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Aquaponic cultivation of pearl millet (*Pennisetum glaucum* L.), finger millet (*Eleusine coracana* L.), and quinoa (*Chenopodium quinoa* L.) for sustainable food and fodder production

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This study investigated the potential of aquaponics, a sustainable food production method that integrates aquaculture and hydroponics, for cultivating pearl millet, finger millet, and quinoa irrigated with effluent from a tilapia aquaculture unit. Conducted over a six-month period, the experiment utilized a pilot-scale backyard aquaponics system, with tilapia metabolic waste serving as the primary nutrient source. Plant growth performance, yield, and the proximate and mineral composition of grains and leaves were assessed over the experimental period. The system maintained water quality parameters within optimal ranges for both tilapia culture and plant growth throughout the six-month experimental period. Tilapia exhibited a high survival rate (86–88%) accompanied by substantial growth, reaching a final mean weight of approximately 350 g. Among the crops evaluated, quinoa and pearl millet produced the highest grain yields (1,218 g and 1,185 g, respectively). Nutritional analysis indicated that grains from all crops possessed favourable nutritional profiles, with quinoa exhibiting higher protein content and pearl millet showing elevated antioxidant levels. The research study highlights the aquaponics potential to enhance both fish production and grain production with nutritional quality, thereby contributing to sustainable food and agriculture production practices through efficient nutrient utilization.

KEYWORDS

aquaponics, fish, millet production, nutrients, sustainable food, water quality

1 Introduction

Aquaponics is a sustainable, soilless food production system that integrates hydroponics with a recirculating aquaculture system (RAS), enabling the efficient reuse of water and nutrients (König et al., 2018; Kagali et al., 2025). In this bio-integrated system, nutrients derived from fish waste are converted through nitrification into plant-available forms, primarily nitrate, by nitrifying bacteria in the biofilter. This process supports plant growth while simultaneously improving water quality for fish (Madigan et al., 2003; Gold, 1999). This nutrient cycling,

particularly the nitrogen (N) cycle, is fundamental to aquaponics and underpins its resource efficiency and environmental sustainability (Palm et al., 2018). With increasing global population pressure on arable land and freshwater resources, aquaponics has emerged as a viable approach to enhance food and fuel production while minimizing environmental impacts (Fedoroff et al., 2010; FAO, 2018). The integration of fish and crop cultivation can also improve system profitability by creating a self-sustaining micro-ecosystem driven by natural biological interactions and microorganisms (König et al., 2016; Timmons et al., 2002; Kasozi et al., 2021; Nair et al., 2025). Fish waste acts as a natural fertilizer for plants, while plants contribute to water purification, reducing aquaculture effluents and promoting sustainable food production (Kagali et al., 2025).

A wide range of fish species, including rainbow trout (Adler et al., 2000), Nile tilapia (Radhakrishnan, 2020; Subramanian et al., 2025), barramundi (Shete et al., 2015), carp (Filep et al., 2016), and African catfish (Baßmann et al., 2018), have been successfully cultured in aquaponic systems. Similarly, various crops such as lettuce (*Lactuca sativa*), basil (*Ocimum basilicum*), tomato (*Solanum lycopersicum*), and cucumber (*Cucumis sativus*) have demonstrated strong adaptability to aquaponic conditions (Pantarella et al., 2012; Filep et al., 2016; Radhakrishnan and Belal, 2022; Nishanth et al., 2025). Due to its environmental benefits, efficient resource use, and capacity for local production of nutritious fish and leafy greens, aquaponics has gained considerable popularity over the past three decades (Greenfeld et al., 2018). Species selection remains important for system optimization; tilapia are particularly well suited due to their rapid growth, disease resistance, and tolerance to intensive culture conditions (Effendi et al., 2017). Likewise, leafy greens are highly compatible with aquaponics, with green leaf lettuce being especially valued for its fast growth, high biomass production, and multiple harvest potential (Buzby and Lin, 2014; Rakocy et al., 2006). Aquaponics enables the production of fresh vegetables and herbs with flexible deployment in urban environments such as rooftops and parking areas (Lennard and Leonard, 2006). The system is highly resource-efficient, using up to 90% less water and fewer nutrients than conventional aquaculture, while reducing land requirements by utilizing aquaculture wastewater for plant growth (Nishanth et al., 2024; Graber and Junge, 2009). Such integrated, soil-less production approaches are increasingly recognized as viable solutions for enhancing food security and resource efficiency in arid and semi-arid regions (Nair et al., 2024). By integrating fish and plant production through continuous nutrient circulation, aquaponics aligns with sustainable aquaculture principles and efficient resource use (Gold, 1999). Nitrogen cycling is central to system function, with fish-excreted ammonia converted into plant-available nitrates by nitrifying bacteria, thereby supporting plant growth and maintaining water quality (Madigan et al., 2003). This biologically integrated approach addresses increasing food and fuel demands, reduces environmental impacts, and enhances profitability by combining fish and vegetable production within a single system (Fedoroff et al., 2010; FAO, 2018; Timmons et al., 2002). The synergistic interactions among fish, plants, and microorganisms create a sustainable micro-ecosystem in which water is filtered, oxygenated, and detoxified before being recirculated to the fish culture unit (König et al., 2016; Salam et al., 2013).

