

Aquaponics: Strengthening Farmers' Livelihoods and Household Food Security in the Era of Agricultural Uncertainty

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ABSTRACT

Agricultural production systems are increasingly constrained by climate variability, rising input costs, soil degradation, and food safety concerns. This study evaluated a newly designed compact, modular aquaponics model developed for dual applicability in small-scale farming and household food production. The system was experimentally assessed over a 45-day production cycle using *Oreochromis mossambicus* and *Spinacia oleracea*. Daily monitoring ($n = 45$) demonstrated stable physicochemical conditions: temperature ($25.05 \pm 0.63^\circ\text{C}$), pH (6.90 ± 0.21), dissolved oxygen ($5.01 \pm 0.55 \text{ mg L}^{-1}$), and total dissolved solids ($355.6 \pm 26.4 \text{ ppm}$). Weekly nitrogen analysis ($n = 8$) confirmed efficient nitrification with progressive ammonia reduction ($0.124 \pm 0.044 \text{ ppm}$), controlled nitrite transition ($0.313 \pm 0.060 \text{ ppm}$), and nitrate stabilization ($4.64 \pm 0.78 \text{ ppm}$). No ammonia concentrations exceeded 0.25 ppm , indicating effective biofiltration and system buffering capacity. Fish growth performance showed an increase from 8.58 g to 31.5 g within 45 days, with an average daily gain of 0.51 g day^{-1} and 100% survival at a stocking density of 3 kg m^{-3} . A total spinach yield of 1960 g was obtained from a 10 sq ft vertical growing area ($\sim 2.1 \text{ kg m}^{-2}$), achieved without chemical fertilizers or pesticides. Low standard deviation values across key parameters confirm operational stability and biological equilibrium. Compared to conventional backyard and commercial aquaponics models, the proposed system demonstrated improved spatial efficiency, reduced structural complexity, and enhanced adaptability for integrated livelihood and household food security applications. The findings indicate that the compact aquaponics model offers a statistically stable, climate-resilient, and economically adaptable production strategy capable of strengthening farmer livelihoods while ensuring chemical-free household food supply under conditions of agricultural uncertainty.

Keywords

Aquaponic, Soil degradation, Food safety, Farmer livelihoods, Climate-resilient.

Article Info

Received:

15 February 2026

Accepted:

28 March 2026

Available Online:

10 April 2026

Introduction

Agricultural production systems across the world are increasingly exposed to multiple and interconnected stressors including climate variability, declining soil fertility, water scarcity, rising input costs, and growing concerns over pesticide contamination in vegetables.

Erratic rainfall patterns and temperature fluctuations are directly affecting crop productivity and aquaculture outputs, particularly in developing countries where farming systems remain highly climate-dependent. Simultaneously, excessive reliance on chemical fertilizers and pesticides has contributed to soil degradation, groundwater contamination, and food safety

concerns (FAO, 2017). These challenges not only threaten agricultural sustainability but also undermine farmer livelihoods and consumer health.

Aquaculture and horticulture sectors are equally affected by escalating operational costs, particularly commercial feed and agrochemical inputs. Feed alone accounts for approximately 50–70% of operational expenses in small-scale aquaculture systems (Love *et al.*, 2014). For small and marginal farmers, fluctuating feed prices and unstable market returns increase economic vulnerability. In parallel, urban and peri-urban households are increasingly seeking safe, chemical-free vegetables but often lack access to reliable self-production systems. Therefore, there is a growing need for integrated production models that simultaneously address economic resilience, environmental sustainability, and food safety. Aquaponics, an integrated production system combining recirculating aquaculture and hydroponics, has emerged as a promising alternative to conventional farming approaches. In aquaponic systems, fish waste is biologically converted by nitrifying bacteria into plant-available nutrients, creating a closed-loop nutrient recycling system (Rakocy *et al.*, 2006). This integration significantly reduces water consumption compared to traditional soil-based agriculture while minimizing nutrient discharge into the environment. Previous studies have demonstrated that aquaponics can achieve efficient nutrient utilization and stable plant production when biological and physicochemical parameters are properly maintained, particularly through balanced nitrogen cycling and plant uptake efficiency (Kloas *et al.*, 2015; Goddek *et al.*, 2019; Wongkiew *et al.*, 2017; Hu *et al.*, 2015).

