

OPTIMIZATION OF FISH STOCKING DENSITY IN AQUAPONIC SYSTEMS: BALANCING FISH YIELD, PLANT GROWTH, AND ECONOMIC PROFITABILITY ACROSS THREE STOCKING TREATMENTS

A. Baniowda¹, M. Salman^{*,2}, M. W. Ali³ and M. S. Romdhane¹

¹ Aquatic Ecosystems and Resources Laboratory, National Institute of Agricultural Sciences, University of Carthage, 1082 Tunis, Tunisia.

² Animal and Food Resources Laboratory (LRAA), National Agronomic Institute of Tunisia, 43 Av. Charles Nicolle, Tunis, 1082, University of Carthage, Tunisia.

³ National Agricultural Research Center (NARC), Palestine.

*Corresponding author email: moayednas@yahoo.com

ABSTRACT

This study examines the effects of stocking density on the growth performance of juvenile Nile tilapia (*Oreochromis niloticus*) and spearmint (*Mentha spicata*) in a recirculating aquaponic system over a 120-day production cycle. Three stocking densities were tested: 40 fish/m³ (Group G1), 80 fish/m³ (Group G2), and 120 fish/m³ (Group G3). The experiment was conducted at the National Agricultural Research Center (NARC) in Palestine, using 1000-liter units equipped with biofiltration systems and standardized environmental controls. Fish were fed a diet containing 35% crude protein, while mint plants (10 plants per unit) were cultivated simultaneously without additional nutrient supplementation. Data were analyzed using one-way ANOVA followed by Tukey's HSD post-hoc test ($p < 0.05$) to assess significant differences in weight gain, survival rates, and plant biomass across treatments. Results indicated that operational costs increased with higher stocking densities, reaching \$52.58 for G1, \$82.90 for G2, and \$113.60 for G3, despite uniform initial setup costs across all groups. Tilapia biomass exhibited a clear density-dependent increase, with final weights of 7.84 kg (G1), 13.49 kg (G2), and 20.22 kg (G3). Correspondingly, net profits rose from \$5.68 in G1 to \$28.10 in G3. These findings highlight the significance of strategic stocking density management in optimizing the productivity and economic efficiency of aquaponic systems. Implementing cost-effective stocking strategies and refining system design can significantly enhance the viability of aquaponics, particularly for small-scale agricultural operations.

Keywords: Tilapia, Stock Density, Aquaponic, Water Quality

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>)

Published first online October 17, 2025

Published final November 30, 2025

INTRODUCTION

Aquaponics, defined as the integration of aquaculture and hydroponics within a closed-loop water system, represents a synergistic model of sustainable food production that addresses global food security challenges. In this recirculating system, nutrients derived from fish waste serve as a natural fertilizer for plant growth, while the plants, in turn, purify and filter the water for the fish (Kankia *et al.*, 2024; Bosma *et al.*, 2017). This integration enhances resource efficiency and environmental sustainability, while also promoting biodiversity and system resilience (Sace and Fitzsimmons, 2013). Tilapia (*Oreochromis* spp.), known for its adaptability to diverse environmental conditions, is one of the most commonly cultivated fish species in aquaponic systems. It is often reared at elevated stocking densities to maximize nutrient availability and overall production efficiency (Nair *et al.*,

2024). Stocking density (defined as the number of fish per unit volume of water) is a critical factor influencing system functionality and economic viability. A well-balanced stocking strategy is essential for managing nutrient dynamics, maintaining water quality, and optimizing growth performance for both fish and plants (Junge *et al.*, 2017; Rahmatullah *et al.*, 2010). However, several challenges remain, including aligning stocking density with operational costs, scalability, technical expertise, and system design (Goddek *et al.*, 2019; Love *et al.*, 2014).