Rapid urban population growth driven by rural–urban migration, natural population increase, and expanding economic opportunities has placed increasing pressure on urban infrastructure, housing, and food supply systems (UN, 2018). At the same

time, reliance on rural food production and long-distance transport to urban centers has been identified as a major contributor to greenhouse gas emissions, biodiversity loss, water pollution, and land-use degradation (Santos, 2016; Goldstein et al., 2016). Consequently, urban and peri-urban food production systems have been proposed as sustainable strategies to enhance food security while reducing environmental impacts (Armanda et al., 2019).

Aquaponics represents a promising approach within this context, offering a resource-efficient system capable of producing nutrient-rich crops alongside fish. It provides a sustainable solution for cultivating drought-tolerant millets such as pearl millet and finger millet, which are vital for food security in arid regions but have experienced declining productivity due to reduced attention (Manikaran and Nidhi, 2022; Manoharan et al., 2026). Millets are nutritionally superior or comparable to major cereals, with high protein content, substantial dietary fibre, gluten-free and hypoallergenic properties, and rich profiles of essential amino acids (Kumar et al., 2018; Serna Saldivar and Hernández, 2020; Hassan et al., 2021; Sachdev et al., 2023).

Pearl millet (*Pennisetum glaucum* L) is valued for its rapid growth, low input requirements, low glycaemic index, and health benefits related to diabetes and obesity, while retaining its alkaline nature after cooking (Baby et al., 2023). Finger millet (*Eleusine coracana*), widely adapted to dry regions, is notable for its high calcium, iron, fibre, phytochemical, and mineral content (Dhanushkodi et al., 2023). Quinoa (*Chenopodium quinoa* L), a drought-resilient pseudocereal native to the Andes, has demonstrated strong adaptability and high seed quality across diverse agro-climatic conditions (Mujica et al., 2001). Its grains are distinguished by high protein content and a balanced composition of essential amino acids, making it a valuable crop for sustainable food systems (Murphy and Matanguihan, 2012; Adolf et al., 2012; FAO and CIRAD, 2015). This study evaluated the feasibility and efficiency of cultivating pearl millet, finger millet, and quinoa in a backyard aquaponics system integrated with tilapia by analyzing system productivity, water quality dynamics, and the nutritional quality of the fish and grains produced.

2 Materials and methods

2.1 System description

A pilot-scale recirculating aquaponics system (RAS) was specifically designed and constructed for this study following standard aquaponic system principles. The system consisted of a single fish rearing tank, a combined biofilter and waste sedimentation tank, three hydroponic plant culture troughs, and a water collection sump equipped with an electric pump (Aquablue DC-7000, Guangzhou Aquablue Aquarium Technology Co., Ltd., China) to recirculate water back to the fish rearing tank. K1 biofilter media were used to support the growth and activity of nitrifying bacteria within the biofilter unit. All system components were continuously aerated using an electric air compressor (Sweetwater-SL56H, Aquatic Eco-Systems INC, Apopka, Florida, USA), and water circulation occurred through gravity-driven flow from the upper to the lower units. The system configuration is illustrated in Figure 1, and the specific water volumes of each component are presented in Table 1.

