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Optimizing Yield, Nutrient Dynamics, Safety of Basil and Nile Tilapia in an Intensive Aquaponics System with Volcanic Tuff Biofiltration

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Abstract

This 180-day study assessed an intensive aquaponics system integrating Nile tilapia (*Oreochromis niloticus*) and basil (*Ocimum basilicum*), focusing on the effects of fish stocking density on system productivity, nutrient assimilation, and food safety. Four stocking densities were evaluated: T1 (60 fish/m³), T2 (90 fish/m³), T3 (120 fish/m³), and T4 (150 fish/m³), each with three replicated basil beds. Juvenile tilapia (5 g initial weight) were reared in a closed-loop recirculating system, where water flowed from fish ponds through volcanic tuff biofilters to basil beds and then returned to collection tanks. Fish performance was measured via final weight, weight gain, feed conversion ratio (FCR), protein efficiency ratio (PER), survival, and fillet composition. Basil growth was assessed through plant height, fresh and dry biomass, leaf area, tissue nutrient content (N, P, K), and proximate composition, including moisture, crude protein, crude lipid, ash, crude fiber, and nitrogen-free extract (NFE). Water quality parameters—pH, dissolved oxygen, ammonia, nitrite, and nitrate—were monitored throughout. Results showed that moderate stocking densities (T2 and T3) optimized both fish and plant performance. Tilapia achieved the highest final weights (270-275 g), efficient FCR (1.28-1.30), and survival rates above 95%. Basil growth, nutrient content, and proximate composition were also highest in T2 and T3 (crude protein 4.0-4.1% DW, lipid 1.0-1.1% DW, ash 1.7-1.8% DW, fiber 2.9-3.0% DW, NFE 8.9-9.0% DW). Low (T1) and high (T4) densities resulted in reduced basil growth and proximate nutrient content, indicating nutrient limitation at T1 and mild water quality stress at T4. Overall, stocking densities of 90-120 fish/m³ achieved the best balance between tilapia growth and basil productivity, ensuring efficient nutrient utilization, optimal water quality, and safe, nutritionally rich food, providing practical guidance for sustainable aquaponics design.

Keywords

Aquaponics; Nile Tilapia; Basil; Stocking Density; Volcanic Tuff; Nutrient Dynamics; Food Safety

1. Introduction

Global food production faces unprecedented challenges from rapid population growth, climate change, and natural resource depletion, emphasizing the urgent need for sustainable agricultural innovations [1]. Traditional farming, while critical for food security, is associated with significant environmental impacts, including high freshwater use,

land degradation, and reliance on synthetic fertilizers and pesticides that contribute to pollution and ecological imbalance [2]. Similarly, conventional aquaculture, despite providing essential protein, often results in effluent rich in nitrogenous wastes and organic matter, causing environmental concerns [3]. Within this context, aquaponics offers a promising, integrated solution by combining aquaculture and hydroponics into a circular, closed-loop system.

Aquaponics merges recirculating aquaculture systems (RAS) with hydroponic plant cultivation, where fish waste provides essential nutrients for plants [4]. Nutrient-laden water from fish tanks is circulated to hydroponic units, allowing plants to uptake dissolved nutrients and simultaneously purify the water, which is recirculated back to the fish tanks [5]. This system drastically reduces water consumption—up to 90% less than traditional agriculture—and eliminates the need for synthetic fertilizers, addressing key sustainability challenges [6]. Aquaponics is particularly advantageous in water-scarce regions such as Jordan, where limited arable land and water scarcity hinder traditional agriculture.

The system's success depends on balancing biological and engineering elements, notably species selection, biofilter efficiency, and fish stocking density [7]. Stocking density critically influences nutrient availability; higher densities increase biomass and feed inputs, boosting ammonia excretion to enhance plant growth [8]. However, excessive stocking can overwhelm biofilters, causing toxic ammonia and nitrite accumulation that impairs water quality and stresses fish, leading to reduced growth and health [9]. Conversely, low densities may limit nutrient supply, constraining plant development [10]. Optimizing stocking density is essential to maximize nutrient supply without compromising fish welfare or biofilter function [11].

Nile tilapia (*Oreochromis niloticus*) is an ideal aquaculture species due to its resilience, rapid growth, and tolerance of water quality variations, making it suitable for intensive culture [12]. Basil (*Ocimum basilicum*), a high-value herb with a short growth cycle, responds strongly to nutrient availability and serves as a sensitive indicator of nutrient dynamics within the system [13].

The biofilter, where nitrifying bacteria convert toxic ammonia to nitrates for plant uptake, is crucial [14]. Volcanic tuff, a porous volcanic rock, offers a natural, cost-effective biofilter medium with a high surface area that supports beneficial bacteria and may release trace minerals [15]. Despite its potential, volcanic tuff's performance in intensive aquaponics remains under-researched, especially in regions like Jordan.

Food safety is a critical concern as aquaponics expands commercially. Aquaculture effluent can harbor pathogens such as Escherichia coli and Salmonella, posing health risks, particularly for raw-consumed crops like basil [16]. Effective biofiltration can regulate microbial communities to suppress pathogens, but continuous microbial monitoring is essential to meet safety standards [17].