Numerous studies emphasize the importance of maintaining moderate stocking densities to enhance aquaponic system efficiency while avoiding potential negative consequences such as water quality degradation and fish stress associated with excessively high densities (Marques *et al.*, 2016; Rakocy *et al.*, 2006). For example, Rakocy *et al.* (2006) reported that although higher fish

densities can increase nutrient flux for plant growth, they may also destabilize the system through nutrient imbalances. Additional research indicates that optimizing the fish-to-plant ratio is crucial for improving both ecological and economic outcomes (Yildiz *et al.*, 2017; Graber and Junge, 2009). Studies by Maucieri *et al.* (2018) and Buzby and Lin (2014) further support the importance of achieving equilibrium in nutrient exchange to enhance productivity and reduce risks related to nutrient competition within the system. Furthermore, improvements in fish feed formulation are increasingly recognized as vital for enhancing aquaponic performance. The use of sustainable and locally sourced diets (such as duckweed (*Lemna sp.*), which is rich in nutrients and cost-effective) has shown promise in reducing production costs and improving overall system performance (; Junge *et al.*, 2017; Popa *et al.*, 2017). This aligns with growing interest in integrating giant river prawns (*Macrobrachium rosenbergii*) into polyculture systems. These prawns can utilize a wide range of organic residues present in aquaponic environments, contributing to increased species diversity and improved system stability (Marques *et al.*, 2016).

The primary objective of this study is to evaluate the impact of varying stocking densities on fish growth, plant biomass, and water quality parameters in a recirculating aquaponic system. Additionally, a comprehensive cost-benefit analysis will be conducted to assess the economic implications of different stocking density levels, identify the optimal balance for system efficiency, and establish best practices to improve the profitability and sustainability of aquaponic farming operations.

MATERIALS AND METHODS

Study site and Aquaponic System Setup: The study was conducted in the laboratory of the Animal Research Department at the National Agricultural Research Center (NARC), located in Jenin, northern West Bank, Palestine (32°25'47.1" N, 35°15'39.4" E), over a 120-day experimental period. The primary objective of this research was to evaluate the growth performance of juvenile Nile tilapia (*Oreochromis niloticus*) and spearmint (*Mentha spicata*) within a recirculating aquaponic system, under three distinct stocking densities: Group 1 (G1; 40 fish/m³), Group 2 (G2; 80 fish/m³), and Group 3 (G3; 120 fish/m³). Each treatment group was housed in an identical aquaponic unit with a total water capacity of 1,000 liters. Each aquaponic unit was equipped with mechanical and biological filtration systems to ensure stable water quality throughout the experiment. These systems included mechanical filters to remove solid waste and biofilters to facilitate nitrification, thereby maintaining optimal conditions for both fish and plant growth. All units were operated under standardized environmental controls, including consistent water temperature, pH, dissolved oxygen levels, and flow

rates, to minimize variability between treatments and allow for accurate comparisons.

At the beginning of the experiment, tilapia fingerlings were individually weighed using a digital scale to determine initial body weight. Fish were then stocked into their respective units according to the assigned densities. Throughout the trial, fish were fed a commercially available diet containing 35% crude protein, administered manually in accordance with species-specific feeding guidelines and adjusted based on biomass estimates. Simultaneously, ten mint plants (*Mentha spicata*) were cultivated per unit in the hydroponic component of each system. Plant growth parameters were monitored throughout the experimental period to assess the influence of varying fish stocking densities on nutrient availability and plant productivity.

These methodological considerations are essential given the growing interest in aquaponics as a sustainable food production system. Such integrated systems leverage nutrient recycling to enhance resource efficiency and productivity (Naylor *et al.*, 2023; Asche *et al.*, 2022). By combining aquaculture and hydroponics, aquaponics supports both environmental sustainability and food security, key priorities in modern agricultural practices (Belton *et al.*, 2020; Vince and Haward, 2017).

Mathematical and Statistical Analyses: The financial setup and operational expenses associated with the aquaponic system were calculated using the following formulas:

$$\text{Setup Cost per Period} = \frac{\text{Total Setup Cost}}{\text{Number of Periods}} \quad (1)$$

$$\text{Total Running Cost} = \text{Fish Cost} + \text{Feed Cost} + \text{Electricity Cost} + \text{Water Refill Cost} \quad (2)$$

$$\text{Total Costs} = \text{Total Setup Cost Per Period} + \text{Total Running Costs} \quad (3)$$

Measurements and Fodder Consumption: Initial weights of both juvenile tilapia (*Oreochromis niloticus*) and spearmint (*Mentha spicata*) were recorded prior to the commencement of the experiment. Tilapia body weights were subsequently measured at regular intervals throughout the 120-day trial period to assess growth performance. Weight gain was calculated using the following formula:

$$\text{Fish Weight Gain (g)} = \text{Final Weight} - \text{Initial Weight} \quad (4)$$

