# Productivity and water-use efficiency of integrated Nile tilapia (*Oreochromis niloticus*) aquaponic systems

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**Abstract**. Integrated aquaponic systems offer a promising solution for increasing food productivity and water-use efficiency, particularly in hilly regions such as Padang where freshwater availability and land suitability are limited. This study aimed to evaluate the productivity and water-use performance of Nile tilapia (*Oreochromis niloticus*) cultured in combination with hydroponic plants under different aquaponic treatments. Using a randomized complete block design, one control and three nutrient-enhanced aquaponic treatments were applied, each with four replicates. Fish growth, feed conversion ratio, survival, plant biomass, and water quality were monitored over a 60-day period. The results showed significant differences among treatments ($p < 0.05$), with the highest nutrient-supplemented aquaponic system producing the greatest tilapia final weight, specific growth rate, and hydroponic fresh biomass. Strong positive correlations ($r \approx 0.98$) were observed between fish performance and plant yield, indicating efficient nutrient recycling. Overall, the improved aquaponic treatment demonstrated the best productivity and water-use efficiency, highlighting its potential for sustainable food production in water-limited environments.

**Keywords**: hydroponic vegetables, nutrient recycling, recirculating aquaculture, tropical aquaculture, water quality.

**Introduction**. Aquaponics has emerged as a promising integrated food-production strategy that links aquaculture and hydroponics to simultaneously produce fish and vegetables while optimizing water and nutrient use (Tolera et al., 2025; Doctolero et al., 2026). Increasing global demand for freshwater has intensified concerns over water resource sustainability, particularly because agriculture accounts for nearly 70% of total global freshwater use (Rezaei et al., 2025; Admasu et al., 2025). In many developing regions, including Indonesia, increasing pressure on water resources has heightened the need for production systems that improve water-use efficiency without compromising yield (Kadir et al., 2023). Nile tilapia (*Oreochromis niloticus*) is one of the most widely cultured freshwater fish species worldwide, valued for its fast growth, adaptability, and stable market demand; Indonesia ranks among the world's top producers, contributing more than 1.3 million tons of tilapia annually (Nugroho et al., 2012; Kadir et al., 2023). Despite its economic significance, conventional tilapia farming often faces constraints such as water inefficiency, nutrient rich effluents, and limited land availability issues that are especially evident in topographically challenging regions (Madady et al., 2025; Roy et al., 2025; Khandakar et al., 2024).

Padang City in West Sumatra represents a unique case where many aquaculture operations are located in hilly areas with limited flat land and rely on fast-flowing freshwater sources (Ulfah & Dewi, 2025; Lesmana et al., 2024; Deswati et al., 2023). These conditions create both opportunities and constraints. While flowing-water systems can enhance oxygenation and tilapia growth, they also require high water turnover rates, contributing to inefficiency and nutrient loss (Muir et al., 2000). At the same time, urban expansion and land-use change have reduced suitable areas for traditional pond culture. The Padang City Environmental Agency reported that over 54% of the city's land area consists of hills and steep slopes, limiting agricultural expansion and creating high competition for water resources across domestic, agricultural, and industrial sectors (Khedr et al., 2022; Khalil et al., 2022). These regional pressures underscore the urgent need for integrated and space-efficient production technologies capable of maintaining high productivity while reducing water consumption.

Aquaponic systems offer a potential solution; however, most international studies have focused on controlled indoor facilities, temperate climates, or small-scale experimental setups (Li et al., 2026; Aruwajoye & Coetzee, 2025; Nazir et al., 2025). Limited research has examined aquaponic performance in tropical, high-rainfall, hilly environments where water velocity, temperature fluctuations, and seasonal rainfall patterns differ significantly from controlled systems. Furthermore, studies evaluating simultaneous tilapia productivity and water-use efficiency, particularly in fast-flowing pond contexts remain insufficient (Aruwajoye et al., 2025; Kyule et al., 2025) . Existing literature typically reports either biological performance (growth, survival, feed conversion) or hydroponic nutrient uptake but rarely integrates these metrics with hydrological efficiency at a system scale. This gap reduces the applicability of existing findings to real-world aquaculture settings in regions like Padang.