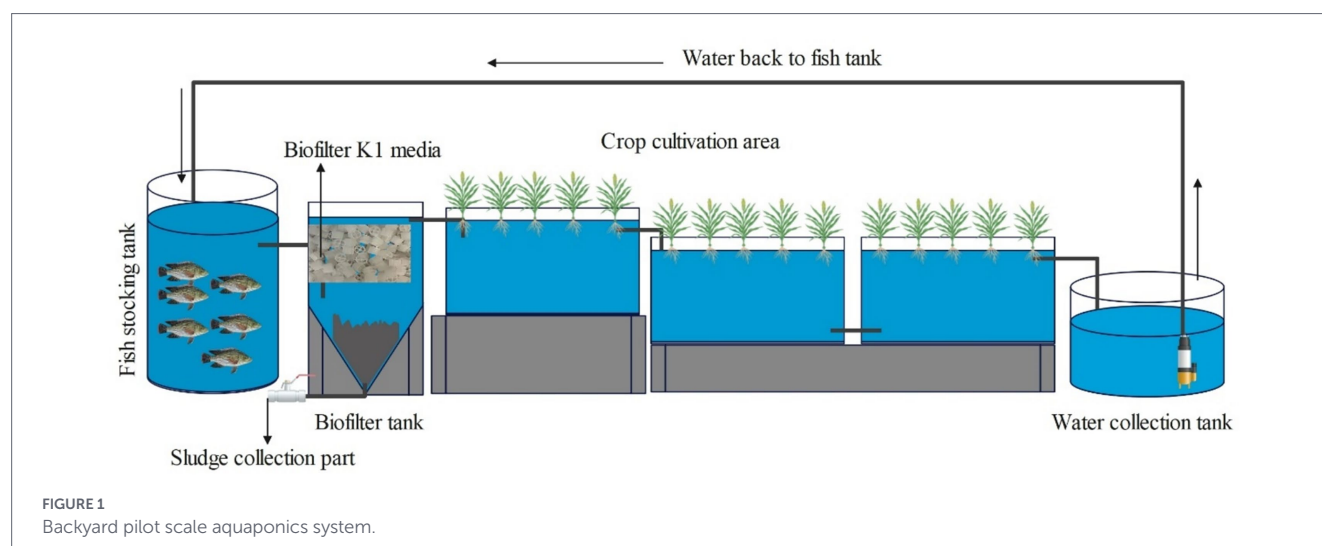


TABLE 1 Experimental system dimensions (m) and water volume (gal) capacity.

Part of the system	Height	Length/width	Filling depth	Water volume	No of the tanks	Total water volume
Fish stocking tank	1	0.55	0.85	53.35	2	106.7
Bio filter tank	1	0.55	0.85	53.35	2	106.7
Plant culture raceway	0.25	0.9	0.2	10.01	3	30.03
Collect and pumping tank	0.5	0.9	0.3	29.25	2	58.5
Total						301.93

2.2 Procurement and acclimatization of the experimental fish

Nile tilapia (*Oreochromis niloticus*) used in the experiment were obtained from the Aquaculture Research Station, Falaj Hazza, UAE University, Al Ain. Fish of uniform size were directly stocked into the experimental systems for acclimatization. The experiment was conducted in triplicate, with three independent pilot-scale aquaponics systems per treatment, resulting in a total of nine systems (3 × 3). Each system was stocked with 20 fish, giving a total of 180 fish, with an average initial weight of 33.44 g. Fish were fed ad libitum twice daily with a commercial diet (3 mm floating feed) containing 36% crude protein, 4% fat, 4% fiber and the feed is fortified with vitamins, amino-acids, antioxidants and minerals (ARASCO Feeds Corporation, Saudi Arabia). After a one-week acclimatization period, the millet cultivation experiment was initiated. Sludge management during the experimental period involved daily removal of floating solids using a cloth net, while settled sludge was periodically collected through the sludge outlet pipe.

2.3 Plant growth setup

Millet and quinoa seeds were procured from a certified local agricultural market in Al Ain. The seeds were soaked in fresh water overnight to enhance germination, then air-dried and directly placed into neutralized (with water) rockwool cubes moistened with fresh water. The seeded rockwool trays were kept in a dark room to initiate

germination. Following emergence, the trays were transferred to a controlled day–night environment until seedlings reached the two-leaf stage, which occurred within 7–10 days. Subsequently, individual seedling cubes were separated and placed into 2-inch-diameter plastic cups, which were inserted into holes in floating polystyrene (styrofoam) sheets within the aquaponics system. Plants were spaced at 30 cm intervals. The plant culture raceway was continuously aerated using an air compressor system. Additionally, yellow sticky traps were strategically positioned around the plant cultivation area to monitor and control flying insect pests.