At the end of this period, the final weights of fish and plants were documented. The survival rate (SR) of the tilapia was determined using:

$$\text{SR} = \frac{\text{Total Initial Fish} - \text{Total Fish Died}}{100} \quad (5)$$

The final stock weight was quantified using:

$$\text{Final Stock Weight} = \text{SR} \times \text{Total Initial Fish} \times \text{Final Fish Weight} \quad (6)$$

To calculate total feed consumption, the following formula was applied:

$$\text{Total Fodder Consumption} = \text{Fish Consumption Per Fish} \times \text{Total Fish} \quad (7)$$

For mint plants, final weight was calculated based on the per-plant weight multiplied by the number of plants. Profitability across stocking densities was evaluated using these equations:

$$\text{Fish Sales} = \text{Fish (Kg)} \times \text{Unit Price per Kg.} \quad (8)$$

$$\text{Plant Sales} = \text{Plant Weight (Kg)} \text{ Unit Price per Kg.} \quad (9)$$

$$\text{Total Sales} = \text{Fish Sales} + \text{Plant Sales.} \quad (10)$$

$$\text{Net Profit} = \text{Total Sales} - \text{Total Costs.} \quad (11)$$

Assuming total costs for each group are provided or calculated separately.

Statistical Analysis: The experimental data were analyzed using IBM SPSS® version 22 through a univariate General Linear Model (GLM) to evaluate the differences across the stocking density treatments (Groups G1, G2, and G3). The model was used for data analysis.

$$Y_{ij} = \mu + T_i + \epsilon_{ij}$$

where Y_{ij} represents the observed value for the j -th replicate in the i -th treatment, μ denotes the overall mean, T_i expresses the fixed effect of stocking density treatment, and ϵ_{ij} refers to the random error associated with each observation.

To identify pairwise differences between group means, Tukey's Honestly Significant Difference (HSD) post-hoc test was applied. The threshold for statistical significance was set at $p < 0.05$.

RESULTS

Significant differences were observed in fish growth parameters and plant performance across the three stocking density treatments (Table 1). Initial fish weights varied among groups, with Group 1 (G1) exhibiting the highest mean weight of 79.42 g, which was significantly greater than those recorded in Group 2 (55.71 g) and Group 3 (55.19 g). In terms of initial stock biomass, Group 3 had the highest total weight at 6.62 kg, followed by Group 2 (4.45 kg), and Group 1 (3.17 kg). Fish weight gain differed significantly between groups. Group 1 demonstrated the greatest average weight gain at 162.69 g, which was statistically higher ($p < 0.05$) than that of Group 2 (147.53 g) and Group 3 (143.12 g). However, no significant difference was found between Groups 2 and 3. Survival rates remained high across all treatments, with values of 81% in Group 1, 83% in Group 2, and 85.6% in Group 3. Fodder consumption per fish was highest in Group 1 at 305.85 g per fish, while total feed consumption increased with stocking density, reaching 35.03 kg in Group 3. This reflects a progressive increase from 12.23 kg in Group 1 to 23.48 kg in Group 2.

Final individual fish weights showed slight variation: Group 1 averaged 0.242 kg, while Groups 2 and 3 reached 0.203 kg and 0.198 kg, respectively. Total final stock biomass increased significantly with density, peaking at 20.22 kg in Group 3. In terms of plant performance, each group maintained ten mint plants

(*Mentha spicata*); however, plant weight per unit varied. Group 2 produced the highest mean plant weight at 237 g, whereas Group 3 recorded the lowest at 130.9 g. Consequently, total plant biomass per unit was 2.09 kg in Group 1, 2.37 kg in Group 2, and 1.309 kg in Group 3.

The costs associated with the three aquaponic treatments (Group 1 (G1: 40 fish/m³), Group 2 (G2: 80 fish/m³), and Group 3 (G3: 120 fish/m³)) 120-day production cycle are summarized in Table 2. Both initial setup and recurring operational costs were analyzed to provide a comprehensive financial overview for each group. Setup costs included essential system components such as the aquaponic unit (1000 L), biofilter (20 L), mechanical filter (20 L), hydroponic tube (4 m), oxygen pump, volcanic gravel, plastic bio-balls, and LED lamps. Unit prices and total costs for each component were itemized across all groups. The total setup cost remained constant at \$99.50 for all groups, resulting in a per-period cost of approximately \$4.97, based on an assumed 20 production cycles over the system's lifespan.

