevated SGR readings are frequently noted with reduced stocking densities. A study indicated that the SGR was elevated at lower densities (80 fish m⁻³) compared to higher densities (100 fish m⁻³) (Tadeo and Malaya, 2021). The survival rate is typically elevated throughout all stocking densities; however, it diminishes at very high densities. A study in a biofloc system with fish densities of 150, 200, 250, and 300 fish m⁻³ demonstrated survival rates over 90% across all treatments, with the maximum survival rate observed at the lowest density (Pai *et al.*, 2024).

The Feed Conversion Ratio (FCR) quantifies feed efficiency, where reduced values signify superior feed usage. The Feed Conversion Ratio (FCR) generally rises with elevated stocking densities. In a study examining fish densities of 106, 142, and 177 fish/m³, the feed conversion ratio (FCR) varied from 2.19 to 2.69 and shown a positive correlation with density (Rahmatullah *et al.*, 2010). A separate investigation in a biofloc system demonstrated that the feed conversion ratio (FCR) was reduced at middle densities (150 fish m⁻³) compared to higher densities (Kobir *et al.*, 2024).

For growth performance of lettuce; the outcomes derived from the experiment underscored a discernible trend that demonstrated a significant enhancement in the average biomass accumulation of lettuce as the stocking density of fish increased across the various experimental treatments implemented. More specifically, it was observed that the treatments characterized by higher stocking densities, particularly the one set at 4.5 kg m⁻³, were associated with a notable increase in biomass accumulation among the lettuce plants, which also included enhancements in

metrics such as the mean wet head weight, the dimensions of leaf length and width, as well as the overall root length of the plants. This observation implies a potential positive correlation exists between the density of tilapia stocking and the overall growth performance of lettuce, which is consistent with the findings previously reported by (Estrada-Perez *et al.*, 2018; Delaide *et al.*, 2016).

The positive impact of fish stocking density on lettuce growth dynamics can be attributed to the increased microbial activity within the aquaponics environment, essential for nutrient cycling and overall system health (Sas-Paszt *et al.*, 2023). As fish density inside the system increases, there is a concomitant rise in the population of nitrifying bacteria and rhizosphere-associated bacteria, both of which are essential for nutrient conversion activities (Delaide *et al.*, 2017; Goddek, 2017; Kasozi *et al.*, 2021).

Nonetheless, the inadequate growth performance of lettuce at a fish stocking density of 1.5 kg m⁻³ can likely be attributed to the insufficient nitrate availability for the plants in this treatment, particularly in contrast to the more advantageous conditions encountered by plants in treatments with higher densities of 4.5 kg m⁻³ and 3 kg m⁻³. Enhanced plant growth performance is expected when nitrogen is supplied synergistically, utilizing both ammonium and nitrate forms, which has been demonstrated to maximize nutrient uptake and promote vigorous plant development (Maucieri *et al.*, 2019).

Increased stocking densities can enhance the availability of key nutrients, such as nitrogen, vital for plant growth. A study on Nile tilapia and spinach indicated that elevated stocking density resulted in increased spinach yields due to enhanced nutrient availability in the system (Al-Zahrani *et al.*, 2023).

Increasing fish density has been shown to improve plant productivity. Stocking density affects the volume of fish waste generated, which serves as the primary nutrition source for plants in aquaponic systems. Elevated fish numbers may result in enhanced nutrient availability, especially nitrogen, which is essential for plant growth (Al-Zahrani *et al.*, 2023; Hadiroseyani *et al.*, 2023).

In a study of red tilapia and bok choy, higher fish densities led to increased bok choy production, indicating that increased fish waste resulted in better nutrient availability for plants (Hadiroseyani *et al.*, 2023). Similarly, a study of largemouth bass and lettuce (Bordignon *et al.*, 2020; Sabwa *et al.*, 2022).

The synergistic nature of aquaponics becomes evident when examining how an optimal stocking density range that maximizes output of both fish and plants (Rayhan *et al.*, 2018; Masese *et al.*, 2024). This synergy extends to total system productivity, where increasing the density of both fish and lettuce plants can increase the total biological production of fish and plants, though this requires careful control of both fish and plant densities to maintain high nitrogen recovery rates (Kitaya *et al.*, 2023).

The interactive dynamics create bidirectional benefits that exemplify true system synergy. Fish stocking density ratio significantly affects both plant productivity and water quality, with the synergy between fish farming and water plant growing resulting in better water quality compared to fish farming without plants (Andriani *et al.*, 2017). This mutual benefit allows plants to utilize fish metabolism products in forms of ammonium, nitrate, and phosphate to reduce nitrogen percentages in the media while simultaneously increasing plant growth levels, creating a closed-loop system where waste from one component becomes resources for another (Andriani *et al.*, 2017).

The system's interactive nature requires optimization of multiple variables simultaneously rather than individual component optimization. There is a direct correlation between the number of fish and photosynthetic performance of lettuce plants, with optimal cultivation outcomes achieved through specific fish-plant ratios rather than maximizing either component alone (Jaszczuk *et al.*, 2023). Success depends on maintaining appropriate stocking densities that generate adequate nutrients for plant growth while ensuring that stocking density does not affect fish growth performance due to overcrowding (Harika *et al.*, 2023). This balance among feeding, fish density, and plant absorption capacity is essential to maintain a sustainable aquaponic system, with research showing that 80% of nitrogen use efficiency in aquaponics can be

attributed to the plant hydroponic cultivation subsystem when properly balanced (Kitaya *et al.*, 2023).

Conclusions

In an NFT-based aquaponic system, optimizing fish stocking density is essential for maximizing the growth performance of tilapia (*Oreochromis niloticus*) and lettuce (*Lactuca sativa*), particularly in arid regions where water scarcity and high temperatures pose significant challenges. The relationship between stocking density and growth efficacy is modulated by factors such as water quality, nutrient availability, and system architecture, all of which are integral to the sustainability of aquaponic systems. In arid conditions, meticulous management of these resources is imperative to safeguard the welfare of both aquatic and terrestrial organisms, as the nutrient-dense recirculated water from tilapia directly facilitates the growth of lettuce. Consequently, comprehending the optimal stocking density can enhance productivity and resource-use efficiency in aquaponics, thereby rendering it a feasible strategy for food production in challenging environments. These findings demonstrate that strategic density selection must align with production objectives. For maximizing vegetable yield in water-limited environments, (4.5 kg m⁻³) is recommended, leveraging enhanced nutrient cycling for superior plant growth. Conversely, fish-focused operations should implement lower densities (1.5 kg m⁻³) to ensure optimal growth performance and feed efficiency. This research provides evidence-based guidelines for aquaponic practitioners in arid regions, highlighting how density optimization can enhance both resource-use efficiency and system sustainability in integrated food production systems.

Declarations

The authors have no competing interests.

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