2.4 Fish and plant growth parameters

2.4.1 Fish growth parameters

The experiment was conducted over a six-month period with replicates. At the conclusion of the experiment, key growth performance parameters of tilapia were evaluated, including survival rate, weight gain (WG), specific growth rate (SGR), feed intake (FI), and feed conversion ratio (FCR). These parameters were calculated using the following equations:

$$\text{Survival rate (\%)} = \frac{\text{No of live fish (Final)}}{\text{Initial No of fish}} \times 100$$

$$\text{Weight gain (g)} = \text{Final weight (g)} - \text{Initial weight (g)}$$

$$\text{Specific growth rate (\%)} = \frac{\log \text{ of final weight (g)} - \log \text{ of initial weight (g)}}{\text{No of days}} \times 100$$

$$\text{Feed conversion rate} = \frac{\text{Feed intake (g)}}{\text{Weight gain (g)}}$$

2.4.2 Plant growth parameters

Throughout the experimental period, plant growth parameters, including total plant height, shoot length, and root length, were measured (1 m stainless steel ruler) and recorded in monthly twice. Crop performance was evaluated by assessing plant survival percentage and grain yield per plant. The $\text{FCR}^{\text{plant}}$ was calculated as following formula;

$$\text{FCR plant} = (\text{Total feed input}) / (\text{Total plant weight gain})$$

2.5 Water quality parameters

Aquaponics water quality parameters, including ammonia, nitrate, and nitrite concentrations, were analyzed following standard methods (APHA, 1998) using a HACH DR900 multiparameter colorimeter (HACH Company, Loveland, CO, USA). Total ammonia nitrogen (TAN) was determined using the Ammonia Nitrogen Salicylate TNT method, nitrate was measured by the cadmium reduction method, and nitrite was analyzed using the diazotization method. Water pH, temperature, and electrical conductivity were measured using a portable HACH HQd meter (Model HQ40d; HACH Company, Loveland, CO, USA). Dissolved oxygen concentration was determined using an Orion Star™/Star Plus dissolved oxygen meter (Thermo Scientific, USA).

2.6 Proximate composition analysis

The proximate composition of fish carcass and plant samples, including moisture, crude protein, crude fat, crude ash, crude fiber, and total carbohydrate contents, was determined using standard procedures outlined by the Association of Official Analytical Chemists (AOAC, 2005). Moisture content was determined using the oven-drying method, while ash content was calculated as the ratio of post-ashing weight to the original sample mass. Ash and moisture content determined by the following formula;

$$\text{Moisture (\%)} = \frac{(\text{Wet weight} - \text{Dry weight})}{\text{Wet weight}} \times 100$$

$$\text{Ash (\%)} = \frac{\text{Weight of Ash (g)}}{\text{Weight of sample taken (g)}} \times 100$$

Crude protein content was determined using the Kjeldahl method. Crude fat was analyzed using the Soxhlet extraction method with petroleum ether as the solvent, while crude fiber was determined by acid digestion. Crude fiber percentage was calculated as the difference between the dried residue weight and ash

weight after calcination, expressed relative to the original sample weight. Carbohydrate content was estimated by using the formula: % of carbohydrates = 100 – (% moisture + % protein + % fat + % crude ash + % crude fiber) (Suwannatrai et al., 2023; Subramanian et al., 2025). Mineral composition of experimental water, plant leaves, and grain samples was analyzed following APHA (2005) methods using an inductively coupled plasma optical emission spectrometer (ICP-OES; Model 710-ES, Varian, USA) at the College of Agriculture and Veterinary Medicine, United Arab Emirates University.

2.7 Application of supplementation in aquaponics system

In the present study, chelated iron and agricultural limestone were supplemented to maintain optimal water quality and support fish and plant health. Chelated iron was applied as Ferro Active – Iron Chelate 6% EDDHSA (Deretil Agronutritional, Spain) at a rate of 2 g/m² of the cultivation area. Agricultural limestone powder, sourced from Noora Suppliers, Al Ain, United Arab Emirates, through Al Busat Al Akhdar Agricultural Services Co. LLC, was used to regulate system alkalinity and pH. Limestone supplementation was carried out by placing 100 g of powdered limestone in a cloth bag suspended within each experimental water collection tank. After completion of the leaching process, the bag was replaced with a freshly filled one to ensure continuous buffering and stabilization of water quality parameters.

2.8 Statistical analysis

All data were subjected to one-way ANOVA to determine significant ($p < 0.05$) differences among the treatment means $\pm$ SD. DMRT tests were used to distinguish significant differences among treatment means and statistical done with SPSS software (IBM SPSS Statistics, 29.0.0.0).