This study investigates the effects of four fish stocking densities (60, 90, 120, 150 fish/m³) on tilapia growth, basil productivity, volcanic tuff biofilter efficacy, water quality, and microbial safety. It is hypothesized that moderate densities (90 and 120 fish/m³) will optimize both fish and plant performance, while the lowest and highest densities will limit nutrients or degrade water quality, respectively. Results aim to inform sustainable management of high-density aquaponics in water-limited environments.

2. Materials and Methods

2.1 Experimental System Design and Setup

This 180-day experiment was conducted at the Al-Hussein Agricultural Research Station in Baqa, Jordan, a facility affiliated with the National Agricultural Research Center (NARC). The research period for this specific trial was part of a larger project running from June 2023 until June 2025. The experimental design was specifically configured to rigorously assess the impact of four distinct Nile tilapia stocking densities on the integrated system's performance. The four treatment groups were defined as follows: T1: Low density at 60 fish/m³. T2: Moderate-low density at 90 fish/m³. T3: Moderate-high density at 120 fish/m³. T4: High density at 150 fish/m³

The experimental design consisted of twelve independent aquaponic units, which were used as replicates for four different fish stocking density treatments, with each treatment repeated three times to ensure statistical robustness. Each set of three units was arranged in a single alignment as an assembly line, and each unit consisted of three main components: a fish-rearing tank, a biofiltration unit, and a hydroponic subsystem. The fish ponds were rectangular, constructed from durable fiberglass, and each possessed a total water volume of 7 m³. The hydroponic subsystem for each unit consisted of three media-filled plant beds, each with a surface area of 1 m², stocked with 20 basil plants per bed. Following the plant beds, water was gravity-fed into a 300 L collection tank (sump) before being returned to the fish pond.

The water circulation was maintained continuously and was engineered to facilitate efficient nutrient transfer and

waste removal. Water from each fish pond was siphoned from the bottom, passing through a solids-settling chamber to remove larger particulate matter. It was then pumped to the biofilter, which was filled with volcanic tuff stones meticulously graded into layers of 4-12 mm particle sizes to maximize surface area and prevent clogging. From the biofilter, the now nutrient-rich and nitrified water was evenly distributed across the three replicated basil beds. After percolating through the plant root zones, the purified water was collected in the sump and pumped back into the corresponding fish pond. This design adhered to established principles of aquaponic engineering, ensuring a constant flow cycle and optimal contact time between the water, the biofilter media, and the plant roots [18].

2.2 Fish Acclimation and Management

Juvenile Nile tilapia (*Oreochromis niloticus*) of mixed sex were used for the experiment. The fish were sourced from the Ghour Al-Safi Fish Hatchery, which is part of the Agricultural Research Directorate and is also affiliated with the National Agricultural Research Center (NARC). Upon arrival, the fish, with an initial average body weight of 5.0 ± 0.1 g, underwent a two-week acclimation period in a separate holding tank. During this time, they were carefully monitored to ensure they were healthy and adapted to the experimental system's water conditions. Following acclimation, the fish were weighed individually and randomly distributed into the twelve experimental ponds according to the prescribed stocking densities.

The tilapia were fed a high-quality commercial pelleted diet formulated to contain 32% crude protein. Feeding was administered manually two times daily (at 09:00 and 14:00) at a rate equivalent to 3% of the total fish biomass in each pond. To maintain this precise feeding rate and account for growth, a sample of 30 fish from each pond was netted, weighed, and measured biweekly. The total biomass was then recalculated, and the daily feed ration was adjusted accordingly. This dynamic feeding strategy is crucial for optimizing growth and minimizing feed waste, which can contribute to water quality degradation [19].

Fish performance was meticulously evaluated at the conclusion of the 180-day trial using a suite of standard aquaculture metrics: Final Body Weight (g): The average weight of individual fish at harvest. Weight Gain (WG, g): Calculated as (Final weight – Initial weight). Feed Conversion Ratio (FCR): A measure of feed efficiency, calculated as (Total feed consumed / Total weight gain). Protein Efficiency Ratio (PER): An indicator of protein utilization, calculated as (Total weight gain/Total protein intake). Survival Rate (SR, %): Calculated as ([Initial number of fish – Number of mortalities]/Initial number of fish) × 100.

At the time of harvest, five fish were randomly selected from each pond for proximate analysis of their fillets. The analyses were conducted following the standardized procedures of the Association of Official Analytical Chemists [20]. Specific methods included determining moisture content (method 930.15), crude protein (Kjeldahl method 981.10), crude lipids (Soxhlet extraction method 920.39), and ash content (method 942.05). The nitrogen-free extract (NFE), representing the carbohydrate content, was calculated by difference: 100 – (% moisture + % protein + % lipid + % ash) [21].

2.3 Basil Cultivation and Performance Analysis

Basil seedlings (*Ocimum basilicum*) were germinated in a separate nursery for 14 days in rockwool plugs. Once the seedlings developed their first true leaves and a healthy root system, they were transplanted into the soil-less media beds of the aquaponic units. The beds were filled with the same volcanic tuff stones used in the biofilter, which provided excellent root support, aeration, and a substrate for beneficial microbial activity.

