Optimal stocking density of Nile tilapia (*Oreochromis niloticus*) fingerlings for integrated lettuce-tomato production

[1]Yamoussa Bangoura, [1]Arnauld Djissou, [2]Diane K. Gangbazo, [3]Kandè Bangoura

[1] Department of Fisheries and Aquaculture, Higher Institute of Veterinary Sciences and Medicine of Dalaba, Dalaba, Guinea; [2] Research Unit in Aquaculture and Fisheries Management, School of Aquaculture, National University of Agriculture, Porto-Novo, Benin; [3] Guinea Maritime and Coastal Research Centre, Conakry, Guinea. Corresponding author: Y. Bangoura, yamoussabangoura77@gmail.com

Abstract. The integration of fish farming and vegetable farming is a promising approach for utilizing fish farm effluents, which are rich in nitrogen, phosphorus, and potassium, while diversifying food production in agroaquaculture systems in West Africa. This study evaluated the effect of three stocking densities of Nile tilapia (*Oreochromis niloticus*) fingerlings, namely D1 (40 fingerlings m^{-3}), D2 (60 fingerlings m^{-3}), and D3 (80 fingerlings m^{-3}), each tested with three replicates, on the zootechnical performance of the fish after 75 days of rearing, on the physicochemical quality of the effluent, and on the agronomic performance of lettuce (*Lactuca sativa*, 56 days) and tomato (*Solanum lycopersicum*, 70 days) grown in an integrated system. The results show that the average final weight, average daily gain, survival rate, and specific growth rate of the fish decreased significantly in D3 compared to D1 and D2 ($p < 0.05$), while the feed conversion ratio increased, reflecting a decline in feed efficiency at high stocking densities. At the same time, the concentrations of non-ionized ammonia, nitrite, nitrate, and potassium in the effluent increased significantly and almost linearly with stocking density ($r = 1.00$ for nitrate), without any notable change in temperature, pH, or dissolved oxygen. From an agronomic perspective, lettuce yield did not vary significantly across stocking densities ($p > 0.05$) but reached its maximum at D2. For tomato, the number of fruits, average fruit weight, total weight harvested per plant, and plant height were significantly higher at D2 than at D1 ($p < 0.05$). Density D2 (60 fingerlings m^{-3}) thus appears to be the optimal compromise between fish production and vegetable production, ensuring sufficient enrichment of the effluent with assimilable nutrients without compromising fish growth or survival. These results provide a scientific basis for optimizing integrated systems in tropical regions and for the circular utilization of fish farm effluent in vegetable farming.
Keywords: circular utilization, fish effluent, *Lactuca sativa*, *Solanum lycopersicum*, stocking density.

Introduction. Food and nutritional security remain major challenges in West Africa, where demand for animal protein and fresh vegetables is growing faster than local supply. In Guinea, domestic demand for fish is estimated at several hundred thousand metric tons per year, while national aquaculture production covers only a small portion of this demand, leading to heavy reliance on imports and pressure on foreign exchange reserves (FAO, 2026). In this context, inland aquaculture, in particular the farming of Nile tilapia (*Oreochromis niloticus*), has been identified as a priority sector for reducing this deficit and creating rural jobs (Ogunji & Wuertz, 2023). At the same time, peri-urban vegetable farming is a major source of income and fresh vegetables for local populations, but it faces challenges posed by the high cost of mineral fertilizers and soil degradation in several production areas.

Integrated aquaculture, which combines fish farming with crop cultivation, offers a comprehensive solution to these two challenges: aquaculture effluents, rich in ammoniacal nitrogen, nitrate, and minerals derived from feces and uneaten feed, are recycled as a nutrient solution for plants, simultaneously reducing pollution from aquaculture discharges and the need for synthetic fertilizers (Ibrahim et al., 2023; Okomoda et al., 2023). Among crop production techniques coupled with aquaculture, integrated fish farming is used for growing leafy vegetables and fruit vegetables due to its low water consumption, ease of implementation, and effective control of root oxygenation (Outa et al., 2025).

Fish stocking density is one of the most critical control parameters in an integrated system, as it determines both the amount of feed distributed – and thus the nutrient load available to plants – and the well-being and growth of the fish themselves. Numerous studies have shown that excessive stocking density degrades water quality (accumulation of ammonia, nitrite, and suspended solids), increases stress and intraspecific competition, and consequently reduces growth, survival rate, and the feed conversion ratio of tilapia (Al Tawaha et al., 2021; Metwaly et al., 2025). Conversely, too low stocking density limits nutrient supply and can hinder plant growth due to nutrient deficiency (Ani et al., 2022; Sabwa et al., 2022). Therefore, for each system configuration, there is an optimal stocking density that balances zootechnical and agronomic performance, what several authors refer to as the central trade-off in integrated production design (Maucieri et al., 2019; Hussain & Brown 2024).