3 Results

3.1 Water quality parameters of the aquaponics system

Water quality parameters in the aquaponics systems remained within acceptable ranges throughout the six-month experimental period, while exhibiting significant temporal changes indicative of system maturation (Table 2). Water temperature and dissolved oxygen (DO) did not differ significantly ($p > 0.05$) among months within each crop system. In contrast, pH values showed significant ($p < 0.05$) differences over time, with higher values recorded during the initial months and lower values observed in later months across all crop treatments. Total dissolved solids (TDS) and electrical conductivity (EC) increased significantly ($p < 0.05$) over the experimental period in all systems. Early-month values were statistically lower, while significantly higher values were recorded in during the months of five and six.

Ammonia concentrations differed significantly ($p < 0.05$) among months in all crop systems, with lower values observed during the initial months and significantly higher values recorded during the later

TABLE 2 Monthly average water quality parameters of aquaponics effluent in aquaponic systems.

Crops	Months	Temperature (°C)	DO (mg/l)	pH	TDS (ppm)	EC (mS/cm)	Ammonia (mg/l)	Nitrate (mg/l)	Nitrite (mg/l)	Fe (mg/l)
Pearl millet	1	21.71 ± 0.20 ^a	4.88 ± 0.21 ^a	7.29 ± 0.86 ^a	180.00 ± 14.61 ^{de}	0.12 ± 0.05 ^c	0.16 ± 0.08 ^c	7.34 ± 2.03 ^f	0.13 ± 0.02 ^c	0.12 ± 0.03 ^c
	2	21.30 ± 0.59 ^a	4.90 ± 0.14 ^a	6.89 ± 0.56 ^{ab}	231.63 ± 2.30 ^{cd}	0.19 ± 0.07 ^d	0.17 ± 0.02 ^c	11.46 ± 5.83 ^c	0.18 ± 0.04 ^{de}	0.14 ± 0.03 ^d
	3	21.30 ± 0.59 ^a	4.90 ± 0.14 ^a	6.89 ± 0.56 ^{ab}	314.28 ± 26.83 ^{bcd}	0.24 ± 0.21 ^d	0.17 ± 0.02 ^c	11.46 ± 5.83 ^{cd}	0.23 ± 0.03 ^{cd}	0.14 ± 0.03 ^d
	4	21.40 ± 0.49 ^a	4.67 ± 0.38 ^a	6.59 ± 0.16 ^{bc}	375.63 ± 21.21 ^{bc}	0.35 ± 0.04 ^{cd}	0.18 ± 0.01 ^c	17.08 ± 0.10 ^{bc}	0.22 ± 0.01 ^{cd}	0.20 ± 0.02 ^{de}
	5	22.14 ± 0.49 ^a	5.03 ± 0.07 ^a	6.51 ± 0.07 ^{cd}	422.56 ± 39.16 ^{ab}	0.51 ± 0.23 ^{ab}	0.67 ± 0.14 ^{ab}	21.48 ± 1.30 ^a	0.24 ± 0.02 ^{bc}	0.55 ± 0.06 ^{bc}
	6	21.75 ± 0.06 ^a	5.01 ± 0.10 ^a	6.58 ± 0.17 ^{cd}	502.75 ± 17.15 ^a	0.81 ± 0.33 ^a	0.83 ± 0.06 ^a	18.79 ± 2.51 ^b	0.24 ± 0.05 ^{bc}	0.61 ± 0.14 ^{ab}
Finger millet	1	21.51 ± 0.28 ^a	4.83 ± 0.21 ^a	7.19 ± 0.14 ^a	146.67 ± 23.57 ^c	0.11 ± 0.04 ^c	0.15 ± 0.01 ^c	7.19 ± 0.21 ^f	0.15 ± 0.01 ^c	0.12 ± 0.01 ^c
	2	21.62 ± 0.46 ^a	4.89 ± 0.14 ^a	6.69 ± 0.27 ^b	231.63 ± 0.00 ^{cd}	0.19 ± 0.08 ^d	0.15 ± 0.03 ^c	11.52 ± 0.08 ^{de}	0.18 ± 0.01 ^{de}	0.14 ± 0.03 ^c