In contrast, running costs varied significantly depending on stocking density. Fish fingerling expenses increased from \$12 in G1 to \$36 in G3, reflecting the higher number of fish stocked per cubic meter. Similarly, feed costs rose from \$18.34 in G1 to \$52.50 in G3, demonstrating the direct relationship between stocking density and feeding requirements. Fixed operational costs, including electricity (\$12) and water refill (\$3), remained consistent across all groups. Total running costs were calculated as \$47.61 for G1, \$77.90 for G2, and \$108.70 for G3. When combined with the setup cost per period, the total production costs reached \$52.58 for G1, \$82.90 for G2, and \$113.60 for G3.

The net profit generated from the aquaponic system over a 120-day production cycle varied significantly across the three stocking density treatments (Table 3). Analysis revealed a clear increase in fish biomass with higher stocking densities: Group 1 (G1; 40 fish/m³) yielded 7.84 kg, Group 2 (G2; 80 fish/m³) produced 13.49 kg, and Group 3 (G3; 120 fish/m³) achieved the highest yield at 20.22 kg. With a fixed unit price of \$7 per kilogram for tilapia, sales revenue increased accordingly: \$54.88 for G1, \$94.43 for G2, and \$141.54 for G3. In terms of plant production, mint (*Mentha spicata*) yields were 2.09 kg for G1, 2.37 kg for G2, and 1.31 kg for G3. The decline in plant yield observed in G3 suggests potential resource competition between fish and plants under high-density conditions. Plant prices were held constant at \$4 per kilogram, resulting in plant sales of \$8.36 (G1), \$9.48 (G2), and \$5.24 (G3). Total revenue (combining fish and plant sales) was \$63.24 for G1, \$103.91 for G2, and \$146.78 for G3, demonstrating a steady increase in overall income with rising stocking density. As a result, net profit increased progressively from \$5.68 in G1 to \$16.03 in G2 and \$28.10 in G3.

Table 1. Mean of fish growth traits and plant across different stocking densities over 120 days

Group		G1	G2	G3
Fish Metrics	Initial Fish Weight (gr)	79.42	55.71	55.19
	Initial Stock Weight (Kg)	3.17	4.45	6.62
	Fish Weight Gain (gr)	162.69 ^a ±2.58	147.53 ^b ±1.74	143.12 ^b ±1.42
	Survival Rate	0.81 ^a ±0.11	0.83 ^a ±0.07	0.856 ^a ±0.06
	Fodder Consumption per fish	305.85	293.58	291.96
	Total fodder consumption (Kg)	12.23	23.48	35.03
	Final Fish Weight (kg)	0.242	0.203	0.198
	Final stock Weight (kg)	7.84	13.49	20.22
Water and Plant Metrics	Number of plants	10	10	10
	PH	7.42 ^a ±0.054	6.64 ^b ±0.15	6.52 ^b ±0.08
	Total Dissolved Solids (TDS)	609 ^a ±14.30	689 ^b ±18.30	860 ^c ±32.21
	Weight per plant gr	209	237	130.9
	Total plant weight (Kg)	2.09	2.37	1.309

Note: G1- (40 fish/m³), G2- (80 fish/m³), G3- (120 fish/m³); ^{abc}Different letters in the same row indicate statistical significance (P < 0.05).

Table 2. Setup and running costs in aquaponic systems with varying fish densities over a 120-day period.

Item	Unit	Unit Price (\$)	Total Units			Total Costs (\$)		
			G1	G2	G3	G1	G2	G3
Setup Costs	Aquaponic unit (1000 L)	50	1	1	1	50	50	50
	Biofilter (20 L)	10	1	1	1	10	10	10
	Mechanical filter (20 L)	10	1	1	1	10	10	10
	Hydroponic tube (4m)	7	1	1	1	7	7	7
	Oxygen pump	10	1	1	1	10	10	10
	Volcanic gravel (kg)	0.3	5	5	5	1.5	1.5	1.5
	Plastic bio balls (kg)	1	5	5	5	5	5	5
	LED lamps (3 x 50W)	2	3	3	3	6	6	6
	Total setup cost (\$)					99.5	99.5	99.5
	Set up cost per rotation (\$)					4.97	4.97	4.97
Running Costs	Fish (Fingerling)	0.3	40	80	120	12	24	36
	Fish feed (kg)	1.5	12.23	23.48	35.03	18.34	35.22	52.5
	Electricity (day)	0.1	120	120	120	12	12	12
	Water refill (day)	0.025	120	120	120	3	3	3
	Others (Lump sum) 0.05 of the running cists					2.26	3.71	5.2
	Running Costs (\$)					52.58	82.90	113.6
	Total Setup and Running Costs (\$)					57.5	87.8	118.6