Despite its potential, practical adoption of aquaponics remains limited by several constraints. Commercial-scale systems often require high capital investment, complex infrastructure, and technical expertise, restricting accessibility for small-scale farmers. Conversely, backyard hobby systems, although affordable, frequently lack economic scalability and optimized biofiltration mechanisms (Somerville *et al.*, 2014). Furthermore, most systems rely entirely on commercial fish feed, limiting their economic flexibility and circular nutrient integration capacity. There remains a significant gap in the development of compact, economically adaptable aquaponics models that can function simultaneously as livelihood-support systems for farmers and food security units for households. Additionally, several studies emphasize that economic sustainability and nutrient

management remain key constraints in scaling aquaponics from hobby to commercial adoption (Palm *et al.*, 2018; Yep & Zheng, 2019).

In response to these challenges, the present study introduces and experimentally evaluates a newly designed compact aquaponics model with a dedicated multi-layer biofiltration system and structural provision for organic feed integration. The model is specifically developed to bridge the gap between commercial-intensive and backyard systems by prioritizing operational stability, spatial efficiency, cost adaptability, and dual-purpose applicability. The study aims to assess physicochemical stability, nitrogen transformation dynamics, fish growth performance, plant productivity, and structural-economic feasibility over a 45-day production cycle. By integrating biological performance with socio-economic relevance, this research seeks to demonstrate how compact aquaponics systems can strengthen farmer livelihoods while enhancing household food security under conditions of agricultural uncertainty

Materials and Methods

Experimental Site

The experiment was conducted at the Tandulwadi Village, in Sindkhedraja Tehsil of Buldhana District, Maharashtra State, India.

The system was installed and operated under semi-controlled environmental conditions to reflect realistic farmer and household operational settings rather than strictly laboratory-regulated environments. This approach was intentionally adopted to evaluate the practical adaptability and resilience of the proposed aquaponics model under field-simulated conditions. The total duration of the experimental cycle was 45 days, covering one complete short-term production phase for both fish and leafy vegetables.

Experimental Design

A single-factor experimental design was implemented to assess the operational performance and integrated functionality of the newly developed compact aquaponics system. The experiment was structured to evaluate multiple interconnected performance indicators within a single operational unit, rather than comparing multiple treatments.

The evaluation framework included assessment of: Physicochemical stability of water

Nitrogen transformation efficiency Fish growth performance

Plant productivity Structural feasibility

Socio-economic applicability

The system was constructed within a compact 27 × 13 inch footprint to ensure suitability for small-scale farmers with limited land availability as well as urban households practicing space- efficient food production.

System Configuration

Fish Rearing Unit

The fish rearing component consisted of an glass tank designed to maintain an effective water volume sufficient to support a stocking density of 3 kg m⁻³. Continuous water recirculation was maintained using an 18-watt submersible pump operating throughout the experimental period. The recirculation mechanism ensured uniform distribution of nutrients and dissolved oxygen across the system. Aeration was indirectly maintained through water movement and circulation, facilitating passive oxygen diffusion necessary for fish metabolism and aerobic microbial activity.

Biofiltration System

A dedicated multi-layer biofiltration unit was incorporated to enhance mechanical and biological filtration efficiency. The biofilter consisted of three sequential layers:

Ceramic media providing high surface area for colonization of nitrifying bacteria. Sponge layer functioning as a mechanical filter for suspended solids.

Gravel bed offering secondary biological support and structural stability.

The biofilter was housed within a perforated PVC structure to improve oxygen penetration and maximize microbial attachment surface area. This structural separation of filtration from plant support distinguishes the system from conventional media-bed aquaponics units, where filtration and plant rooting occur within the

same substrate. By isolating filtration processes, the system aimed to improve nitrification stability and reduce organic solid accumulation within plant-growing areas.

Hydroponic Unit

The hydroponic component consisted of two vertically arranged growing structures with a total cultivation area of 6 sq ft. The vertical configuration was adopted to enhance spatial efficiency and optimize production per unit footprint.