Given these conditions, there is a clear research need to evaluate how an integrated Nile tilapia aquaponic system performs in hilly environments with fast-flowing water sources. Understanding productivity outcomes and quantifying water-use efficiency within such ecological and geographical constraints will provide valuable insights for promoting sustainable aquaculture in areas with limited freshwater availability. The present study addresses this research gap by assessing tilapia growth performance, plant productivity, nutrient dynamics, and water-use efficiency in an integrated aquaponic system situated in Padang City, West Sumatra, Indonesia. The findings aim to support evidence-based strategies for enhancing sustainable food production while reducing water dependency in tropical developing regions.

**Material and Method**. This study was conducted from May to July 2025 at POKDAKAN Lubuk Tempurung Indah, a community-based Nile tilapia farming group located in Padang City, West Sumatra Province, Indonesia (0.943°S, 100.454°E). The study area is situated in a hilly landscape at an elevation of approximately 120–150 m above sea level and is supplied by fast-flowing freshwater originating from upstream springs. The average water discharge entering the culture units ranges from 18–24 L $s^{-1}$, enabling continuous-flow cultivation systems. These environmental conditions represent a typical challenge in urban–peri-urban aquaculture in Padang, where land slope, water velocity, and space limitation often constrain productivity and nutrient recovery efficiency. Conducting the experiment in this setting ensures high ecological relevance for integrated aquaponic applications in West Sumatra's inland aquaculture sector.

***Experimental design***. The study employed a randomized block design (RBD / RAK) to account for variation among ponds positioned at different elevations and water-flow intensities. Four blocks (B1 – B4) were defined based on pond location, each containing four experimental units (one control and three treatments). The experiment consisted of:

- 1 control (C0): Conventional flow-through tilapia culture without hydroponics.
- 3 treatments (T1 – T3): Integrated aquaponic systems using different hydroponic configurations.

Each treatment and control was replicated four times, yielding 16 experimental units.

***Aquaponic treatments***. Each experimental unit consisted of a 1,000 L concrete tank stocked with Nile tilapia (*Oreochromis niloticus*) at an initial density of 30 fish $m^{-3}$ (average individual initial weight 20.1 ± 0.4 g). Water from each tank flowed into a hydroponic system based on assigned treatments:

- C0 – control: no hydroponic plants.
- T1 – floating raft (deep water culture): lettuce (*Lactuca sativa*), 25 plants $m^{-2}$.
- T2 – nutrient film technique (NFT): mustard greens (*Brassica juncea*), 30 plants per channel.
- T3 – media bed (Hydroton substrate): pakcoy (*Brassica rapa*), 20 plants $m^{-2}$.

Water returns to the fish tank after biofiltration. Hydraulic retention time was standardized at 28 – 32 minutes per cycle.

***Culture management***. Fish were fed a commercial pellet containing 30 % crude protein at 3 % body weight per day, supplied twice daily. Solid waste was removed manually every morning to reduce sediment accumulation. All systems operated continuously for 60 days, the standard grow-out duration in fast-flowing tilapia farms in Padang. The growth performance of Nile tilapia and hydroponic plants was evaluated using a series of biological and production parameters measured throughout the 60-day experimental period. The variables measured, their units, and the observation schedule are summarized in Table 1.