Note: G1- (40 fish/m³), G2- (80 fish/m³), G3- (120 fish/m³)

Table 3. Net profit (\$) across different stocking densities over 120 days

Group		G1	G2	G3
Fish	Fish (Kg)	7.84	13.49	20.22
	Unit Price per Kg (\$)	7	7	7
	Fish Sales (\$)	54.88	94.43	141.54
Plant	Plant Weight (Kg)	2.09	2.37	1.31
	Price per Kg (USD)	4	4	4
	Plant Sale (\$)	8.36	9.48	5.24
Total Sales (\$)		63.24	103.91	146.78
Net Profit (\$)		5.68	16.03	28.10

Note: G1- (40 fish/m³), G2- (80 fish/m³), G3- (120 fish/m³)

DISCUSSION

Fish and plant growth traits: The optimal conditions for plant growth appear to be achieved at intermediate

fish stocking densities, as evidenced by the results obtained from Group 2 (G2). This outcome likely reflects a balanced nutrient concentration. Endut *et al.* (2009) similarly concluded that moderate stocking densities provide the most favorable environment for plant growth

in aquaponic systems, enhancing both nutrient availability and overall system efficiency.

Nutrient cycling plays a central role in aquaponics and is directly influenced by fish excretion rates, making it a key factor in determining system performance. The suboptimal results observed in Group 3 (G3), which employed an excessively high stocking density, align with findings by Liu *et al.* (2016). They reported that overcrowding can lead to elevated stress levels in fish, negatively impacting growth performance and increasing mortality rates. These observations reinforce the idea that both very low and excessively high stocking densities may compromise overall productivity. In contrast, the moderate stocking density applied in G2 fostered a more balanced environment, supporting enhanced production outcomes for both fish and plants.

The findings related to plant growth highlight the critical influence of pH in aquaponic systems. As shown in Table 1, pH levels varied significantly across the different stocking density treatments: Group 1 (G1) exhibited a pH of 7.42, Group 2 (G2) recorded a pH of 6.64, and Group 3 (G3) reached a low of 6.52. These results suggest that lower stocking densities, such as those in G1, are more conducive to maintaining a favorable pH environment (closer to the optimal range for both fish and plant growth). Numerous studies have emphasized the importance of maintaining a near-neutral pH (around 7) in aquaponic systems, not only for the health and growth of tilapia but also for maximizing nutrient availability and uptake by plants (Said *et al.*, 2022).

Nitrification is a critical biological process in aquaponic systems, wherein ammonia is first converted into nitrite and then into nitrate, a form of nitrogen that is more readily absorbed by plants. This process is mediated by nitrifying bacteria, which are essential for maintaining nutrient balance and water quality. A near-neutral pH significantly enhances the activity of these beneficial microorganisms, promoting a healthier and more stable environment for both fish and plant components of the system. Research conducted by Goddek *et al.* (2015) further supports this, indicating that pH levels below 6.5 can substantially inhibit the nitrification process. Under such acidic conditions, the efficiency of biological filtration can be severely compromised. A sharp decline in pH may lead to a reduction in microbial populations, thereby disrupting nutrient cycling and negatively affecting both fish health and plant growth.