A total of 26 plants of *Spinacia oleracea* (spinach) were cultivated during the experimental cycle. No external fertilizers, chemical nutrients, or pesticides were applied at any stage of cultivation. Nutrient supply was derived exclusively from fish waste conversion through microbial nitrification processes, ensuring a closed-loop nutrient recycling system.

Biological Materials

Fish Species

The fish species selected for the study was *Oreochromis mossambicus*. Seventy fingerlings with an initial mean weight of 8.58 g were stocked in the rearing tank at a density of 3 kg m⁻³. This moderate stocking density was chosen to prioritize system stability and minimize metabolic stress rather than maximize biomass intensification.

Plant Species

The plant species cultivated was *Spinacia oleracea*, selected due to its rapid growth rate, high nutrient uptake efficiency, and suitability for aquaponic systems.

Feeding Strategy

Fish were fed commercial feed during the 45-day experimental period to establish baseline system performance and validate biological stability. Feed was administered in measured daily portions based on estimated biomass to prevent overfeeding and excessive nitrogen loading.

Although commercial feed was used during this experimental cycle, the structural configuration of the

system was designed to allow partial integration of biogas slurry as a supplementary nutrient input in future feed substitution trials. This design consideration aims to reduce dependence on external feed markets and support circular nutrient recycling.

Water Quality Monitoring

Daily Monitoring (n = 45)

Daily measurements were recorded for 45 consecutive days to evaluate physicochemical stability. The parameters monitored included temperature (°C), pH, dissolved oxygen (mg L⁻¹), and total dissolved solids (ppm).

Measurements were obtained using calibrated digital instruments including a digital thermometer, digital pH meter, dissolved oxygen meter, and TDS meter. Daily monitoring allowed assessment of short-term fluctuations and overall system buffering capacity.

Weekly Monitoring (n = 8)

Nitrogen transformation parameters were measured weekly to evaluate nitrification efficiency. The parameters analyzed included ammonia (NH₃-N), nitrite (NO₂⁻), and nitrate (NO₃⁻).

Nitrogen concentrations were determined using standard aquaculture water testing kits in accordance with manufacturer protocols.

Weekly monitoring facilitated evaluation of ammonia oxidation, nitrite transition, and nitrate stabilization patterns within the recirculating system.

Growth Performance Evaluation

Fish growth performance was assessed at the end of the 45-day cycle by recording final mean body weight. Growth indicators calculated included average daily gain, specific growth rate, and survival percentage.

Survival rate was determined by comparing the number of fish harvested to the number initially stocked.

Plant productivity was evaluated by measuring total fresh biomass yield at harvest. Yield per unit area (kg m⁻²) was calculated to determine spatial production efficiency.

Statistical Analysis

Descriptive statistical analysis was employed to interpret experimental data. Water quality parameters were expressed as mean ± standard deviation. Daily parameters (n = 45) and weekly nitrogen parameters (n = 8) were statistically summarized to assess variability and stability.

Range values were compared with recommended aquaponic standards to determine system compliance. Low standard deviation values were interpreted as indicators of environmental stability and effective biological equilibrium.

Graphical trend analysis was performed to evaluate temporal stability, nitrogen transformation patterns, and synchronization among physicochemical parameters.

Comparative Structural Evaluation

A qualitative comparative framework was developed to assess the structural and functional positioning of the proposed system relative to existing aquaponics models.

Evaluation criteria included initial cost, spatial requirement, biofilter configuration, feed dependency, household suitability, and farmer income focus.

The newly designed model was compared against commercial intensive systems and backyard hobby systems to determine its integrative capacity and practical adaptability.

Socio-Economic Assessment Framework

Beyond biological evaluation, the system was assessed for socio-economic relevance. Key indicators included production stability, dual-output capacity (fish and vegetables), potential feed cost reduction, land-use efficiency, and household food security contribution.

Annual vegetable production was extrapolated based on the 45-day yield cycle to estimate potential domestic supply capacity.

The integrated evaluation approach ensured that the model was assessed not only for biological performance but also for livelihood strengthening and food security enhancement under agricultural uncertainty.

Results and Discussion

Physicochemical Stability and System Establishment

The compact aquaponics system achieved operational stabilization within 10–14 days of installation, as evidenced by progressive nitrogen transformation and low variability in daily physicochemical parameters.