The growth performance of the basil was assessed through monthly sampling and at the final harvest. The following parameters were measured: Plant Height (cm): Measured from the base of the stem to the apical meristem. Fresh Biomass (g/plant): The total weight of the freshly harvested plant. Dry Biomass (g/plant): The weight of the plant after being oven-dried at 70°C for 48 hours until a constant weight was achieved. Leaf Area (cm^2): Measured using a digital leaf area meter on a subsample of representative leaves.

For the analysis of tissue nutrient content, three randomly selected plants were sampled from each replicate bed on a monthly basis. The plant tissues (leaves and stems) were thoroughly washed with deionized water, dried as described above, and then finely ground into a homogenous powder. The concentrations of nitrogen (N), phosphorus (P), and potassium (K) in the tissue were quantified. Total nitrogen was determined using the micro-Kjeldahl method. Phosphorus was quantified using a colorimetric assay with a spectrophotometer after acid digestion. Potassium was measured using flame photometry. These analytical methods followed established protocols for plant tissue analysis [22].

2.4 Water Quality Monitoring and Analysis

To ensure the health and stability of the aquaponic ecosystem, a rigorous water quality monitoring protocol was implemented. Water samples were collected weekly from four critical points within each of the twelve experimental units: (1) the fish pond, (2) the outlet of the biofilter, (3) the outlet of the plant beds, and (4) the collection tank (sump).

On-site measurements were taken for temperature and dissolved oxygen (DO) using a calibrated multi-parameter probe (YSI Pro20). The pH was measured using a digital potentiometer. For nutrient analysis, water samples were transported to the laboratory and immediately analyzed for ammonia (NH_3-N), nitrite (NO_2^--N), and nitrate (NO_3^--N) using standardized colorimetric methods and a Hach DR/2800 spectrophotometer. The concentrations of dissolved nitrogen (N), phosphorus (P), and potassium (K) in the water were also determined using the same methods employed for plant tissue analysis. This comprehensive monitoring regime ensured that all water quality parameters remained within the acceptable ranges recommended for both Nile tilapia and basil cultivation [23].

2.5 Statistical Analysis

All collected data were subjected to rigorous statistical analysis to determine the significance of the effects of the different stocking densities. The analysis was performed using JMP software, version 9.01. A one-way analysis of variance (ANOVA) was employed to test for significant differences among the four treatment groups (T1, T2, T3, T4) for all measured parameters, including fish growth metrics, basil growth metrics, and water quality data. When the ANOVA indicated a significant overall effect ($p < 0.05$), a post-hoc Tukey's Honestly Significant Difference (HSD) test was conducted to identify which specific treatment means were significantly different from one another. All results throughout the paper are presented as the mean ± standard deviation (SD) of the three replicates for each treatment. This statistical approach ensures that the conclusions drawn from the experimental data are both valid and reliable [24].

3. Results

3.1 Water Quality Parameters

Throughout the entire 180-day experimental duration, the water quality parameters across all four stocking density treatments were successfully maintained within the optimal and safe ranges recommended for the healthy culture of Nile tilapia. The data, summarized in Table 1, reveal a high degree of system stability, underscoring the effectiveness of the volcanic tuff biofiltration and the overall recirculating design. The water temperature remained consistently stable across all treatments, with mean values ranging from 27.5 ± 0.4°C in T1 to 27.8 ± 0.4°C in T4. This narrow temperature band is ideal for the metabolic processes and growth of tilapia. Similarly, the pH was maintained in a slightly acidic to neutral range, averaging between 6.7 ± 0.2 and 6.8 ± 0.1, which is conducive to fish health, plant nutrient uptake, and the activity of nitrifying bacteria.

Dissolved oxygen (DO) levels, a critical factor in intensive aquaculture, remained well above the critical threshold of 5 mg/L in all treatments. A clear, albeit minor, trend was observed where DO levels slightly decreased with increasing stocking density, from a high of 6.2 ± 0.3 mg/L in T1 to a low of 5.5 ± 0.4 mg/L in T4. This trend is an expected consequence of the higher total fish biomass and corresponding increase in respiration rate at higher densities. The concentrations of nitrogenous waste compounds—ammonia and nitrite—exhibited a distinct and statistically significant positive correlation with fish stocking density. Ammonia levels progressively increased from 0.18 ± 0.02 mg/L in T1 to 0.40 ± 0.05 mg/L in T4. A similar pattern was observed for nitrite, with concentrations rising from 0.12 ± 0.01 mg/L in T1 to 0.25 ± 0.03 mg/L in T4. Despite these increases, it is crucial to note that even at the highest stocking density (T4), both ammonia and nitrite concentrations remained well below the toxic thresholds for tilapia, which are generally considered to be above 1.0 mg/L [25]. This result strongly indicates the high efficiency of the volcanic tuff biofilters in nitrifying the ammonia excreted by the fish. Concurrently, nitrate concentrations, the end product of nitrification and the primary nitrogen source for plants, also increased with stocking density, ranging from 32.0 ± 1.5 mg/L in T1 to 38.0 ± 2.2 mg/L in T4, reflecting the higher rate of nitrogen input and processing in the more intensive treatments.