While the relationship between stocking density, water quality, and tilapia growth has been extensively documented in temperate and Asian contexts, studies that simultaneously combine zootechnical monitoring of the fish, detailed physicochemical characterization of the effluent, and the agronomic response of two contrasting vegetable species (a short-cycle leafy vegetable (lettuce) and a longer-cycle fruit vegetable (tomato) remain few in number in sub-Saharan Africa and virtually nonexistent in Guinea. This study aims to fill this gap by providing local references that can be directly applied by fish farmers and vegetable growers in the subregion.

The overall objective of this study is to determine the optimal stocking density of Nile tilapia fingerlings to jointly maximize fish production and vegetable production (lettuce and tomato) in an integrated system.

Material and Method

***Experimental design and stocking densities**.* The setup consisted of tilapia rearing tanks arranged side-by-side with vegetable beds irrigated with fish effluent via sprinklers from January to March 2026. A completely randomized design was used with three treatments, each with three replicates, resulting in nine independent experimental units. The three stocking densities tested were: D1 = 40 fingerlings m^{-3}, D2 = 60 fingerlings m^{-3}, and D3 = 80 fingerlings m^{-3}. Each rearing unit was coupled with an independent growing bed receiving effluent from the corresponding tank, allowing each cropping regime to be linked to its original fish stocking density. The fish farming experiment lasted 75 days; the vegetable-growing cycles, conducted in parallel using the same effluent, lasted 56 days for lettuce and 70 days for tomato, corresponding to the typical growing cycles for these two species in a humid tropical zone.

***Biological material**.* Nile tilapia fingerlings with a uniform initial average weight (IBW) of 5.04±0.03 g were used. Lettuce (*Lactuca sativa*) and tomato (*Solanum lycopersicum*) seedlings were transplanted at the 3-4 true-leaf stage into beds measuring 2 m² each following a standard nursery phase, at an identical planting density across all treatments to isolate the effect of stocking density on plant performance.

***Fish rearing management**.* The fingerlings were fed commercial feed (Loumo) distributed in split daily rations, adjusted every 15 days based on estimated biomass. Water quality (temperature, pH, dissolved oxygen) was monitored daily on-site, while nitrogen compounds (NH_3, NO_2^-, NO_3^-), phosphate (PO_4^{3-}), and potassium (K^+) in the effluent were measured at regular intervals (25 days) using standard spectrophotometric methods for water analysis. At the end of the 75-day rearing period, all fish in each unit were weighed individually to calculate zootechnical indices.

***Management of vegetable crops on the beds**.* The raised beds were irrigated with fish effluent using watering cans at the base of the root system, without the addition of any supplemental mineral fertilizers, to strictly evaluate the fertilizing effect of the effluent based on its original concentration. The lettuce production beds were watered twice a day (high water requirement), unlike the tomato beds, which were watered once a day (in the morning) to avoid excess water. The watering rates were 4 L m^{-2} for lettuce and 6 L m^{-2} for tomato.

The agronomic parameters measured at the end of the cycle included lettuce (treatments D1L, D2L, D3L over 56 days), the fresh weight per plant, the total weight harvested per bed, the number of leaves, and plant height. For tomato (treatments D1T, D2T, D3T over 70 days), the number of fruits harvested per plant, the average weight per fruit, the total fruit weight per plant, the size (diameter) of a fruit, the number of leaves, and plant height were determined.

Calculated zootechnical parameters*.* Aquaculture performance indices were calculated using standard formulas in aquaculture zootechnics:

Average daily gain, ADG (g day^{-1}) = (Average final weight − Average initial weight) / rearing period (days)

Biomass gain, BG (g) = Final biomass − Initial biomass

Survival rate, SR (%) = (Final stock / Initial stock) × 100

Feed conversion ratio, FCR = Amount of feed distributed (g) / Weight gain (g)

Protein efficiency ratio, PER = Weight gain (g) / Amount of protein ingested (g)

Specific growth rate, SGR (% day^{-1}) = [(ln Final weight − ln Initial weight) / duration (days)] × 100

Statistical analyses*.* The data were subjected to a one-way analysis of variance (ANOVA 1, density factor) after verifying the conditions of normality (Shapiro-Wilk test) and homogeneity of variances (Levene's test). Means were compared pairwise using Tukey's multiple comparison test (HSD). The relationships between stocking density and the various zootechnical, physicochemical, and agronomic parameters were explored using regression analysis and Pearson's correlation coefficient (r), calculated based on the mean values of the three tested densities. All statistical analyses and graphical representations were performed using GraphPad Prism 5 software; the significance level was set at 5%.

Results

Zootechnical performance of tilapia fry after 75 days of rearing*.* After 75 days of rearing (Table 1), stocking density had a highly significant effect on all growth indices.