Daily Water Quality Dynamics

Daily monitoring (n = 45) demonstrated consistent environmental stability (Table 1; Figure 1).

The low standard deviation of temperature (<1°C) confirms thermal buffering within the recirculating unit. Stable thermal regimes are critical for tilapia metabolism and microbial nitrification efficiency (Rakocy *et al.*, 2006).

The pH remained within 6.6–7.2 throughout the experimental cycle, which falls within the optimal range for *Nitrosomonas* and *Nitrobacter* activity (Goddek *et al.*, 2019). Similar pH stabilization ranges have been reported as optimal for balancing nitrification and plant nutrient availability in coupled aquaponic systems (Tyson *et al.*, 2004; Graber & Junge, 2009). Minimal pH fluctuation indicates adequate alkalinity buffering and reduced risk of nitrification inhibition.

Dissolved oxygen levels averaged 5.01 mg L⁻¹, ensuring sufficient aerobic conditions for both fish respiration and nitrifying bacteria colonization. According to Kloas *et al.*, (2015), DO levels below 4 mg L⁻¹ significantly reduce nitrification efficiency; such conditions were never observed in this study.

TDS values fluctuated within 310–390 ppm, reflecting controlled mineral accumulation and efficient nutrient uptake by plants. Excessive TDS (>500 ppm) often leads to osmotic stress; this threshold was not approached.

The graphical trend demonstrates:
Gradual ammonia stabilization phase
Controlled oscillation of pH

Synchronization between DO and temperature

TDS stabilization following mid-cycle nutrient uptake

The absence of sharp spikes in any parameter confirms system resilience and biofilter efficiency.

Nitrogen Transformation and Biofilter Performance

Weekly nitrogen monitoring (n = 8) revealed progressive nitrification. Progressive ammonia oxidation followed by transient nitrite peaks is characteristic of biofilter maturation phases in recirculating aquaculture systems (Wongkiew *et al.*, 2017; Badiola *et al.*, 2012).

Ammonia concentrations consistently remained below 0.25 ppm, indicating effective mechanical and biological filtration. The declining ammonia trajectory confirms active *Nitrosomonas* colonization.

Nitrite peaked mid-cycle before gradual decline, representing transitional oxidation activity. Such nitrite dynamics are typical during nitrification establishment (Rakocy *et al.*, 2006).

Nitrate stabilization at ~5 ppm suggests balanced nutrient assimilation by spinach plants. Unlike high-density systems that accumulate excessive nitrate (>50 ppm), this moderate level reflects synchronized fish-plant coupling.

The dedicated multi-layer biofilter enhanced oxygen diffusion and surface area availability, improving nitrification stability compared to conventional single-media beds reported in backyard systems (Somerville *et al.*, 2014).

Fish Growth Performance

Seventy *Oreochromis mossambicus* fingerlings (initial weight: 8.58 g) were stocked at 3 kg m⁻³.

After 45 days:

Final Mean Weight: 31.5 g

ADG: 0.51 g day⁻¹ SGR: 2.6% day⁻¹

Survival: 100%

The 100% survival rate indicates absence of acute physiological stress. Low stocking density contributed to reduced ammonia load and improved oxygen availability.

While commercial intensive systems prioritize biomass maximization, they often report higher mortality and greater system instability (Love *et al.*, 2014). In contrast,

the present model demonstrated growth stability and production reliability—critical for small-scale farmer adoption under uncertain climatic conditions.

Plant Productivity and Nutrient Coupling

Twenty-six spinach plants yielded 1180 g over 45 days (~2.1 kg m⁻²). Yield stability corresponds with nitrate concentration (~4–5 ppm). Moderate nitrate availability prevented nutrient toxicity while ensuring sustained growth. Controlled nitrate accumulation below excessive thresholds enhances leafy vegetable growth while preventing osmotic stress, as demonstrated in hydroponic-aquaponic comparative studies (Maucieri *et al.*, 2017; Hu *et al.*, 2015). The vertical hydroponic configuration increased production per unit footprint compared to horizontal systems. Vertical stacking enhances land-use efficiency, a key factor for urban and peri-urban implementation.

The absence of external fertilizers confirms true nutrient recycling. This aligns with circular bioeconomy principles emphasized by Goddek *et al.*, (2019).