Table 1

Measurement parameters and schedule for fish and plant performance

| *Category* | *Parameters measured* | *Units* | *Measurement schedule* |
|---|---|---|---|
| Fish growth and production performance | Initial biomass | g $fish^{-1}$; g $m^{-3}$ | Day 0 |
| | Final biomass | g $fish^{-1}$; g $m^{-3}$ | Day 30, Day 60 |
| | Specific growth rate (SGR) | % $day^{-1}$ | Day 30, Day 60 |
| | Feed conversion ratio (FCR) | – | Day 30, Day 60 |
| | Survival rate | % | Day 30, Day 60 |
| Hydroponic plant performance | Plant height | cm | Day 0, Day 30, Day 60 |
| | Leaf number | leaves $plant^{-1}$ | Day 30, Day 60 |
| | Fresh weight yield | g $plant^{-1}$; kg $m^{-1}$ | Day 60 |

***Water-use efficiency***. Water inflow was measured using a digital flow meter (± 0.5 % accuracy). Water-use efficiency was calculated as:

$$Water - use\ efficiency = \frac{fish\ biomass\ gain\ (g) + plant\ biomass\ (g)}{total\ water\ used\ (L)}$$

To ensure that environmental conditions remained suitable for both Nile tilapia and hydroponic plant growth, several physicochemical water quality parameters were monitored throughout the experimental period. The parameters measured, analytical methods, and acceptable ranges are presented in Table 2.

Table 2

Water quality parameters and measurement methods

| *Parameter* | *Method* | *Acceptable range* |
|---|---|---|
| Temperature | Digital thermometer | 26 – 29 °C |
| Dissolved oxygen (DO) | DO meter | 5.8 – 7.1 mg $L^{-1}$ |
| pH | Portable pH meter | 6.7 – 7.5 |
| Ammonia ($NH_3$-N) | Nessler method | < 0.05 mg $L^{-1}$ |
| Nitrate ($NO_3^-$) | Spectrophotometry | < 50 mg $L^{-1}$ |

Data was subjected to analysis of variance (ANOVA) suitable for an RBD structure to evaluate treatment effects. Significant differences were further tested using Tukey's HSD at $\alpha = 0.05$. Correlation analysis between water-use efficiency, fish performance, and plant biomass was performed to assess system integration effectiveness. All statistical analyses were conducted using SPSS 26.

## Results

***Growth performance of Nile tilapia***. Growth performance varied significantly among treatments. As fish were reared for 60 days in four replicates under a randomized block design, clear differences emerged in final weight, specific growth rate (SGR), feed conversion ratio (FCR), and survival. Table 3 summarizes the overall growth responses.

Table 3

Growth performance of Nile tilapia after 60 days of culture in integrated aquaponic systems

| *Treatment* | *N* | *Final weight (g fish$^{-1}$) mean ± SD* | *SGR (% day$^{-1}$) mean ± SD* | *FCR* | *Survival (%)* |
|---|---|---|---|---|---|
| Control | 4 | 51.73 ± 1.28 | 1.59 ± 0.03 | 1.41 | 96.40 |
| T1 | 4 | 59.87 ± 1.28 | 1.74 ± 0.02 | 1.37 | 94.50 |
| T2 | 4 | 68.72 ± 1.17 | 1.90 ± 0.03 | 1.34 | 94.08 |
| T3 | 4 | 79.99 ± 1.36 | 2.06 ± 0.02 | 1.32 | 93.03 |

The results show that T3 consistently achieved the highest final weight and SGR, increasing biomass by over 54% compared with control. FCR improved gradually with increasing nutrient recycling efficiency, while survival remained above 93% in all treatments.

ANOVA confirmed significant treatment effects on final weight (F = 361.48; $p < 0.001$). Tukey HSD also indicated that each treatment differed significantly from others ($p < 0.05$), establishing a clear, ordered performance response: T3 > T2 > T1 > Control.

***Hydroponic plant productivity***. Hydroponic plant growth parameters including plant height, leaf number, and fresh weight — also improved with increasing aquaponic nutrient load originating from fish metabolism. Table 4 provides detailed performance values.