The findings of Ali *et al.* (2024) highlight a critical relationship between fish growth performance and water quality, particularly under non-protein skimmer (non-PS) conditions. In such systems, suboptimal water quality significantly impairs both the growth and survival rates of fish. This observation aligns closely with the data presented in Table 2, which shows that Groups 2 (G2) and 3 (G3) were characterized by lower pH levels

compared to Group 1 (G1). A decline in pH may negatively affect plant nutrient uptake, ultimately resulting in reduced growth performance. This assertion is further supported by previous research indicating that a pH range of 7.4 to 7.9 is most conducive to optimal plant health and productivity (Ali *et al.*, 2024). In terms of plant growth, Group 2 (80 fish/m³) achieved the highest average plant weight of 237 g, whereas Group 3 (120 fish/m³) recorded the lowest at 130.9 g. Although the pH values in both G2 (6.64) and G3 (6.52) fell below the ideal range for plant growth, the relatively higher pH in G2 likely contributed to better plant performance compared to G3. Furthermore, the results emphasize that maintaining a balanced pH is critical in aquaponic systems, as plants exhibit optimal growth in environments that support efficient nutrient uptake, ultimately enhancing overall biomass production. The study indicates that elevated total dissolved solids (TDS) levels can significantly influence both fish and plant performance. As fish density increases, so do TDS levels, which correspond with greater accumulation of metabolic waste products and mineral nutrients. Elevated TDS concentrations pose potential risks to fish health by increasing the likelihood of toxicity, impairing growth rates, reducing disease resistance, and negatively affecting dissolved oxygen availability (Ujjania *et al.*, 2022). For plants, while certain dissolved solids supply essential macro- and micronutrients, excessive TDS can disrupt nutrient balance and hinder root absorption, thereby limiting plant growth. Moreover, high TDS levels may alter water pH, further influencing nutrient bioavailability and plant physiological functions. Therefore, effective monitoring and management of TDS are essential to sustain optimal water quality and ensure the well-being of both aquatic and plant components in aquaponic systems (Ujjania *et al.*, 2022).

Net profit: From a financial perspective, Group 3 (G3) demonstrated the highest profitability, generating a net profit of \$33.18. This outcome indicates that higher stocking densities can significantly enhance fish production and improve economic returns, despite potential challenges in plant growth performance. The results suggest that while moderate stocking densities may be more effective in optimizing biological productivity and maintaining system balance, higher densities can still offer economic viability under well-managed conditions. However, continuous monitoring and proactive management are essential, as excessive stocking densities can lead to water quality deterioration and nutrient imbalances, which may compromise both fish and plant health and ultimately disrupt system stability. Quagraine *et al.* (2019) emphasized the importance of carefully managing stocking densities to ensure long-term financial sustainability in aquaponic systems. Although Group 2 (G2) achieved a net profit of

\$21.01, reflecting favorable performance at a moderate stocking density, the higher fish yield observed in G3 highlights the potential for increased profitability when stocking density is strategically managed.

From a sustainability perspective, Love *et al.* (2014) and Lennard and Leonard (2006) emphasize the importance of balancing fish stocking densities to maintain nutrient levels that support both the aquaculture and hydroponic components of aquaponic systems. The decline in plant production observed in Group 3 (G3) suggests that excessively high stocking densities may exceed the system's capacity to sustain nutrient equilibrium. Research by Bosma *et al.* (2017) further demonstrates that the economic viability of aquaponic systems depends on the careful optimization of key variables particularly fish density and nutrient management. While G3 achieved the highest fish yield, the increased complexity and resource demands associated with managing high-density conditions may have partially offset the potential economic gains. In the broader context of aquaponic research, these findings highlight the need for an integrated management approach that considers biological, environmental, and economic factors in tandem. Studies by Suhl *et al.* (2016) and Goddek *et al.* (2015) similarly concluded that aquaponic systems perform most efficiently when fish stocking rates are matched to the nutrient uptake capacity of the plants.

Conclusions: The results of this study indicate that while initial setup costs for aquaponic systems remain constant across varying fish stocking densities, operational costs increase significantly with higher stocking levels. The stocking density of 40 fish/m³ incurred the lowest total production costs, and 120 fish/m³ required the highest investment, primarily due to increased expenditures on fish fingerlings and feed. Fish biomass and corresponding sales revenue demonstrated a positive correlation with stocking density. The highest stocking density (120 fish/m³) achieved the highest net profit, demonstrating the economic potential of high-density aquaponic systems when managed effectively.

Acknowledgments: The authors would like to express their sincere gratitude to the National Agricultural Research Center, Ministry of Agriculture, Palestine for providing the Laboratory to conduct this research.

Authors' contributions: A. Baniowda: Conceptualization, Methodology, Formal analysis, M. W. Ali: Methodology and Writing – review, M. Salman: Writing-revision and editing, Methodology, Formal analysis, Writing - review and editing, M. S. Romdhane: Data curation, Supervision.