Table 1

Zootechnical performance of Nile tilapia (*Oreochromis niloticus*) fingerlings fed the commercial Loumo feed after 75 days of rearing, according to stocking density

Parameters	*D1 (40 fish m^{-3})*	*D2 (60 fish m^{-3})*	*D3 (80 fish m^{-3})*	*p-value*
IBW (g)	5.04±0.03	5.04±0.01	5.03±0.02	0.658 (ns)
AFW (g)	62.2±0.74^a	62.2±1.39^a	51.5±0.59^b	< 0.0001
BG (g)	4330±25.5^a	6280±107^b	6370±271^b	< 0.0001
SR (%)	95.0±1.25^a	92.2±1.27^a	87.1±2.82^b	0.0065
FCR	1.68±0.01^a	1.65±0.02^a	2.02±0.11^b	0.0008
PER	1.42±0.01^a	1.44±0.02^a	1.18±0.06^b	0.0003
SGR (% day^{-1})	3.35±0.01^a	3.35±0.04^a	3.10±0.02^b	< 0.0001

Different letters within the same row indicate a significant difference between stocking densities ($p < 0.05$). IBW = initial body weight; AFW = average final weight; BG = biomass gain; SR = survival rate; FCR = feed conversion ratio; PER = protein efficiency ratio; SGR = specific growth rate.

The average final weight (AFW) reached 62.2 g at D1 and D2, compared to only 51.5 g at D3 ($p < 0.0001$), representing a 17% reduction at the highest stocking density. Total biomass gain (BG), however, was significantly lower at D1 (4330 g) than at D2 and D3 (6280 and 6370 g, respectively; $p < 0.0001$), a result consistent with a greater number of individuals stocked at these densities despite reduced individual growth at D3. The survival rate (SR) decreased significantly with density ($p < 0.05$), reflecting increased mortality under higher stocking densities. Finally, feed efficiency deteriorated significantly at D3: the feed conversion ratio (FCR) increased from 1.65-1.68 (D2-D1) to 2.02 (D3; $p = 0.0008$). Furthermore, the significant decrease in the protein efficiency ratio (PER) between D1-D2 and D3 indicates less efficient feed utilization at high stocking densities ($p < 0.05$).

As shown in Figure 1, the average daily weight gain observed for D3 (0.62±0.01 g day^{-1}) is significantly lower ($p < 0.05$) than those obtained for D1 and D2 (0.76±0.01 and 0.76±0.02 g day^{-1}, respectively). The same trend was observed for the specific growth rate, which was lower with D3 (Table 1).

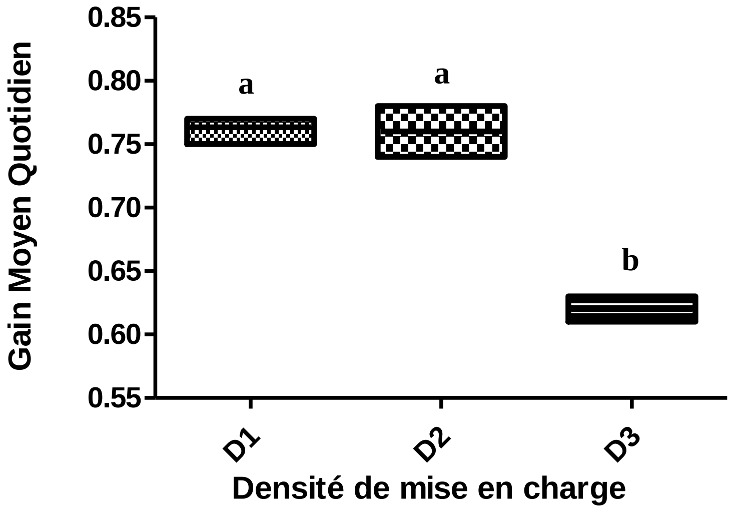

Figure 1. Average daily gain of Nile tilapia (*Oreochromis niloticus*) fingerlings after 75 days of rearing according to stocking density.

Physicochemical quality and nutritional value of fish farm effluent. Table 2 shows that there is not significance difference ($p > 0.05$) for physicochemical quality parameters (temperature, pH and DO). For the nutritional quality of the effluent, it varies significantly with stocking density for most of the parameters measured. The ammonia concentration remained low and comparable between D1 and D2 (0.01 mg L^{-1}) but doubled at D3 (0.02±0.002 mg L^{-1}). Nitrate levels varied significantly, ranging from 43.3±4.73 mg L^{-1} at D1 to 69.7±7.09 mg L^{-1} at D3 ($p = 0.0058$). Potassium followed a similar trend, with a marked increase at D3 (45.1±1.39 mg L^{-1}) compared to D1 and D2 (30.0 and 32.4 mg L^{-1} respectively; $p < 0.0001$). Only the orthophosphate concentration did not vary significantly with density (0.93 to 1.14 mg L^{-1}; $p = 0.093$), although an upward trend was observed.