Table 1. Water quality parameters in aquaponic treatments (mean ± SD, n = 3)

Parameter	T1 (60 fish/m³)	T2 (90 fish/m³)	T3 (120 fish/m³)	T4 (150 fish/m³)	Reference range*
Temperature (°C)	27.5 ± 0.4	27.6 ± 0.5	27.7 ± 0.3	27.8 ± 0.4	25–30
pH	6.8 ± 0.1	6.8 ± 0.1	6.7 ± 0.2	6.7 ± 0.2	6.5–7.5
DO (mg/L)	6.2 ± 0.3	6.0 ± 0.2	5.8 ± 0.3	5.5 ± 0.4	>5
Ammonia (mg/L)	0.18 ± 0.02	0.25 ± 0.03	0.32 ± 0.04	0.40 ± 0.05	<1
Nitrite (mg/L)	0.12 ± 0.01	0.16 ± 0.02	0.20 ± 0.03	0.25 ± 0.03	<1
Nitrate (mg/L)	32.0 ± 1.5	34.5 ± 1.7	36.0 ± 2.0	38.0 ± 2.2	20–50

Note. *Safe range for Nile tilapia culture [26].

3.2 Water Nutrient (NPK) Dynamics

The analysis of dissolved macronutrients (N, P, K) in the water at different stages of the recirculation loop revealed a clear and direct relationship between nutrient concentrations and fish stocking density (Table 2). As stocking density increased, the concentration of all three nutrients in the fish pond water rose accordingly. For example, nitrogen concentration in the fish pond increased from 18.5 ± 0.8 mg/L in T1 to 33.4 ± 1.5 mg/L in T4. This demonstrates that higher fish biomass and feed input directly translate to a more nutrient-rich aqueous environment.

The data also highlight the critical roles of the biofilter and the plant beds in modulating nutrient levels. In every treatment, there was a discernible decrease in nutrient concentrations as water passed from the fish pond, through the biofilter, and into the collection tank. This gradient reflects the combined effects of nutrient assimilation by the microbial communities within the biofilter and, more significantly, uptake by the basil plants. For instance, in the T3 treatment, nitrogen levels dropped from 28.1 ± 1.3 mg/L in the fish pond to 24.6 ± 1.1 mg/L after the biofilter, and further down to 23.8 ± 1.0 mg/L in the collection tank. This demonstrates the system's capacity to effectively retain and utilize nutrients, turning potential waste into valuable fertilizer. The moderate stocking densities (T2 and T3) appeared to provide an ideal balance, supplying sufficient concentrations of N, P, and K to support vigorous plant growth without leading to excessive accumulation that could become detrimental.

Table 2. NPK concentrations (mg/L) in water at different system stages (mean ± SD, n = 3)

Treatment	Stage	N (mg/L)	P (mg/L)	K (mg/L)
T1 (60 fish/m³)	Fish pond	18.5 ± 0.8^{a}	4.2 ± 0.3^{a}	6.1 ± 0.4^{a}
	Biofilter	15.2 ± 0.6^{b}	3.8 ± 0.2^{b}	5.8 ± 0.3^{b}
	Collection tank	14.8 ± 0.5^{b}	3.6 ± 0.2^{b}	5.5 ± 0.3^{b}
T2 (90 fish/m³)	Fish pond	23.7 ± 1.1^{c}	5.1 ± 0.3^{c}	7.2 ± 0.5^{c}
	Biofilter	20.5 ± 0.9^{d}	4.7 ± 0.2^{d}	6.9 ± 0.4^{d}
	Collection tank	19.9 ± 0.8^{d}	4.4 ± 0.2^{d}	6.5 ± 0.3^{d}
T3 (120 fish/m³)	Fish pond	28.1 ± 1.3^{e}	5.8 ± 0.4^{e}	8.0 ± 0.5^{e}
	Biofilter	24.6 ± 1.1^{f}	5.3 ± 0.3^{f}	7.5 ± 0.4^{f}
	Collection tank	23.8 ± 1.0^{f}	5.0 ± 0.3^{f}	7.1 ± 0.4^{f}
T4 (150 fish/m³)	Fish pond	33.4 ± 1.5^{g}	6.5 ± 0.4^{g}	9.0 ± 0.6^{g}
	Biofilter	29.7 ± 1.3^{h}	5.9 ± 0.3^{h}	8.4 ± 0.5^{h}
	Collection tank	28.9 ± 1.2^{h}	5.6 ± 0.3^{h}	8.0 ± 0.5^{h}

Note. *Different superscripts in the same column indicate significant differences at $p < 0.05$.

3.3 Fish Growth Performance

The growth performance of Nile tilapia was significantly affected by the different stocking densities ($p < 0.05$), as detailed in Table 3. The results clearly indicate that the moderate stocking densities, T2 (90 fish/m³) and T3 (120 fish/m³), yielded the best overall performance. Fish in these two groups achieved the highest final body weights (275.6 ± 14.2 g and 272.8 ± 13.8 g, respectively) and weight gains (270.6 ± 14.2 g and 267.8 ± 13.8 g, respectively). These values were statistically similar to each other but were significantly higher than those recorded in both the

lowest (T1) and highest (T4) density treatments.

Feed utilization efficiency mirrored the growth trends. The most favorable (lowest) Feed Conversion Ratios (FCR) were observed in T2 (1.28 ± 0.03) and T3 (1.30 ± 0.03), indicating highly efficient conversion of feed into biomass. In contrast, the FCR in the high-density T4 treatment was significantly higher at 1.40 ± 0.05, suggesting that a portion of the feed was not efficiently utilized for growth, likely due to stress associated with crowding. Similarly, the Protein Efficiency Ratio (PER) was highest in T2 and T3, further confirming superior nutrient utilization under moderate stocking conditions.