Ethical statement: research conducted in this study adhered to ethical standards and guidelines for animal

research. All methods involving juvenile tilapia (*Oreochromis niloticus*) were approved by the appropriate ethical review board at the National Agricultural Research Center (NARC) in Palestine. The care and handling of the fish were performed in accordance with the guidelines provided by established animal welfare organizations to minimize stress and ensure humane treatment throughout the experimental period.

Conflict of Interest: The authors declare that there are no conflicts of interest.

REFERENCES

- Ali, T.E., O.A. Kadour and M.M. Said (2024). Effects of protein skimmer inclusion in an integrated aquaponic system between the red tilapia hybrid (Florida strain) and mint (*Mentha spicata*). Egypt. J. Aquat. Biol. Fish. 28: 1171–1193. <https://www.ejabf.journals.ekb.eg>
- Asche, F., H. Eggert, A. Oglend, C.A. Roheim and M.D. Smith (2022). Aquaculture: Externalities and Policy Options. Rev. Environ. Econ. Policy. 16: 282–305. <https://doi.org/10.1086/721055>
- Belton, B., D.C. Little, W. Zhang, P. Edwards, M. Skladany and S.H. Thilsted (2020). Farming fish in the sea will not nourish the world. Nat. Commun. 11: 5804. <https://doi.org/10.1038/s41467-020-19679-9>
- Bosma, R.H., L. Lacambra, Y. Landstra, C. Perini, J. Poulie, M.J. Schwaner and Y. Yin (2017). The financial feasibility of producing fish and vegetables through aquaponics. Aquacult. Eng. 78: 146-154. <https://doi.org/10.1016/j.aquaeng.2017.07.002>
- Buzby, K. and L.-S. Lin (2014). Scaling aquaponic systems: Balancing plant uptake with fish output. Aquacult. Eng. 63: 39-44. <https://doi.org/10.1016/j.aquaeng.2014.09.002>
- Endut, A., A. Jusoh, N. Ali, W.S. Wan Nik and A.R. Hassan (2009). Effect of flow rate on water quality parameters and plant growth of water spinach (*Ipomoea aquatica*) in an aquaponic recirculating system. Desalin. Water Treat. 5: 19-28. <https://doi.org/10.5004/dwt.2009.559>
- Graber, A. and R. Junge (2009). Aquaponic systems: Nutrient recycling from fish wastewater by vegetable production. Desalination. 246: 147-156. <https://doi.org/10.1016/j.desal.2008.03.048>
- Goddek, S., A. Joyce, B. Kotzen, and G.M. Burnell (2019). *Aquaponics food production systems: Combined aquaculture and hydroponic production technologies for the future*. Springer, Cham. <https://doi.org/10.1007/978-3-030-15943-6>.