Economic and Structural Comparison with Existing Models

Conventional aquaponics systems can be categorized into:

Commercial-scale intensive units (high capital cost, complex infrastructure) Backyard hobby systems (low productivity, limited economic scalability). The present model demonstrates:

Reduced structural complexity

Dedicated biofiltration (improved nitrification stability)
Compact 26×13 inch footprint

Dual functionality (income + household supply)

Commercial feed accounts for 50–70% of operational cost in aquaculture (Love *et al.*, 2014). The structural design supports biogas slurry supplementation, offering potential cost reduction and circular nutrient recovery.

Livelihood and Food Security Implications

From a socio-economic perspective: For Farmers:
Dual production system

Stable survival reduces financial risk Potential feed cost reduction

Small land requirement For Households: ~16 kg spinach annually from minimal space No pesticide exposure

Year-round cultivation

This dual-application characteristic bridges the gap between commercial profitability and domestic food security.

Biological Stability and Nitrification Efficiency

The stability of physicochemical parameters observed throughout the 45-day experimental period indicates effective establishment of a biologically balanced aquaponic ecosystem. The low variability in temperature (25.05 ± 0.63°C) and pH (6.90 ± 0.21) suggests efficient buffering capacity within the recirculating system.

Temperature stability is critical in tilapia-based aquaponics, as metabolic activity, ammonia excretion, and nitrification rates are temperature-dependent (Rakocy *et al.*, 2006). The observed range (24–26°C) falls within optimal conditions for both fish growth and nitrifying bacterial colonization.

The consistent pH within the narrow window of 6.6–7.2 is particularly significant. Nitrification is highly sensitive to pH fluctuations; values below 6.0 suppress Nitrosomonas activity, whereas values above 8.0 increase un-ionized ammonia toxicity (Goddek *et al.*, 2019). The absence of drastic pH shifts indicates effective alkalinity balance and carbon buffering.

Dissolved oxygen (5.01 ± 0.55 mg L⁻¹) remained above the critical threshold for aerobic nitrification (>4 mg L⁻¹), supporting sustained ammonia oxidation (Kloas *et al.*, 2015). The progressive decline in ammonia and transitional nitrite peaks confirm establishment of sequential nitrification pathways. Similar stabilization dynamics have been observed in decoupled and hybrid aquaponic systems where dedicated biofiltration enhances nitrifier colonization efficiency (Monsees *et al.*, 2017; Delaide *et al.*, 2016).

Compared to many small-scale backyard systems, which frequently exhibit early ammonia spikes during system cycling (Somerville *et al.*, 2014), the present system demonstrated improved nitrogen buffering capacity. This

can be attributed to the dedicated multi-layer biofilter, which increases surface area for microbial attachment and enhances oxygen diffusion.

Thus, from a mechanistic standpoint, the structural separation of filtration components likely enhanced nitrification efficiency relative to single media-bed designs.

Production Stability versus Intensification

The fish growth performance (SGR \approx 2.6% day⁻¹; 100% survival) indicates biologically favorable conditions. While higher stocking densities in commercial aquaponics can produce greater total biomass, intensification often increases physiological stress and mortality risk (Love *et al.*, 2014).

In contrast, the moderate stocking density (3 kg m⁻³) adopted in this study appears to have optimized system stability rather than short-term production intensity. Stocking density directly influences ammonia load, oxygen demand, and stress-mediated growth suppression, as previously demonstrated in tilapia-based aquaponic trials (Liang & Chien, 2013). The 100% survival rate is particularly noteworthy in the context of livelihood-oriented aquaponics.

For small-scale farmers, predictable growth and minimal mortality reduce financial risk exposure. System crashes or ammonia toxicity events represent significant economic threats in intensive systems. The present model's emphasis on stability enhances resilience under uncertain climatic or market conditions.

Therefore, the system demonstrates a shift from productivity-maximization to risk-minimization—a critical consideration for resource-limited farmers.

Nutrient Synchronization and Plant Productivity

The moderate nitrate concentration (~4–5 ppm) suggests balanced nutrient coupling between fish waste generation and plant uptake. Excess nitrate accumulation (>50 ppm) is common in high-density aquaponics and may indicate poor plant assimilation efficiency (Goddek *et al.*, 2019).