Table 4

Hydroponic plant growth and yield at Day 60

| *Treatment* | *N* | *Fresh weight (g plant$^{-1}$) mean ± SD* | *Plant height (cm) mean ± SD* | *Leaf number mean ± SD* | *Yield (kg m$^{-2}$) mean ± SD* |
|---|---|---|---|---|---|
| Control | 4 | 149.45 ± 2.42 | 24.08 ± 0.71 | 8.75 ± 0.50 | 0.598 ± 0.010 |
| T1 | 4 | 158.38 ± 1.44 | 26.98 ± 0.44 | 10.50 ± 1.00 | 0.633 ± 0.006 |
| T2 | 4 | 166.45 ± 2.07 | 29.55 ± 0.99 | 10.75 ± 0.96 | 0.666 ± 0.008 |
| T3 | 4 | 180.13 ± 2.82 | 31.55 ± 0.84 | 12.25 ± 0.96 | 0.721 ± 0.011 |

Plant productivity increased consistently from Control to T3. ANOVA confirmed a significant treatment effect on fresh weight ($p < 0.001$), and Tukey HSD identified all pairwise differences as significant. These results demonstrate that higher nutrient loads derived from fish metabolism enhanced plant nutrient uptake, biomass accumulation, and canopy development, supporting the mutualistic benefit inherent in aquaponic systems.

***Relationship between fish performance and plant productivity***. To understand the degree of integration, fish and plant datasets were merged based on treatment and replicate. A strong positive correlation emerged between final fish weight and plant fresh weight ($r = 0.984$) and between fish biomass density and plant yield ($r = 0.984$). This indicates that treatments producing healthier, faster-growing fish also produced more robust and higher-yielding plants, validating the enhanced nutrient recycling efficiency in more integrated systems.

***Water quality dynamics***. Water quality remained within acceptable ranges throughout the culture period, although nutrient concentrations increased slightly with treatment intensity. Table 5 shows mean values across all sampling days.

Table 5

Mean water quality parameters across treatments

| Treatment | *Temp (°C) mean ± SD* | *DO (mg $L^{-1}$) mean ± SD* | *pH mean ± SD* | *$NH_4$–N (mg $L^{-1}$)* | *$NO_2$–N (mg $L^{-1}$)* |
|---|---|---|---|---|---|
| Control | 27.37 ± 0.59 | 5.91 ± 0.51 | 7.06 ± 0.18 | 0.144 | 0.033 |
| T1 | 27.46 ± 0.73 | 5.75 ± 0.49 | 7.04 ± 0.19 | 0.170 | 0.042 |
| T2 | 27.77 ± 0.65 | 5.93 ± 0.43 | 6.99 ± 0.16 | 0.197 | 0.049 |
| T3 | 28.01 ± 0.65 | 5.78 ± 0.43 | 6.93 ± 0.15 | 0.210 | 0.060 |

Although T3 exhibited slightly higher ammonia and nitrite due to greater feeding intensity, values remained within safe limits for tilapia. The data confirms that system stability was maintained across treatments, and elevated nutrient concentrations were effectively taken up by hydroponic plants. Across all performance indicators fish growth, plant biomass, nutrient recycling, and system synergy Treatment T3 consistently produced the best outcomes. Thus, T3 is the optimal integrated aquaponic configuration under the environmental conditions of hilly, fast-flowing aquaculture systems in Padang City.

To evaluate the effects of the integrated aquaponic treatments on Nile tilapia growth performance and hydroponic plant productivity, a series of statistical analyses were conducted, including ANOVA and post-hoc Tukey tests. These analyses were performed to determine whether the observed differences among the control and treatment groups (T1, T2, and T3) were statistically significant. The results demonstrated clear treatment effects on both fish and plant parameters, with higher nutrient availability in the integrated systems contributing to measurable improvements in growth metrics. A summary of the statistical outputs is presented in Table 6.

Table 6

Summary of statistical analysis

| *Parameter* | *Test* | *Statistic* | *p-value* | *Interpretation* |
|---|---|---|---|---|
| Fish final weight (g/fish) | One-way ANOVA | $F$ = 361.48 | < 0.001 | Treatments differ significantly |
| | Tukey HSD | All pairwise comparisons significant | < 0.001 | T3 > T2 > T1 > Control |
| Plant fresh weight (g/plant) | One-way ANOVA | $F$ = 228.31 | < 0.001 | Treatments differ significantly |
| | Tukey HSD | All pairwise comparisons significant | < 0.001 | T3 > T2 > T1 > Control |
| Fish final weight vs plant fresh weight | Pearson correlation | $r$ = 0.984 | < 0.001 | Very strong positive correlation |
| Biomass vs plant yield | Pearson correlation | $r$ = 0.984 | < 0.001 | Aquaponic nutrient reuse strongly improves plant yield |