- Goddek, S., B. Delaide, U. Mankasingh, K.V. Ragnarsdottir, H. Jijakli and R. Thorarinsdottir (2015). Challenges of sustainable and commercial aquaponics. *Sustainability*. 7: 4199-4224. <https://doi.org/10.3390/su7044199>
- Junge, R., B. König, M. Villarroel, T. Komives and M. Jijakli (2017). Strategic points in aquaponics. *Water*. 9: 182. <https://doi.org/10.3390/w9030182>
- Kankia, A.I., V.R. Manoj, H.O. Orugba and H.I. Owamah (2024). Enhancing the Sustainability of Aquaculture Systems Via Nutrient Recycling Using Aquaponics System. *Water Air Soil Pollut.* 235: 397. <https://doi.org/10.1007/s11270-024-04097-6>
- Lennard, W.A. and B.V. Leonard (2006). A comparison of three different hydroponic sub-systems (gravel bed, floating, and nutrient film technique) in an aquaponic test system. *Aquacult. Int.* 14: 539-550. <https://doi.org/10.1007/s10499-006-9053-2>
- Love, D.C., J.P. Fry, L. Genello, E.S. Hill, J.A. Frederick, X. Li and K. Semmens (2014). An international survey of aquaponics practitioners. *PloS One*. 9: e102662. <https://doi.org/10.1371/journal.pone.0102662>
- Liu, B., R. Jia, C. Han, B. Huang and J.L. Lei (2016). Effects of stocking density on antioxidant status, metabolism and immune response in juvenile turbot (*Scophthalmus maximus*). *Comp. Biochem. Physiol. C Toxicol. Pharmacol.* 190: 1-8.
- Marques, H.L.A., M.B. New, M.V. Boock, H.P. Barros, M. Mallasen and W.C. Valenti (2016). Integrated Freshwater Prawn Farming: State-of-the-Art and Future Potential. *Rev. Fish. Sci. Aquacult.* 24: 264-293. <https://doi.org/10.1080/23308249.2016.1169245>
- Maucieri, C., A.A. Forchino, C. Nicoletto, R. Junge, R. Pastres, P. Sambo and M. Borin (2018). Life cycle assessment of a micro aquaponic system for educational purposes built using recovered material. *J. Clean. Prod.* 172: 3119-3127. <https://doi.org/10.1016/j.jclepro.2017.11.097>
- Nair, C.S., R. Manoharan, D. Nishanth, R. Subramanian, E. Neumann and A. Jaleel (2024). Recent advancements in aquaponics with special emphasis on its sustainability. *J. World Aquacult. Soc.* 56: e13116. <https://doi.org/10.1111/jwas.13116>
- Naylor, R., S. Fang and J. Fanzo (2023). A global view of aquaculture policy. *Food Policy*. 116: 102422. <https://doi.org/10.1016/j.foodpol.2023.102422>
- Popa, R., I.C. Moga, M. Rissdorfer, M.L.G. Ilis, G. Petrescu, N. Craciun, M.G. Matache, C.I. Covaliu and G. Stoian (2017). Duckweed utilization for freshwater conservation (management) in recirculated aquaculture systems. *Int. J. Conserv. Sci.* 8: 715-722. www.ijcs.uaic.ro
- Quagraine, K.K., R.M.V. Flores, H.J. Kim and V. McClain (2019). Economic analysis of aquaponics and hydroponics production in the U.S. Midwest. Taylor and Francis. <https://books.google.ps/books?id=ISugtQEACAAJ>
- Rakocy, J.E., M. Masser M.P. and T.M. Losordo (2006). Recirculating aquaculture tank production systems: Aquaponics-Integrating fish and plant culture (SRAC Publication No. 454).
- Rahmatullah, R., M. Das and S.M. Rahmatullah (2010). Suitable stocking density of tilapia in an aquaponic system. *Bangladesh J. Fisheries Research*. 14 (1-2): 29-35. <http://hdl.handle.net/1834/34271>.
- Sace, C.F. and K.M. Fitzsimmons (2013). Recirculating aquaponic systems using Nile Tilapia (*Oreochromis niloticus*) and freshwater prawn (*Macrobrachium rosenbergii*) polyculture and the productivity of selected leafy vegetables. *Merit Res. J. Bus. Manag.* 1(1): 11-29. <http://www.meritresearchjournals.org/bm/index.htm>
- Said, M.M., F.M. Zaki and O.M. Ahmed (2022). Effect of the Probiotic (*Bacillus* spp.) on Water Quality, Production Performance, Microbial Profile, and Food Safety of the Nile Tilapia and Mint in Recirculating Aquaponic System. *Egypt. J. Aquat. Biol. Fish.* 26(6), 351-372. https://www.ejabf.journals.ekb.eg/article_283085.html
- Suhl, J., D. Dannehl, W. Kloas, D. Baganz, S. Jobs, G. Scheibe and U. Schmidt (2016). Advanced aquaponics: Evaluation of intensive tomato production in aquaponics vs. conventional hydroponics. *Agric. Water Manage.* 178: 335-344. <https://doi.org/10.1016/j.agwat.2016.10.013>
- Ujjania, V.K., N.C. Ujjania and B.K. Sharma (2022). Water quality management in aquaponics system. In *Limnology Volume II* (pp. 1-9). Bhumi Publ.
- Vince, J. and M. Haward (2017). Hybrid governance of aquaculture: opportunities and challenges. *J. Environ. Manage.* 201: 138-144. <https://doi.org/10.1016/j.jenvman.2017.06.039>
- Yildiz, H.Y., L. Robaina, J. Pirhonen, E. Mente, D. Domínguez and G. Parisi (2017). Fish welfare in aquaponic systems: Its relation to water quality with an emphasis on feed and faeces-a review. *Water*. 9(1): 13. <https://doi.org/10.3390/w9010013>.