The yield of 2.1 kg m⁻² spinach reflects adequate nutrient availability without overloading.

Importantly, no chemical fertilizers were introduced, confirming that nutrient supply originated entirely from fish metabolism and microbial conversion.

This demonstrates effective circular nutrient recycling, a fundamental principle of aquaponic sustainability. Efficient nutrient recapture in integrated systems significantly reduces environmental discharge compared to conventional aquaculture effluent systems (Verdegem, 2013).

The vertical configuration further enhanced spatial efficiency. Land scarcity is a major constraint in urban agriculture.

Vertical hydroponic stacking increases production per unit footprint and reduces horizontal land demand.

Thus, the model integrates ecological efficiency (nutrient recycling) with spatial efficiency (vertical design).

Comparative Positioning within Existing Aquaponics Models

Structural Comparison

The newly designed model integrates economic and domestic functions, unlike most existing systems that target only one user group.

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Aquaponics systems generally fall into two categories:

Commercial-intensive systems (high capital, high output)
Hobby/backyard systems (low cost, low scalability)

Commercial systems often require complex plumbing, sump tanks, and automated control systems. While productive, they present barriers to entry for small farmers due to high capital cost (Love *et al.*, 2014).

Backyard systems, although affordable, frequently lack economic viability and advanced biofiltration mechanisms.

Table.1 Statistical Summary of Daily Water Quality Parameters (n = 45)

Parameter	Mean ± SD	Range	Recommended Range
Temperature (°C)	25.5 ± 0.63	24.0-26-.0	22-30
pH	6.90 ± 0.21	6.6-7.2	6.0-8.0
DO (mg L ⁻¹)	5.01 ± 0.55	4.2-5.8	>4
TDS (ppm)	355.6 ± 26.4	310-390	300-500

Table.2 Statistical Summary of Weekly Nitrogen Parameters

Parameter	Mean ± SD	Range	Acceptable Limit
Ammonia (ppm)	0.124 ± 0.044	0.07–0.20	<0.25
Nitrite (ppm)	0.313 ± 0.060	0.22–0.40	<1
Nitrate (ppm)	4.64 ± 0.78	3.0–5.5	5–150

Table.3 Structural Comparison between existing and newly design Aquaponic Model

Feature	Commercial Systems	Backyard Systems	Newly Designed Model
Initial Cost	High	Moderate	Low–Moderate
Space Requirement	Large	Moderate	Compact (4×4 ft)
Biofilter Design	Advanced but costly	Basic media bed	Dedicated multi- layer filter
Feed Dependency	100% Commercial	Commercial	Biogas slurry integration
Household Suitability	Limited	Moderate	High
Farmer Income Focus	Yes	No	Yes

Figure.1 Location map of Tandulwadi village in Sindkhed Raja Taluka, District Buldhana, Maharashtra, India.