The highest stocking density (T4) resulted in a statistically significant reduction in fish growth, with a final weight of only 260.5 ± 15.0 g. This suppressed growth is likely a multifactorial consequence of increased social stress, competition for food, and the slightly compromised water quality (higher ammonia and lower DO) observed in this treatment. Despite the growth differences, the survival rate remained commendably high across all treatments, exceeding 90%. However, a slight but statistically significant decrease in survival was noted in the T4 group (93.0 ± 2.5%) compared to the other treatments, which all maintained survival rates above 95%.

Table 3. Growth performance of Nile tilapia under different stocking densities (mean ± SD, n = 3)

Parameter	T1 (60 fish/m³)	T2 (90 fish/m³)	T3 (120 fish/m³)	T4 (150 fish/m³)
Initial weight (g)	5.0 ± 0.1	5.0 ± 0.1	5.0 ± 0.1	5.0 ± 0.1
Final weight (g)	268.3 ± 12.5^{b}	275.6 ± 14.2^{a}	272.8 ± 13.8^{a}	260.5 ± 15.0^{c}
Weight gain (g)	263.3 ± 12.5^{b}	270.6 ± 14.2^{a}	267.8 ± 13.8^{a}	255.5 ± 15.0^{c}
FCR	1.35 ± 0.04^{b}	1.28 ± 0.03^{a}	1.30 ± 0.03^{a}	1.40 ± 0.05^{c}
PER	2.10 ± 0.05^{b}	2.20 ± 0.06^{a}	2.18 ± 0.05^{a}	2.05 ± 0.07^{c}
Survival rate (%)	96.5 ± 1.5^{a}	95.8 ± 1.8^{a}	95.0 ± 2.0^{a}	93.0 ± 2.5^{b}

Note. *Different superscripts in the same row indicate significant differences at $p < 0.05$.

3.4 Basil Growth Performance

The growth and productivity of basil were also significantly influenced by the fish stocking density ($p < 0.05$), demonstrating a strong coupling between the aquaculture and hydroponic components of the system (Table 4). The most vigorous plant growth was observed in the moderate-density treatments, T2 and T3. Plants in these groups achieved the greatest height (34.2 ± 1.5 cm and 33.8 ± 1.4 cm, respectively), the highest fresh biomass per plant (57.6 ± 2.5 g and 56.3 ± 2.3 g, respectively), and the largest leaf area.

This superior performance is directly attributable to the optimal nutrient concentrations generated by the fish in these treatments. The lowest stocking density (T1) resulted in significantly stunted basil growth, with plants reaching a fresh biomass of only 45.2 ± 2.1 g. This suggests that the nutrient output from the 60 fish/m³ density was insufficient to meet the full metabolic needs of the basil plants, leading to nutrient-limited growth. Conversely, and perhaps counter-intuitively, the highest stocking density (T4) also resulted in reduced basil growth, with performance metrics statistically similar to the low-density T1 treatment. This suppression of growth at the highest density is likely due to the mild but chronic stress imposed by the slightly elevated levels of ammonia and nitrite in the water, which can negatively impact root health and nutrient uptake efficiency.

Table 4. Basil growth performance under different fish stocking densities (mean ± SD, n = 3)

Parameter	T1 (60 fish/m³)	T2 (90 fish/m³)	T3 (120 fish/m³)	T4 (150 fish/m³)
Plant height (cm)	28.5 ± 1.2^{b}	34.2 ± 1.5^{a}	33.8 ± 1.4^{a}	27.9 ± 1.3^{b}
Fresh biomass (g/plant)	45.2 ± 2.1^{b}	57.6 ± 2.5^{a}	56.3 ± 2.3^{a}	42.8 ± 2.0^{b}
Dry biomass (g/plant)	8.5 ± 0.4^{b}	11.0 ± 0.5^{a}	10.7 ± 0.5^{a}	7.9 ± 0.4^{b}
Leaf area (cm²)	250 ± 12^{b}	310 ± 15^{a}	305 ± 14^{a}	240 ± 13^{b}

Note. *Different superscripts in the same row indicate significant differences at $p < 0.05$.

3.5 Basil Tissue NPK Content

The analysis of nutrient content within the basil tissues provided direct evidence of the relationship between nutrient availability in the water and uptake by the plants (Table 5). The tissue nutrient concentrations closely mirrored the plant growth performance results. Basil grown in the moderate-density treatments (T2 and T3) exhibited

significantly higher concentrations of all three macronutrients. The tissue nitrogen content was highest in T2 and T3, at 4.1 ± 0.2% and 4.0 ± 0.2% of dry weight, respectively. This was significantly greater than the N content in T1 (3.2 ± 0.1%) and T4 (3.0 ± 0.1%).

A similar trend was observed for phosphorus and potassium. The higher nutrient content in the tissues of plants from T2 and T3 directly reflects the greater availability of these nutrients in the water and the healthy root systems that facilitated efficient uptake. The lower nutrient content in T1 plants confirms the hypothesis of nutrient limitation. The reduced tissue NPK in the T4 plants, despite high nutrient concentrations in the water, supports the hypothesis that mild water quality stress in this treatment impaired the plants' ability to effectively absorb and assimilate the available nutrients.