The statistical analysis showed a highly significant effect of treatments on both fish performance and hydroponic plant productivity. As presented in Table 1, ANOVA results indicated strong differences among treatments ($p$ < 0.001), with Tukey HSD confirming that all treatments were significantly higher than the control. Treatment T3 consistently produced the highest final fish weight and plant fresh weight, followed by T2 and T1. Correlation tests further revealed an extremely strong positive association ($r$ = 0.984) between fish growth and plant biomass, supporting the functional linkage within the integrated aquaponic system.

**Discussion**. The present study demonstrates that integrating Nile tilapia (*Oreochromis niloticus*) aquaculture with hydroponic vegetable production in an aquaponic system substantially improves both fish productivity and plant performance relative to the conventional control treatment. The consistent improvements observed across growth, FCR, biomass yield, and plant fresh weight suggest that nutrient recycling between fish and plants establishes a more efficient ecological synergy. These findings align strongly with the foundational principles of aquaponics who emphasized the role of nutrient-rich effluent in enhancing plant growth while stabilizing aquatic conditions for fish (Nair et al., 2025; Bhattacharjee, 2025; Ibrahim et al., 2023).

***Fish growth performance***. Tilapia reared under integrated aquaponic treatments (T1 – T3) exhibited significantly higher final weights and SGR values than the control, indicating superior growth conditions. The T3 group — representing the highest aquaponic intensity — produced the greatest growth response, suggesting optimal nutrient exchange and water-flow compatibility. This finding is consistent with previous studies showing that tilapia benefit substantially from enhanced microbial nitrification processes, which improve water quality and reduce physiological stress (Eissa et al., 2015; Barbosa et al., 2022). Improved growth performance in tilapia cultured within recirculating aquaponic systems has also been attributed to reduced ammonia accumulation and more stable dissolved oxygen levels (Trang et al., 2017; Setiadi et al., 2018).

The increased productivity in T2 and T3 may also be linked to higher feed utilization efficiency reflected in lower FCR values. Comparable outcomes were reported by Wongkiew et al. (2017), who found that improved water filtration by plants lowers FCR by creating a more favourable metabolic environment for fish. The high positive correlation ($r \approx 0.98$) between fish growth and plant performance in the present study suggests that nutrient transformation efficiency directly benefits both trophic levels, reinforcing the concept of nutrient uptake synchrony between fish and plants (Setiadi et al., 2018; Khedr et al., 2022).

***Plant production performance***. Plant parameters — including height, leaf number, and fresh biomass — improved progressively from T1 to T3. This trend reflects increasing nutrient availability originating from higher fish metabolic output and efficient microbial conversion of ammonia to nitrate. The results echo those of previous research showing that nitrate-enriched aquaponic water can enhance leafy vegetable performance beyond what is achievable in conventional hydroponics using inorganic fertilizers (Sabwa et al., 2022). Additionally, evidence indicates that aquaponic nutrient solutions provide a wider micronutrient profile, supporting more robust plant physiological development (Azad et al., 2018).

The superior yield in T3 suggests an optimal nutrient concentration and balanced stocking density. In contrast, low nutrient availability (Control, T1) can restrict plant growth, while excessively high nutrient loads (not observed in this study) may cause nitrate imbalance or dissolved oxygen depletion. The absence of water-quality threshold violations in this experiment indicates that system performance remained within ideal operational parameters for coupled aquaponic designs (Nadia et al., 2023; Babatunde et al., 2022).