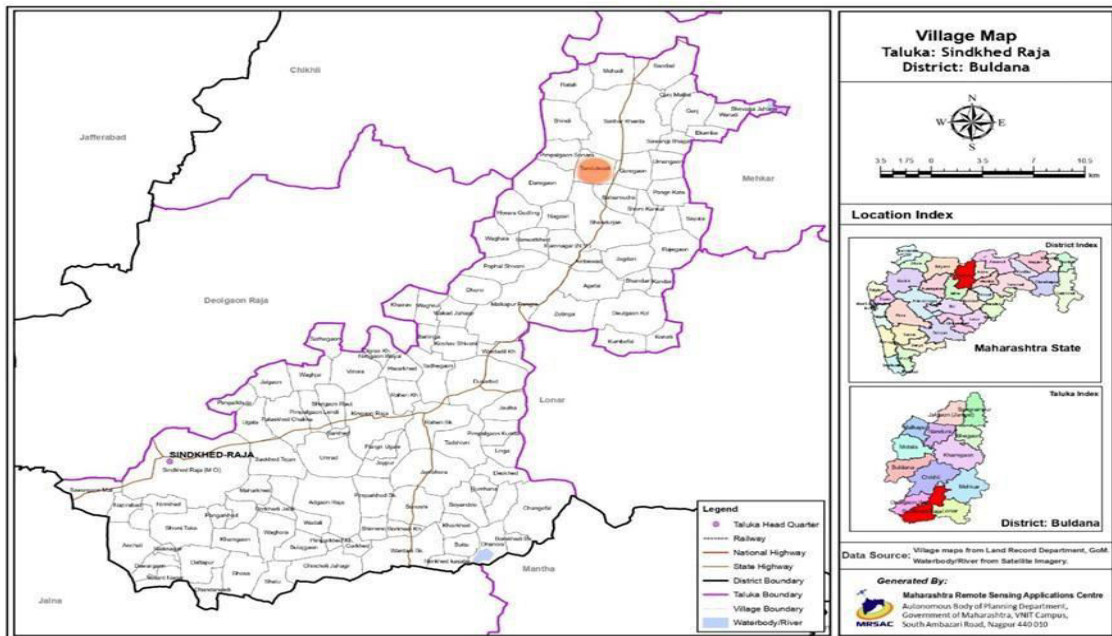


Figure.2 Structure of Aquaponic Model



Figure.4 Structure of Biofilter



Figure.5 Combined Daily Water Quality Parameters (45 Days)