Table 2

Nutrient parameters of fish farm effluent based on the stocking density of Nile tilapia (*Oreochromis niloticus*) fingerlings

Parameters	*D1*	*D2*	*D3*	*p-value*
NH_3 (mg L^{-1})	0.01±0.003^a	0.01±0.002^a	0.02±0.002^b	0.0213
NO_3^- (mg L^{-1})	43.3±4.73^a	56.9±6.41^{ab}	69.7±7.09^b	0.0058
PO_4^{3-} (mg L^{-1})	0.93±0.14	1.08±0.04	1.14±0.08	0.0925 (ns)
K^+ (mg L^{-1})	30.0±2.01^a	32.4±0.62^a	45.1±1.39^b	< 0.0001
Temperature (°C)	30.6±0.41	30.8±0.10	30.8±0.06	0.6797 (ns)
pH	5.98±0.01	6.02±0.08	6.00±0.04	0.6199 (ns)
Oxygen (mg L^{-1})	6.03±0.10	6.06±0.02	6.04±0.10	0.9319 (ns)

Different letters within the same row indicate a significant difference between stocking densities ($p < 0.05$).

Regarding nitrite (Figure 2), its concentration increased gradually and significantly with stocking density, ranging from 0.04±0.007 mg L^{-1} at D1 to 0.07±0.005 mg L^{-1} at D3 ($p < 0.05$).

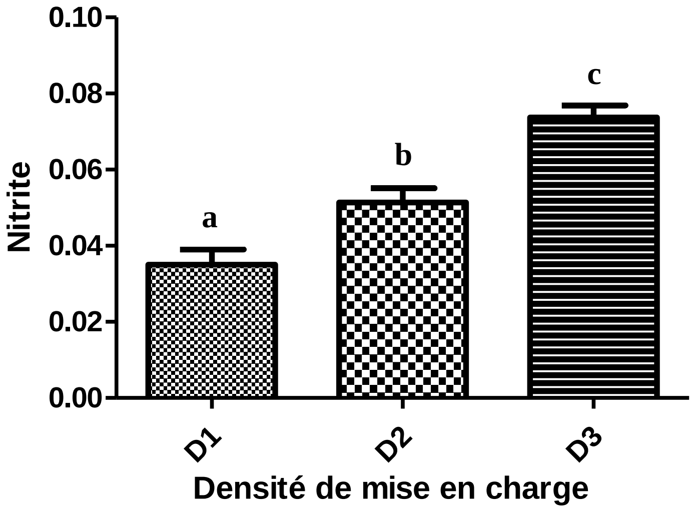

Figure 2. Nitrite content of fish farm effluent as a function of the stocking density of Nile tilapia (*Oreochromis niloticus*) fingerlings.

Agronomic performance of lettuce. As shown in Table 3, none of the agronomic parameters measured for lettuce showed a statistically significant difference between stocking densities. The fresh weight of a lettuce plant increased from 230±11.4 g (D3L) to 252±3.06 g (D2L), with no significant difference ($p > 0.05$). Similarly, the total weight harvested per bed, the number of leaves, and plant height did not differ significantly between treatments ($p > 0.05$), although a trend toward slightly higher performance at D2L and slightly lower performance at D3L was observed for all these parameters.

Table 3

Agronomic performance of lettuce (*Lactuca sativa*) according to the fish stocking density used for fertigation

Parameters	*D1L*	*D2L*	*D3L*	*p-value*
Fresh weight per plant (g)	244±12.5	252±3.06	230±11.4	0.0879 (ns)
Total harvested weight per bed (g)	2140±258	2290±131	1910±102	0.1024 (ns)
Number of leaves	12.0±2.00	13.0±2.65	11.7±1.15	0.7173 (ns)
Height (cm)	32.7±1.53	34.0±1.73	30.3±1.53	0.0773 (ns)

Agronomic performance of tomato. Unlike lettuce, tomato showed a significant response to fish stocking density for most of the measured parameters, with a consistent optimum at the intermediate density D2T (Table 4).

Table 4

Agronomic performance of tomato (*Solanum lycopersicum*) according to the fish stocking density used for fertigation

Parameters	*D1T*	*D2T*	*D3T*	*p-value*
Number of fruits per plant	$4.67±0.58^{a}$	$7.33±1.15^{b}$	$6.33±0.58^{ab}$	0.0194
Average weight per fruit (g)	$100±4.58^{a}$	$115±6.66^{b}$	$107±4.00^{ab}$	0.0313
Total harvested weight per plant (g)	$468±76.9^{a}$	$851±176^{b}$	$679±85.7^{ab}$	0.0237
Fruit size (cm)	$5.23±0.15^{a}$	$5.67±0.12^{b}$	$5.47±0.15^{ab}$	0.0266
Number of leaves	34.3±3.06	40.7±5.51	37.7±1.15	0.1917 (ns)
Height (cm)	$81.7±4.04^{a}$	$95.7±1.53^{b}$	$87.3±3.06^{a}$	0.0040

Different letters within the same row indicate a significant difference between stocking densities ($p < 0.05$).