	3	22.12 ± 0.58 ^a	4.71 ± 0.25 ^a	6.60 ± 0.21 ^{bc}	330.43 ± 11.42 ^{bcd}	0.28 ± 0.13 ^{de}	0.17 ± 0.02 ^c	16.12 ± 3.30 ^{bc}	0.21 ± 0.02 ^{bc}	0.22 ± 0.06 ^{de}
	4	21.30 ± 0.29 ^a	5.10 ± 0.11 ^a	6.40 ± 0.05 ^{bcd}	398.21 ± 15.97 ^{bc}	0.38 ± 0.17 ^{cd}	0.17 ± 0.01 ^c	18.16 ± 0.81 ^{ab}	0.21 ± 0.02 ^{ab}	0.36 ± 0.10 ^{cd}
	5	21.91 ± 0.16 ^a	5.06 ± 0.02 ^a	6.48 ± 0.02 ^{bcd}	424.10 ± 1.09 ^{ab}	0.48 ± 0.08 ^{ab}	0.62 ± 0.07 ^{ab}	20.87 ± 0.43 ^a	0.21 ± 0.02 ^{ab}	0.52 ± 0.02 ^{bc}
	6	21.60 ± 0.21 ^a	4.91 ± 0.15 ^a	6.56 ± 0.13 ^{cde}	507.75 ± 7.07 ^a	0.83 ± 0.18 ^a	0.81 ± 0.03 ^a	18.75 ± 0.22 ^{ab}	0.25 ± 0.01 ^a	0.66 ± 0.07 ^{ab}
Quinoa	1	21.37 ± 0.42 ^a	4.80 ± 0.24 ^a	7.16 ± 0.11 ^a	157.93 ± 5.09 ^e	0.12 ± 0.02 ^c	0.17 ± 0.01 ^c	7.62 ± 0.27 ^f	0.14 ± 0.01 ^c	0.12 ± 0.01 ^c
	2	21.21 ± 0.08 ^a	4.53 ± 0.66 ^a	6.81 ± 0.07 ^{ab}	231.95 ± 0.31 ^{de}	0.19 ± 0.03 ^d	0.16 ± 0.03 ^c	12.28 ± 0.78 ^c	0.20 ± 0.02 ^{de}	0.13 ± 0.02 ^d
	3	21.46 ± 0.23 ^a	4.53 ± 0.65 ^a	6.83 ± 0.08 ^{bc}	317.51 ± 4.57 ^{cd}	0.25 ± 0.05 ^{de}	0.16 ± 0.02 ^c	12.39 ± 1.32 ^{de}	0.23 ± 0.01 ^{ab}	0.16 ± 0.02 ^{de}
	4	21.38 ± 0.12 ^a	4.97 ± 0.05 ^a	6.57 ± 0.14 ^{bcd}	380.14 ± 6.39 ^{bc}	0.36 ± 0.03 ^{bcd}	0.18 ± 0.03 ^c	17.24 ± 0.32 ^{bc}	0.25 ± 0.05 ^a	0.24 ± 0.04 ^{cd}
	5	22.01 ± 0.15 ^a	5.06 ± 0.01 ^a	6.49 ± 0.01 ^{bcd}	423.72 ± 0.55 ^b	0.49 ± 0.04 ^{ab}	0.65 ± 0.01 ^{ab}	21.02 ± 0.22 ^a	0.22 ± 0.01 ^{ab}	0.52 ± 0.02 ^{bc}
	6	21.76 ± 0.01 ^a	5.03 ± 0.02 ^a	6.31 ± 0.08 ^d	506.39 ± 3.43 ^a	0.83 ± 0.17 ^a	0.87 ± 0.03 ^a	19.32 ± 0.50 ^{ab}	0.23 ± 0.01 ^{ab}	0.73 ± 0.18 ^a

Each value is Mean ± SD of the 3 individual observations.
Means in the same column sharing a same superscript letter are not significantly different and determined by DMRT test ($p < 0.05$).

months. Similarly, nitrate concentrations showed significant ($p < 0.05$) temporal variation, with peak values observed during the fifth month in all treatments. Nitrite concentrations also varied significantly ($p < 0.05$) over time, with higher values recorded during the later months of the study.

Iron (Fe) concentrations increased significantly ($p < 0.05$) over the experimental period, with statistically lower concentrations during the first two months and significantly higher concentrations observed during months five and six across all crop systems. For most water quality parameters, no significant differences were observed among the three crop treatments at corresponding sampling times.