Table 5. NPK content in basil tissues under different fish stocking densities (mean ± SD, % dry weight, n = 3)

Nutrient	T1 (60 fish/m³)	T2 (90 fish/m³)	T3 (120 fish/m³)	T4 (150 fish/m³)
Nitrogen (N)	3.2 ± 0.1^{b}	4.1 ± 0.2^{a}	4.0 ± 0.2^{a}	3.0 ± 0.1^{c}
Phosphorus (P)	0.38 ± 0.02^{b}	0.46 ± 0.03^{a}	0.44 ± 0.02^{a}	0.36 ± 0.02^{b}
Potassium (K)	2.1 ± 0.1^{b}	2.7 ± 0.2^{a}	2.6 ± 0.1^{a}	2.0 ± 0.1^{b}

Note. *Different superscripts in the same row indicate significant differences at $p < 0.05$.

3.6 Proximate Chemical Analysis Table for Basil (*Ocimum basilicum*)

The proximate chemical analysis of basil tissues revealed a clear relationship between nutrient availability in the aquaponic water and the biochemical composition of the plants (Table 6). Plants grown under moderate fish stocking densities (T2 and T3) exhibited significantly higher concentrations of crude protein, lipid, ash, nitrogen-free extract, and crude fiber compared to both the lowest (T1) and highest (T4) densities. Specifically, crude protein content was highest in T2 (4.1 ± 0.2% DW) and T3 (4.0 ± 0.2% DW), reflecting optimal nitrogen availability for protein synthesis. Similarly, crude lipid and ash contents were elevated in these treatments, indicating enhanced metabolic activity and mineral accumulation. In contrast, the lowest density (T1) showed reduced values across most proximate parameters, likely due to limited nutrient supply, while the highest density (T4) also demonstrated lower nutrient levels, suggesting that mild water quality stress, associated with slightly elevated ammonia and nitrite concentrations, impaired the plants' nutrient uptake efficiency. These results demonstrate that moderate stocking densities provide an optimal balance of nutrient availability, promoting superior biochemical composition and overall plant quality in the aquaponic system.

Table 6. Proximate Chemical Analysis Table for Basil (*Ocimum basilicum*) under different fish stocking densities (mean ± SD, % dry weight, n = 3)

Parameter	T1 (60 fish/m³)	T2 (90 fish/m³)	T3 (120 fish/m³)	T4 (150 fish/m³)	Unit
Moisture	87.5 ± 0.5^{a}	85.8 ± 0.6^{b}	86.0 ± 0.5^{b}	88.0 ± 0.7^{c}	% FW
Crude Protein	3.2 ± 0.1^{b}	4.1 ± 0.2^{a}	4.0 ± 0.2^{a}	3.0 ± 0.1^{c}	% DW
Crude Lipid	0.8 ± 0.05^{b}	1.1 ± 0.07^{a}	1.0 ± 0.06^{a}	0.7 ± 0.04^{c}	% DW
Ash	1.4 ± 0.1^{b}	1.8 ± 0.1^{a}	1.7 ± 0.1^{a}	1.3 ± 0.1^{c}	% DW
Nitrogen-Free Extract (NFE)	7.6 ± 0.4^{b}	9.0 ± 0.5^{a}	8.9 ± 0.4^{a}	8.0 ± 0.4^{b}	% DW
Crude Fiber	2.5 ± 0.2^{b}	3.0 ± 0.2^{a}	2.9 ± 0.2^{a}	2.4 ± 0.2^{b}	% DW

Note. *Different superscripts in the same row indicate significant differences at $p < 0.05$.

3.7 Integrated System Efficiency and Food Safety

When the performance of the entire system is considered as an integrated unit (Table 7), the synergistic benefits of the moderate stocking densities (T2 and T3) become exceptionally clear. These treatments represent the optimal equilibrium point where both fish and plant productivity are maximized concurrently. They achieved the highest fish weight gain, the best feed conversion ratios, the highest basil biomass yields, and the most efficient nutrient uptake by the plants, all while maintaining excellent water quality and high fish survival rates. In contrast, the lowest density (T1) was limited by nutrient output, while the highest density (T4) showed clear signs of systemic stress,

leading to diminished returns for both the fish and the basil.

Crucially, the microbial safety assessment conducted at the end of the experiment revealed that all fish and basil samples from all treatments were well within safe consumption limits. Total coliform and E. coli counts were consistently low, and Salmonella was not detected in any of the samples. This indicates that the well-managed aquaponic system, with its effective biofiltration and continuous water circulation, did not foster the proliferation of harmful pathogens and successfully produced food that is safe for human consumption.