The number of fruits harvested per plant varied significantly between D2T and D1T ($p < 0.05$), with the value for D3T (6.33±0.58) falling in between and being statistically comparable to the other two treatments. The average fruit weight followed the same trend, with a maximum recorded at D2T. The total weight harvested per plant nearly doubled between D1T (468±76.9 g) and D2T (851±176 g), while the average fruit size and plant height were also highest at D2T ($p < 0.05$). The number of leaves, however, did not differ significantly among densities ($p > 0.192$).

Relationships between stocking density, water quality, and zootechnical and agronomic performance*.* Regression analysis performed on the means of the three stocking densities revealed a nearly perfect linear relationship between stocking density and nitrate concentration in the effluent ($r = 1.00$; $R^2 = 1.00$), as well as strong linear relationships with potassium ($r = 0.93$; $R^2 = 0.87$) (Figure 3). Conversely, average daily fish weight gain decreased linearly with stocking density ($r = -0.87$; $R^2 = 0.75$), reflecting the classic trade-off between increased stocking density and individual growth. These relationships confirm that stocking density acts as a single controlling variable that simultaneously governs both the nutrient enrichment of the effluent and fish growth performance, with these two responses evolving in opposite directions.

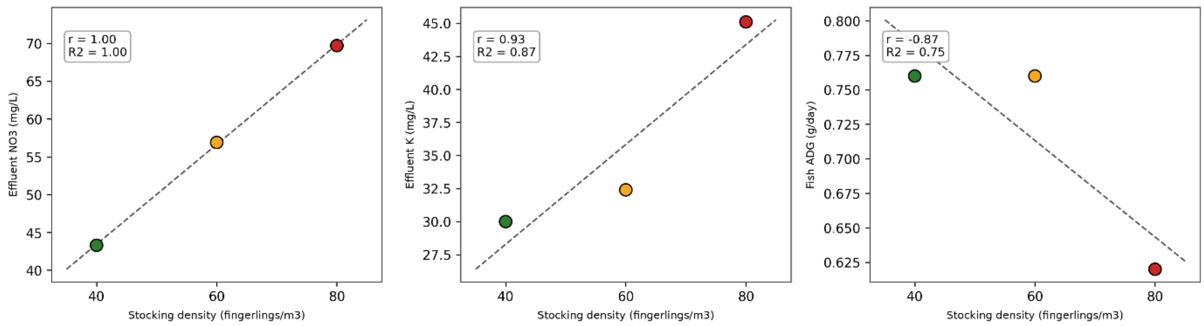

Figure 3. Relationships between the stocking density of Nile tilapia (*Oreochromis niloticus*) fingerlings, the nitrate and potassium concentration of the effluent, and the average daily gain of the fish (regression lines on the means of D1, D2, and D3).

Unlike the stocking density-water-fish chain, which follows a monotonic relationship, the agronomic response of lettuce and tomato to stocking density proved to be non-monotonic, of the dose-optimum type, with a maximum consistently observed at D2 (Figure 4). This profile suggests that there is a window of nitrogen and potassium nutrient concentrations, reached at D2 ($NO_3^- \approx 57$ mg L^{-1}; $K \approx 32$ mg L^{-1}), that is favorable for plant growth; beyond this point (D3: $NO_3^- \approx 70$ mg L^{-1}; $K \approx 45$ mg L^{-1}) the excess ionic load and the corresponding decrease in relative phosphate availability no longer provide any additional benefit and even tend to slightly reduce productivity, particularly in tomato. Density D2 (60 fingerlings m^{-3}) thus appears to be the best compromise, combining zootechnical performance that is statistically equivalent to D1 (and therefore with no density-depressing effect on the fish) with sufficient enrichment of the effluent to maximize vegetable production, particularly fruit production.

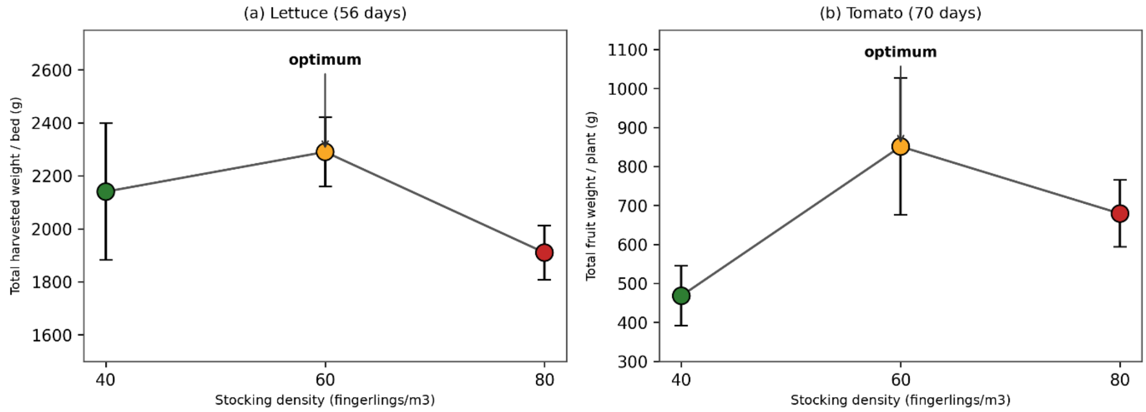

Figure 4. Agronomic response of lettuce and tomato to the stocking density of tilapia fingerlings: a dose-optimum relationship, maximal at D2 (60 fingerlings m^{-3}).