***Water quality dynamics***. Water quality remained stable across treatments, with temperature, dissolved oxygen, pH, and nitrogenous compounds consistently within acceptable ranges for both tilapia and hydroponic plants. Slight increases in ammonium and nitrite concentrations in T2 and T3 were expected due to higher fish biomass but remained below critical thresholds. These patterns are consistent with previous studies demonstrating that well-designed aquaponic systems maintain water quality through continuous microbial nitrification, enabling simultaneous optimization of fish and plant production (Barbosa et al., 2022; Saseendran et al., 2021).

The gradual rise in nitrate availability likely supported enhanced plant biomass, aligning with evidence that increased nitrate concentrations in fish effluent correlate positively with leafy vegetable growth (Lobanov et al., 2025; Wang et al., 2017). The stable pH range of 6.8 – 7.1 throughout the experiment is particularly significant, as both nitrification efficiency and plant nutrient uptake are highly sensitive to near-neutral pH conditions (Venisza et al., 2025; Aslanidou et al., 2024; Jose et al., 2025).

***Comparison with previous international studies***. The magnitude of improvement observed in this study particularly the 55 % increase in fish final weight from Control to T3 closely parallels the growth advantages reported in integrated systems, where tilapia productivity increased by 40 – 60 % under enhanced nutrient recycling (Trang & Brix, 2014). Likewise, the plant yield improvements (20 – 25 % higher fresh weight in T3 than in the Control) are consistent with studies demonstrating that aquaponic integration significantly elevates nutrient cycling efficiency and supports superior plant biomass accumulation (Teng et al., 2025; Tümová et al., 2025).

Moreover, the strong correlations between fish and plant performance indicate a tightly coupled ecological system, similar to what was described in previous work showing that balanced fish–plant ratios generate synergistic production gains beyond those achievable in standalone aquaculture or hydroponics (Teng et al., 2025; Mourantian et al., 2025). The findings of this study further reinforce the role of aquaponics as a sustainable food-production model, particularly relevant for resource-limited regions such as the hilly freshwater-stream environments of Padang City. The substantial improvements in water-use efficiency, reductions in FCR, and notable increases in plant yield demonstrate that integrated systems can provide a viable adaptation strategy for communities facing water scarcity or limited agricultural land. These outcomes align with global trends advocating circular water reuse and ecological intensification in aquaculture (Chairat et al., 2025; Duarte & Cerozi, 2024).

**Conclusions**. This study demonstrates that the integration of Nile tilapia (*Oreochromis niloticus*) culture with a hydroponic plant system in an aquaponic configuration significantly improves both fish productivity and water-use efficiency compared with the control (non-integrated system). The highest performance was consistently observed in Treatment 3 (T3), which produced the greatest final fish weight, biomass accumulation, specific growth rate, and plant fresh weight, supported by stable water-quality parameters throughout the experiment. These results confirm that increasing nutrient recirculation efficiency within the aquaponic system directly enhances overall production outputs. Therefore, the integrated aquaponic approach particularly the configuration represented by T3 offers the most effective model for supporting sustainable food production in hilly, fast-flowing aquaculture environments such as those in Padang City.

**Authors Contributions**. Conceptualization: IK, SA, ZI. Methodology: IK, SA, ID, HP. Formal Analysis: IK, SA, DS, ZI. Investigation: IK, SA, ID, HP, BI. Data Curation: IK, ID, HP. Writing – Original Draft: IK, SA. Writing – Review & Editing: SA, DS, ZI, DR. Supervision: ZI, DS.

**Conflict 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**. The publication of this article was supported by the 2025 Publication Assistance Program for Reputable Journals from the Ministry of Higher Education, Science and Technology of the Republic of Indonesia under Contract No. 805/UNUSB.D/PB/2025.

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Received: 12 December 2025. Accepted: 08 April 2026. Published online: 13 August 2026.
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How to cite this article:
Karina, I., Aisyah, S., Desmiati, I., Putrananda, H., Ikhlas, B., Rustam, D., Suhendra, D., & Ikhsan, Z. (2026). Productivity and water-use efficiency of integrated Nile tilapia (*Oreochromis niloticus*) aquaponic systems. *AACL Bioflux*, *19*(4), 1844-1854.