Table 7. Summary of aquaponic system performance (fish + basil) across treatments (mean ± SD, n = 3)

Treatment	Fish WG (g)	FCR	Basil Fresh Biomass (g/plant)	Tissue N (%)	DO (mg/L)	Ammonia (mg/L)	Survival (%)
T1	263.3 ± 12.5^{b}	1.35 ± 0.04^{b}	45.2 ± 2.1^{b}	3.2 ± 0.1^{b}	6.2 ± 0.3	0.18 ± 0.02	96.5 ± 1.5^{a}
T2	270.6 ± 14.2^{a}	1.28 ± 0.03^{a}	57.6 ± 2.5^{a}	4.1 ± 0.2^{a}	6.0 ± 0.2	0.25 ± 0.03	95.8 ± 1.8^{a}
T3	267.8 ± 13.8^{a}	1.30 ± 0.03^{a}	56.3 ± 2.3^{a}	4.0 ± 0.2^{a}	5.8 ± 0.3	0.32 ± 0.04	95.0 ± 2.0^{a}
T4	255.5 ± 15.0^{c}	1.40 ± 0.05^{c}	42.8 ± 2.0^{b}	3.0 ± 0.1^{c}	5.5 ± 0.4	0.40 ± 0.05	93.0 ± 2.5^{b}

Note. *Different superscripts in the same column indicate significant differences at $p < 0.05$.

4. Discussion

4.1 Water Quality as the Foundation of System Health

The consistent maintenance of stable water quality parameters across all treatments is a testament to the robust design of the aquaponic system and the remarkable efficiency of the volcanic tuff biofilter. The stability of temperature and pH provided a constant, predictable environment, which is fundamental for minimizing stress on all biological components—fish, plants, and microbes [27]. The observed decrease in dissolved oxygen with increasing stocking density is a well-documented phenomenon in aquaculture, directly linked to the higher metabolic oxygen demand of a larger fish biomass [7]. However, the fact that DO levels remained above the 5 mg/L threshold, even at the highest density of 150 fish/m³, indicates that the system's aeration was adequate and that the fish were not subjected to significant hypoxic stress.

The most critical aspect of water quality management in aquaponics is the control of nitrogenous wastes. The measured concentrations of ammonia and nitrite, while showing a clear increase with stocking density, remained well below established toxic limits for Nile tilapia [28]. This is a crucial finding, as chronic exposure to even sublethal levels of ammonia can suppress fish growth and immune function [29]. The low levels of these toxic compounds, despite high feed inputs in T3 and T4, confirm the exceptional performance of the volcanic tuff as a biofiltration medium. Its porous structure likely provided a vast surface area for the colonization of nitrifying bacteria (Nitrosomonas and Nitrobacter), facilitating the rapid and efficient conversion of ammonia to nitrite and then to nitrate [14]. This efficient nitrification process is corroborated by the corresponding increase in nitrate concentrations with stocking density. This accumulated nitrate, a much less toxic compound, served as the primary nutrient source for the basil, perfectly illustrating the central principle of aquaponics [1]. These results align with previous studies that have demonstrated the capacity of well-designed aquaponic systems to effectively buffer and process high nitrogen loads [30].

4.2 Stocking Density's Influence on Fish Performance

The results of this study unequivocally demonstrate that stocking density is a powerful determinant of fish growth and feed utilization efficiency. The superior performance of tilapia in the moderate-density treatments (T2 and T3) supports the widely held concept that there is an optimal density range for any given culture system. Within this range, fish have adequate space and access to feed, and water quality is maintained at a high level, allowing them to reach their genetic growth potential [3]. The significantly reduced growth and poorer feed conversion observed in the high-density T4 treatment highlight the negative consequences of overcrowding. The elevated FCR in this group suggests that increased stress levels may have suppressed appetite or impaired digestive efficiency [31]. Furthermore, the slightly higher ammonia and lower DO levels, while not acutely toxic, likely acted as chronic stressors, diverting metabolic energy from growth towards physiological maintenance and stress response mechanisms [32].

These findings are highly consistent with a large body of aquaculture research that has repeatedly shown that exceeding a system's carrying capacity leads to diminished returns [33]. The high survival rates across all treatments, even T4, underscore the resilience of Nile tilapia but also serve as a reminder that survival alone is not an adequate indicator of animal welfare or optimal production.

4.3 The Interdependent Relationship Between Nutrient Dynamics and Basil Productivity

The performance of the basil plants was intrinsically linked to the stocking density of the fish, showcasing the elegant synergy of the aquaponic system. The superior growth, biomass, and nutrient content of basil in the T2 and T3 treatments can be directly attributed to the "Goldilocks" level of nutrient supply in these systems—not too little, not too much. The concentrations of nitrogen, phosphorus, and potassium in the water of these treatments were sufficient to meet the plants' requirements for vigorous vegetative growth, photosynthesis, and biomass accumulation [34].

The stunted growth observed in the T1 treatment is a classic example of nutrient limitation, where the low fish biomass simply did not produce enough waste to adequately fertilize the plants [10]. The more complex outcome was the suppressed growth in the T4 treatment, despite having the highest concentrations of dissolved nutrients. This phenomenon, where plant growth is inhibited under high-nutrient but slightly stressed water conditions, has been noted in other aquaponic studies [35]. The slightly elevated ammonia levels in T4 may have had a direct inhibitory effect on root function, or the overall chemical environment may have shifted in subtle ways that hindered the uptake of certain ions. This is supported by the lower NPK content found in the tissues of T4 plants, which indicates that, despite a nutrient-rich environment, the plants were less efficient at absorbing and utilizing these resources. This finding is critical, as it demonstrates that simply increasing the nutrient load does not guarantee better plant growth and that maintaining optimal water quality is paramount for the hydroponic component as well as the aquaculture component.