Discussion. The reduction in final weight, average daily weight gain, specific growth rate, and survival rate observed at D3 (80 fingerlings m^{-3}) is consistent with the extensive literature on the inverse relationship between stocking density and individual growth in Nile tilapia. Metwaly et al. (2025) report that an increase in stocking density among juvenile Nile tilapia is accompanied by a moderate but significant reduction in growth, attributed to increased competition for space and feed as well as elevated chronic stress. Similarly, Al Tawaha et al. (2021), in a decoupled aquaponic system combining tilapia and lettuce, observed a deterioration in water quality and impaired fish growth at the highest stocking densities. The concurrent decline in the feed conversion ratio and the protein efficiency ratio at D3 in our study reflects reduced efficiency in converting feed into biomass, likely linked to a more pronounced social hierarchy and heterogeneity in feed intake at high densities, a mechanism widely described in reviews on stocking density in intensive aquaculture.

The decrease in survival rate at D3 may also be linked to the significant increase in non-ionized ammonia (NH_3) observed at this density. Although the measured average concentration (0.02 mg L^{-1}) remains below the chronic toxicity thresholds generally reported for tilapia (in the range of 0.1-2 mg L^{-1} of total ammonia nitrogen (TAN) depending on pH and temperature), prolonged exposure to even sublethal levels of ammonia and nitrite is known to impair fish respiratory, immune, and growth capacities (Metwaly et al., 2025).

Furthermore, the nearly linear increase in nitrite, nitrate, and potassium concentrations with stocking density (Figure 3) confirms the basic principle of integrated aquaculture: the amount of feed distributed, which is directly proportional to the biomass of fish in the system, determines the amount of nitrogen and minerals excreted and subsequently nitrified in the system. This finding is consistent with the observations of Al Tawaha et al. (2021) and Sabwa et al. (2022), who reported increased accumulation of ammonium, nitrite, nitrate, and potassium as tilapia stocking density increased in comparable integrated systems. The stability of temperature, pH, and dissolved oxygen observed in our study, regardless of stocking density, suggests that the nutrient film technique (NFT) system, coupled with adequate aeration, helped maintain favorable physical conditions despite the increased organic load, a critical technical consideration (Ibrahim et al., 2023; Okomoda et al., 2023).

However, the absence of significant variation in phosphate contrasts with the trends in nitrogen and potassium compounds, indicating a stoichiometric N:P:K imbalance in the fish effluent, a limitation already reported in the literature as a structural constraint of single-nutrient-source aquaponic systems, which may become limiting for certain crops with high phosphate requirements (Goda et al., 2024). This finding supports the use of targeted phosphate supplementation in systems operated at high stocking densities, or the exploration of nutritional supplementation strategies such as those proposed in integrated multitrophic systems.

The lack of a significant response in lettuce to stocking density, despite a visual optimum at D2, can be explained by the comparatively modest nutrient requirements and short growth cycle (56 days) of this leafy vegetable, for which the available nitrogen, even at the lowest density (D1), was likely sufficient to meet growth demands. This result is consistent with the work of Mahlangu et al. (2016), who show that lettuce's response to nitrogen fertilization in hydroponics quickly reaches a plateau beyond a certain threshold of nitrogen availability, beyond which additional nitrogen no longer yields a significant increase in yield and may even be associated with a slight reduction in growth in cases of excess, as observed here at D3. Hussain & Brown (2024), in their review of the literature on tilapia-lettuce aquaponics, also noted that this combination remains the most well-documented and robust, as lettuce tolerates a wide range of nutrient concentrations from fish effluent.

Tomato, a fruit crop with a longer growth cycle (70 days) and higher nutrient requirements, particularly for potassium during the fruiting stage, showed, in contrast, a marked and significant response to stocking density, with a clear optimum at D2. This result should be considered considering potassium's major physiological role in tomato fruit filling and quality, notably the transport of photoassimilates to the fruit and osmotic regulation (Karpe et al., 2024). The increase in available potassium between D1 and D2 likely supported fruit set and fruit enlargement, explaining the near doubling of the total weight harvested per plant. At D3, however, despite even higher availability of potassium and nitrate, tomato performance did not exceed that of D2 and even declined slightly for certain parameters (height, weight per fruit), which could result from an ionic imbalance in the nutrient solution, increased overall salinity of the effluent, or relatively lower phosphorus availability compared to nitrogen and potassium at this density. This finding has been reported by numerous authors who have stated that an excess of nitrogen nutrients can induce a nutritional imbalance detrimental to fruit set in aquaponic and hydroponic systems (Elmorsy & Abul-Soud, 2023; Goda et al., 2024).