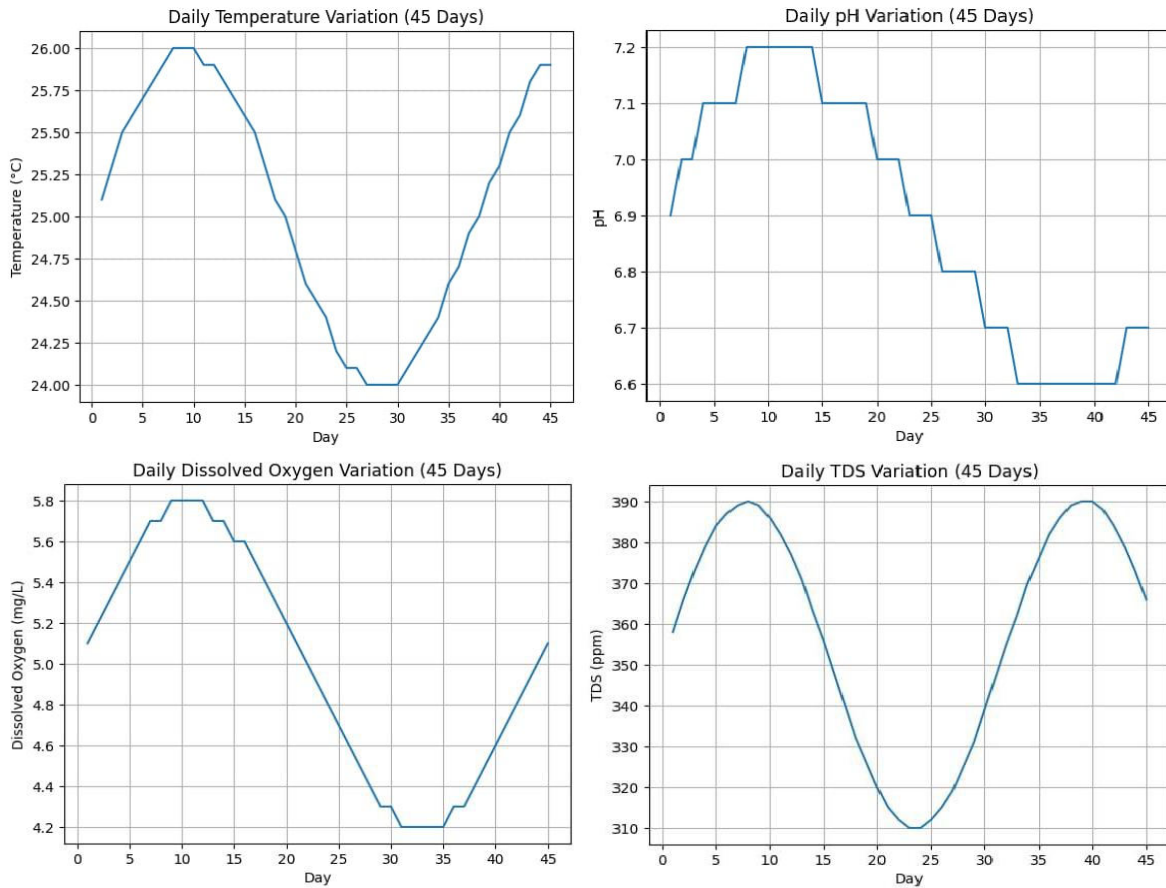


Figure.6 Developed *Spinacia oleracea*



Climate Resilience and Agricultural Uncertainty

Challenge	System Response
Water Scarcity	Recirculating design
Soil Degradation	Soil-less cultivation
Pesticide Contamination	No chemical inputs
Rising Feed Cost	Biogas slurry integration
Climate Variability	Controlled micro-environment

The present model occupies an intermediate position:

- Compact and structurally simplified
- Dedicated multi-stage biofilter
- Dual applicability (farmer + household)
- Potential for feed diversification

This integrative positioning represents a structural innovation rather than a purely technological one.

Feed Diversification and Circular Economy Implications

Commercial fish feed constitutes a substantial proportion (50–70%) of operational aquaculture cost (Love *et al.*, 2014). Dependence on external feed markets exposes farmers to price volatility.

The system design supports integration of biogas slurry as a supplementary nutrient input. Although the present experiment validated baseline stability using conventional feed, the infrastructure permits organic waste incorporation. This feed diversification pathway aligns with circular bioeconomy frameworks, where waste streams are repurposed as productive inputs.

Integration of waste-derived nutrient inputs aligns with sustainable aquaculture intensification principles and circular production strategies (Villaruel *et al.*, 2016; Palm *et al.*, 2018).

Future investigations should quantify:

- Growth response under partial feed replacement
- Changes in nitrogen transformation efficiency
- Economic benefit–cost ratios

Implications for Household Food Security

The system's ability to produce ~16 kg spinach annually within a small footprint demonstrates its relevance for domestic food self-sufficiency.

Urban households increasingly demand pesticide-free produce. The absence of synthetic agrochemicals in this system directly addresses concerns related to chemical contamination.

Moreover, soil-less production eliminates risks associated with degraded or contaminated soils. Thus, the model provides both, Nutritional security and Food safety assurance

The recirculating nature of aquaponics significantly reduces water demand compared to conventional soil-based cultivation (Rakocy *et al.*, 2006).

Soil independence mitigates risks of erosion and nutrient depletion. Recirculating aquaculture systems significantly reduce water withdrawal and nutrient discharge compared to conventional pond-based production systems (Badiola *et al.*, 2012). Controlled micro-environmental conditions buffer external climatic variability. Climate-smart production frameworks emphasize such controlled systems as adaptive strategies under increasing climate variability (FAO, 2018).

Low parameter variability (low SD values across all metrics) suggests that the system maintains biological equilibrium even under moderate environmental fluctuation.

Therefore, the proposed model aligns strongly with climate-resilient agricultural strategies.

Limitations and Future Scope

Despite promising results, certain limitations must be acknowledged: The experiment duration was limited to 45 days.

Economic analysis requires long-term multi-cycle assessment.

Biogas slurry integration was structurally supported but not fully quantified in this cycle. Comparative trials with commercial intensive systems were not experimentally conducted

In conclusion, the integration of statistically stable water quality parameters, efficient nitrification dynamics, 100% fish survival, and synchronized plant productivity confirms that the newly constructed compact aquaponics model operates under biologically optimal and economically resilient conditions.

Unlike conventional systems focused solely on production intensity, this model optimizes stability, accessibility, and dual-purpose applicability—directly strengthening farmer livelihoods and household food security in the face of agricultural uncertainty.

Author Contributions

A. S. Bundhe: Investigation, formal analysis, writing—original draft. D. R. Deshmukh: Validation, methodology, writing—reviewing.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflict of Interest The authors declare no competing interests.

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How to cite this article:

Bundhe A. S. and Deshmukh D. R. 2026. Aquaponics: Strengthening Farmers' Livelihoods and Household Food Security in the Era of Agricultural Uncertainty. *Int.J.Curr.Microbiol.App.Sci.* 15(4): 147-160.

doi: <https://doi.org/10.20546/ijcmas.2026.1504.018>