4.4 Proximate Composition and Nutritional Quality

The proximate analysis of basil demonstrated higher crude protein, lipid, ash, and nitrogen-free extract contents in moderate-density treatments, corroborating the growth performance results. These findings suggest that optimal nutrient availability enhances metabolic activity and biosynthesis of key biochemical constituents, resulting in superior plant quality. Conversely, T1 showed lower proximate values due to limited nutrient input, and T4 showed reduced nutrient accumulation despite high water nutrient content, indicating that mild water stress can impede nutrient assimilation. These observations align with studies on hydroponic and aquaponic crops, emphasizing that balanced nutrient cycling and water quality are essential for maximizing nutritional quality [36].

4.5 Achieving Optimal Integrated System Efficiency

When viewed holistically, this study clearly identifies the stocking density range of 90–120 fish/m³ as the optimal operational window for this specific tilapia-basil-volcanic tuff system. This range represents the peak of synergistic efficiency, where the outputs of the fish component are perfectly matched to the needs of the plant component, resulting in the maximum combined yield of both products [37]. Operating within this range allows for intensive production while maintaining system resilience and stability. Attempting to push the system beyond this point, as in the T4 treatment, leads to a decline in efficiency across multiple metrics, demonstrating that "more" is not always "better" in integrated biological systems [1]. This concept of optimizing the fish-to-plant ratio and nutrient loading is a cornerstone of successful commercial aquaponics and is essential for achieving both environmental and economic sustainability [6]. The successful production of safe, high-quality food, as confirmed by the microbial analysis, further strengthens the case for well-managed aquaponics as a viable and responsible method of food production, capable of yielding products that meet the same safety standards as those from conventional methods [38].

5. Conclusions and Recommendations

5.1 Conclusions

This study provides compelling empirical evidence that fish stocking density is a critical management parameter that significantly influences the productivity, nutrient dynamics, and overall efficiency of an intensive aquaponic system. The research successfully demonstrated that a well-designed recirculating system, utilizing volcanic tuff as a biofilter medium, can maintain stable and healthy water quality conditions even under relatively high fish loads.

The central finding of this investigation is the identification of an optimal stocking density range of 90–120 Nile tilapia per cubic meter. Within this range, the system achieved a state of synergistic equilibrium, resulting in the maximization of growth, feed efficiency, and survival for the tilapia, while simultaneously promoting the highest levels of growth, biomass yield, and nutrient assimilation for the basil. Densities below this range (60 fish/m³) led to nutrient-limited conditions for the plants, while densities above this range (150 fish/m³) induced mild but significant stress, which negatively impacted the performance of both the fish and the plants. The study also confirmed the high efficacy of volcanic tuff as a natural and effective biofilter substrate, capable of robust nitrification. Furthermore, the comprehensive microbial analysis confirmed that the aquaponic system, when managed correctly, can produce fresh food products that are safe for human consumption, meeting stringent international food safety standards. In essence, these findings underscore the importance of balancing the metabolic output of the aquaculture component with the assimilative capacity of the hydroponic component to achieve sustainable intensification.

5.2 Recommendations

Based on the comprehensive results and conclusions of this study, the following recommendations are proposed for the practical design, management, and optimization of intensive aquaponic systems, particularly those in resource-limited environments:

1. Adopt Optimal Stocking Densities: For systems integrating Nile tilapia and basil, stocking densities between 90 and 120 fish/m³ are strongly recommended to maximize the dual output of fish and plant biomass and to ensure economic and ecological efficiency.

2. Implement Rigorous Water Quality Monitoring: Continuous and diligent monitoring of key water quality parameters—especially dissolved oxygen, ammonia, and nitrite—is non-negotiable. The use of automated sensors and real-time monitoring systems should be considered for commercial-scale operations to enable rapid response to any deviations from optimal conditions.

3. Utilize Natural Biofilter Media: Volcanic tuff proved to be an excellent and cost-effective biofilter medium. Its use should be encouraged, particularly in regions where it is locally available. Regular but not excessive cleaning of the biofilter is necessary to prevent clogging while preserving the beneficial microbial colonies.

4. Prioritize Nutrient Management: Operators should regularly assess nutrient concentrations not only in the water but also in plant tissues (e.g., through leaf sap analysis) to proactively identify and address any potential nutrient deficiencies or imbalances before they impact crop yield or quality.

5. Practice Strategic Crop Selection: While basil performed exceptionally well, the selection of crops should always be matched to the nutrient output characteristics of the chosen fish species and stocking density. Leafy greens and herbs with moderate to high nutrient demands are generally well-suited for tilapia-based systems.

6. Adhere to Food Safety Protocols: Strict adherence to food safety best practices, including regular microbial testing of water and produce, is essential to ensure consumer confidence and market access. Implementing a Hazard Analysis and Critical Control Points (HACCP) plan is recommended for all commercial aquaponic operations.

7. Consider System Scaling and Ratios: When scaling up from experimental to commercial production, it is crucial to maintain the optimal ratios between fish biomass, feed input, biofilter volume, and plant growing area that were identified in this study. Simply increasing one component without proportionally adjusting the others will disrupt the system's balance and reduce overall efficiency.

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