Furthermore, a combined analysis of the system's three compartments (fish, water, plants) points to D2 (60 fingerlings m^{-3}) as the most effective stocking density under the experimental conditions of this study. This stocking density, in fact, made it possible to maintain zootechnical performance that was statistically equivalent to that obtained at the lowest stocking density (D1), while generating effluent sufficiently enriched in nitrogen and potassium to maximize tomato production and approach maximum lettuce production. The highest stocking density (D3), although producing the most concentrated effluent, provided no additional agronomic benefits and was accompanied by a significant decline in fish growth, survival, and feed efficiency, making it economically and biologically suboptimal. Several authors have emphasized the need to consider stocking density not solely in terms of maximizing fish biomass, but in terms of the overall balance of the aquaponic system (Zamnuri et al., 2024; Outa et al., 2025).

In practical terms, these results provide a directly applicable reference for producers seeking to develop integrated systems combining tilapia, lettuce, and tomato, particularly within the framework of national strategies for the development of inland aquaculture. They also confirm the value of integrated fish farming as a means of circular utilization of fish effluent, reducing both the pollution associated with intensive tilapia farming and vegetable farming's dependence on imported mineral fertilizers (Ibrahim et al., 2023; Ogunji & Wuertz, 2023).

Conclusions. This study evaluated, in an integrated tilapia-lettuce-tomato system using NFT beds, the effect of three stocking densities of *Oreochromis niloticus* fingerlings (40, 60, and 80 fingerlings m^{-3}) on the fish's zootechnical performance, the physicochemical quality of the effluent, and the agronomic performance of the two vegetable crops. The results show that increasing the stocking density beyond 60 fingerlings m^{-3} significantly impairs the growth, survival, and feed efficiency of tilapia, without providing any additional agronomic benefit for lettuce or tomato, which performed best at the intermediate density of 60 fingerlings m^{-3} (D2). This density thus represents the optimal compromise for balancing fish and vegetable productivity in this type of system and can be recommended as a technical benchmark for managing integrated tilapia-vegetable systems in Guinea and in comparable agroecological zones in West Africa. Beyond its productive benefits, this approach contributes to the circular utilization of fish effluent, reduces dependence on mineral fertilizers, and strengthens local food security.

Acknowledgements. The authors thank all those who have contributed in any way to the completion of this work.

Authors Contributions. YB: Formal analysis, data collection and Writing - Original draft preparation; AD: Methodology Resources, Writing - Review & Editing; DKG and KB: Conceptualization, Supervision, Writing - Review & Editing.

Conflicts of Interest. The authors declare that there is no conflict of interest.

Data Availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Funding. This research received no external funding.

References

Al Tawaha, A. R., Megat Wahab, P. E., Jaafar, H. B., Kee Zuan, A. T., & Hassan, M. Z. (2021). Effects of fish stocking density on water quality, growth performance of tilapia, and yield of butterhead lettuce grown in decoupled recirculating aquaponic systems. *Journal of Ecological Engineering, 22*(1), 8-19. https://doi.org/10.12911/22998993/128692

Ani, J. S., Manyala, J. O., Masese, F. O., & Fitzsimmons, K. (2022). Effect of stocking density on growth performance of monosex Nile tilapia (*Oreochromis niloticus*) in the aquaponic system integrated with lettuce (*Lactuca sativa*). *Aquaculture and Fisheries, 7*(3), 328-335. https://doi.org/10.1016/j.aaf.2021.03.002

Elmorsy, A. T., & Abul-Soud, M. (2023). Effect of tomato plant density on aquaponic system production. *Engineering Heritage Journal (GWK), 7*(2), 63-68. DOI: 10.26480/gwk.02.2023.63.68

FAO. (2026) [Aquaculture: an ambitious goal of 150,000 metric tons of fish by 2030]. FAO in Côte d'Ivoire. Available at: https://www.fao.org/cote-divoire/actualites/detail/aquaculture---objectif-ambitieux-de-150-000-tonnes-de-poissons-%C3%A0-l-horizon-2030/fr Accessed: May, 2026. [in French]

Goda, A. M. A. S., Aboseif, A. M., Taha, M. K. S., Mohammady, E. Y., Aboushabana, N. M., Nazmi, H. M., Zaher, M. M., Aly, H. A., El-Okaby, M. A. S., Ibáñez Otazua, N., & Ashour, M. (2024). Optimizing nutrient utilization, hydraulic loading rate, and feed conversion ratios through freshwater IMTA-aquaponic and hydroponic systems as an environmentally sustainable aquaculture concept. *Scientific Reports, 14*, 14878. https://doi.org/10.1038/s41598-024-63919-7

Hussain, A. S., Brown, P. B. (2024). A literature review of tilapia/lettuce aquaponics - production status, varieties, and research gaps. *Aquaculture Research, 2024*, 2642434. https://doi.org/10.1155/2024/2642434