3.2 Micro and macro minerals content in aquaponics water

Effluent water from aquaponic systems cultivating pearl millet, finger millet, and quinoa was analyzed for essential macro- and micro-nutrients, including Ca, Cu, K, Mg, Mn, Mo, Na, P, S, and Zn, with results summarized in Table 3. Monthly mean mineral concentrations showed statistically significant ($p < 0.05$) temporal variation over the six-month experimental period.

Calcium concentrations increased significantly over time across all crop systems, with significantly higher levels recorded during the final month compared to most earlier sampling periods. Copper concentrations exhibited temporal fluctuations, although peak values were not consistently different from several other months due to variability. Sodium, potassium, phosphorus, magnesium, and sulfur showed significant increasing ($p < 0.05$) trends, with the highest concentrations observed during the final month across all treatments.

Manganese concentrations remained relatively stable throughout the study, with no significant differences detected among most sampling periods. In contrast, molybdenum concentrations decreased significantly over time, with higher values recorded during the initial months and significantly lower ($p < 0.05$) levels observed in the final month. Zinc concentrations increased markedly during the later stages of the experiment, with significantly higher ($p < 0.05$) values recorded during months five and six compared to earlier months.

3.3 Fish growth performance and proximate composition in different millet-based aquaponics systems

Fish growth performance and proximate composition parameters of tilapia fish reared in aquaponics systems integrated with pearl millet, finger millet, and quinoa are presented in Table 4. No statistically significant ($p > 0.05$) differences were observed among treatments for any of the measured parameters.

The initial and final number of fish did not differ significantly among the three systems. Similarly, initial body weight, final body weight, weight gain per fish, and total fish biomass showed no significant variation across treatments. Feed intake, feed conversion ratio (FCR), and survival rate were also statistically similar among fish cultured in pearl millet, finger millet, and quinoa-based aquaponic systems (Table 4).

Proximate composition parameters of fish, including moisture, ash, crude protein, crude fat, crude fiber, and carbohydrate content, did not differ significantly among treatments ($p > 0.05$). All measured compositional parameters exhibited comparable values across the three millet-based aquaponics systems.

3.4 Plant growth parameters in the different millet cultivation aquaponics systems

Plant growth indices, including total plant length, shoot length, root length, survival rate, total grain yield, yield per plant, feed input, and plant feed conversion ratio (FCR^{Plant}), were evaluated in aquaponic systems cultivating pearl millet, finger millet, and quinoa, with results presented in Table 5. Initially, an equal number of plants (75 plants in each system) were established in each millet-based aquaponic system. Significant differences were detected in plant growth characteristics. Total plant length varied significantly among crops ($p < 0.05$), with pearl millet exhibiting the greatest total length, followed by quinoa, while finger millet showed significantly lower values. Shoot length also differed significantly among treatments ($p < 0.05$), with pearl millet recording the highest shoot length and finger millet the lowest, while quinoa showed intermediate values. Root length differed significantly among crops, with pearl millet and quinoa exhibiting significantly longer roots compared to finger millet ($p < 0.05$).

Grain yield parameters showed significant variation among treatments. Total grain yield differed significantly ($p < 0.05$), with pearl millet and quinoa recording significantly higher yields than finger millet. Similarly, yield per plant was significantly lower in finger millet compared to pearl millet and quinoa, which did not differ significantly from each other. Feed input differed significantly among crops ($p < 0.05$), with finger millet requiring a significantly higher input than pearl millet and quinoa. Plant biomass on a wet basis also varied significantly among treatments, with pearl millet exhibiting significantly higher biomass compared to finger millet and quinoa. Plant feed conversion ratio (FCR^{Plant}) showed significant differences among crops ($p < 0.05$), with pearl millet recording significantly lower values than finger millet and quinoa.

3.5 Proximate and mineral composition of the millet and quinoa grains

The proximate composition and macro- and micronutrient contents of pearl millet, finger millet, and quinoa grains produced under aquaponic conditions are presented in Table 6. Biochemical composition differed significantly among the three crops for most parameters. Dry matter content showed significant variation, with all crops differing from one another ($p < 0.05$). Moisture content also differed significantly, with quinoa exhibiting significantly higher values compared to finger millet, while pearl millet showed intermediate values. Ash content varied significantly among crops ($p < 0.05$), with pearl millet recording significantly higher ash content than finger millet and quinoa. Protein content showed significant differences, with quinoa exhibiting significantly higher protein levels compared to pearl millet and finger millet, which did not differ significantly from each other.