Ibrahim, L. A., Shaghaleh, H., El-Kassar, G. M., Abu-Hashim, M., Elsadek, E. A., & Alhaj Hamoud, Y. (2023). Aquaponics: a sustainable path to food sovereignty and enhanced water use efficiency. *Water, 15*(24), 4310. https://doi.org/10.3390/w15244310

Karpe, M., Marcelis, L. F. M., & Heuvelink, E. (2024). Dynamic plant spacing in tomato results in high yields while mitigating the reduction in fruit quality associated with high planting densities. *Frontiers in Plant Science, 15*, 1386950. https://doi.org/10.3389/fpls.2024.1386950

Mahlangu, R. I. S., Maboko, M. M., Sivakumar, D., Soundy, P., & Jifon, J. (2016). Lettuce (*Lactuca sativa* L.) growth, yield, and quality response to nitrogen fertilization in a non-circulating hydroponic system. *Journal of Plant Nutrition, 39*(12), 1766-1775. https://doi.org/10.1080/01904167.2016.1187739

Maucieri, C., Nicoletto, C., Zanin, G., Birolo, M., Trocino, A., Sambo, P., Borin, M., & Xiccato, G. (2019). Effect of stocking density of fish on water quality and growth performance of European carp and leafy vegetables in a low-tech aquaponic system. *PLoS ONE, 14*(5), e0217561. https://doi.org/10.1371/journal.pone.0217561

Metwaly, S., Nasr, H., Ahmed, K., & Fathi, M. (2025). Multifaceted stress response in Nile tilapia (*Oreochromis niloticus*) fingerlings: integrative analysis of salinity, ammonia, and stocking density effects on growth, physiology, and gene expression. *Fish Physiology and Biochemistry, 51*, 48. https://doi.org/10.1007/s10695-025-01462-6

Ogunji, J., & Wuertz, S. (2023). Aquaculture development in Nigeria: the second-largest aquaculture producer in Africa. *Water, 15*(24), 4224. https://doi.org/10.3390/w15244224

Okomoda, V. T., Oladimeji, S. A., Solomon, S. G., Olufeagba, S. O., Ogah, S. I., & Ikhwanuddin, M. (2023). Aquaponics production system: a review of historical perspective, opportunities, and challenges of its adoption. *Food Science and Nutrition, 11*(3), 1157-1165. https://doi.org/10.1002/fsn3.3154

Outa, N., Ogello, E., K'Otuto, G. (2025). Nutrient film technique (NFT) aquaponics enhances the productivity of fish and crops: trials on Nile tilapia, African catfish, lettuce, spinach, and basil. *Aquaculture, Fish and Fisheries, 5*(4), e70089. https://doi.org/10.1002/aff2.70089
Sabwa, J. A., Manyala, J. O., Masese, F. O., Fitzsimmons, K., Achieng, A. O., Munguti, J. M. (2022). Effects of stocking density on the performance of lettuce (*Lactuca sativa*) in a small-scale lettuce-Nile tilapia (*Oreochromis niloticus* L.) aquaponic system. *Aquaculture, Fish and Fisheries, 2*(6), 458-469. https://doi.org/10.1002/aff2.71
Zamnuri, M. A. H. b., Qiu, S., Rizalmy, M. A. A. b., He, W., Yusoff, S., Roeroe, K. A., Du, J., & Loh, K. H. (2024). Integration of IoT in small-scale aquaponics to enhance efficiency and profitability: a systematic review. *Animals, 14*(17), 2555. https://doi.org/10.3390/ani14172555

Received: 03 August 2026. Accepted: 17 August 2026. Published online: 02 September 2026.
Authors:
Yamoussa Bangoura (YB), Department of Fisheries and Aquaculture, Higher Institute of Veterinary Sciences and Medicine of Dalaba, Tangama, BP09 Dalaba, Guinea, e-mail: yamoussabangoura77@gmail.com
Arnauld Djissou (AD), Department of Fisheries and Aquaculture, Higher Institute of Veterinary Sciences and Medicine of Dalaba, Tangama, BP09 Dalaba, Guinea, e-mail: arnauldb52@gmail.com
Diane Kpoguè Gangbazo (DKG), Research Unit in Aquaculture and Fisheries Management, School of Aquaculture, National University of Agriculture, 01 BP55 Porto-Novo, Benin, e-mail: senami_diane@yahoo.fr
Kandè Bangoura (KB), Guinea Maritime and Coastal Research Centre, BP1615 Conakry, Guinea, e-mail: kandebangoura@gmail.com

How to cite this article:
Bangoura, Y., Djissou, A., Gangbazo, D. K., Bangoura, K. (2026). Optimal stocking density of Nile tilapia (*Oreochromis niloticus*) fingerlings for integrated lettuce-tomato production. *AACL Bioflux, 19*(5), 2011-2020.