Acid detergent fiber (ADF) content differed significantly among all three crops ($p < 0.05$), while neutral detergent fiber (NDF) content showed significant variation, with pearl millet and quinoa not differing significantly from each other but both differing from finger millet. Fat content also varied significantly among crops, with pearl millet exhibiting the highest values, followed by quinoa and finger millet. Antioxidant activity (DPPH) differed significantly among all three crops ($p < 0.05$).

Significant differences were also observed in macro- and micro-nutrient composition among the millet grains. Calcium, phosphorus,

TABLE 3 Monthly average Mineral nutrient content in fish effluent water (mg/l).

Crops	Month	Ca	Cu	K	Mg	Mn	Mo	Na	P	S	Zn
Pearl millet	1	0.183 ± 0.005 ^d	0.013 ± 0.002 ^b	0.014 ± 0.002 ^b	0.023 ± 0.003 ^c	0.008 ± 0.002 ^a	0.016 ± 0.003 ^{bc}	0.413 ± 0.010 ^c	0.020 ± 0.000 ^d	0.016 ± 0.001 ^c	0.006 ± 0.000 ^c
	2	0.253 ± 0.070 ^{efg}	0.017 ± 0.004 ^b	0.030 ± 0.016 ^{ab}	0.037 ± 0.014 ^c	0.008 ± 0.001 ^a	0.017 ± 0.001 ^{bc}	0.516 ± 0.103 ^{cd}	0.150 ± 0.130 ^{bcd}	0.033 ± 0.017 ^{de}	0.027 ± 0.021 ^c
	3	0.319 ± 0.001 ^{def}	0.020 ± 0.000 ^b	0.051 ± 0.002 ^{ab}	0.047 ± 0.001 ^c	0.009 ± 0.000 ^a	0.018 ± 0.000 ^a	0.625 ± 0.002 ^{bc}	0.243 ± 0.013 ^{bcd}	0.045 ± 0.002 ^{cde}	0.042 ± 0.002 ^c
	4	0.362 ± 0.009 ^{bcd}	0.024 ± 0.006 ^a	0.059 ± 0.008 ^{ab}	0.156 ± 0.025 ^{ab}	0.009 ± 0.000 ^a	0.018 ± 0.000 ^{ab}	0.705 ± 0.014 ^a	0.260 ± 0.020 ^{bcd}	0.236 ± 0.040 ^{ab}	0.076 ± 0.015 ^c
	5	0.331 ± 0.030 ^{abc}	0.073 ± 0.049 ^{ab}	0.130 ± 0.072 ^{ab}	0.133 ± 0.024 ^{abc}	0.024 ± 0.015 ^a	0.013 ± 0.005 ^{bc}	0.732 ± 0.02 ^{ab}	0.180 ± 0.081 ^{cd}	0.202 ± 0.034 ^{bc}	0.246 ± 0.171 ^{bc}
	6	0.463 ± 0.054 ^a	0.102 ± 0.007 ^b	0.226 ± 0.008 ^a	0.189 ± 0.026 ^a	0.012 ± 0.009 ^a	0.007 ± 0.001 ^d	0.801 ± 0.014 ^a	0.702 ± 0.201 ^{ab}	0.279 ± 0.037 ^a	0.477 ± 0.020 ^a
Finger millet	1	0.266 ± 0.008 ^{def}	0.020 ± 0.000 ^b	0.031 ± 0.011 ^{ab}	0.072 ± 0.040 ^c	0.009 ± 0.000 ^a	0.018 ± 0.000 ^a	0.533 ± 0.029 ^{bcd}	0.170 ± 0.110 ^{bcd}	0.100 ± 0.062 ^{bc}	0.035 ± 0.005 ^c
	2	0.285 ± 0.019 ^{cd}	0.025 ± 0.005 ^b	0.026 ± 0.004 ^{ab}	0.055 ± 0.018 ^c	0.009 ± 0.000 ^a	0.018 ± 0.000 ^a	0.544 ± 0.011 ^b	0.150 ± 0.020 ^{cd}	0.072 ± 0.028 ^{cde}	0.043 ± 0.008 ^c
	3	0.335 ± 0.010 ^{bcd}	0.023 ± 0.003 ^b	0.053 ± 0.010 ^{ab}	0.100 ± 0.021 ^{bc}	0.009 ± 0.000 ^a	0.018 ± 0.000 ^a	0.623 ± 0.023 ^{bc}	0.228 ± 0.033 ^{bc}	0.145 ± 0.034 ^{bc}	0.073 ± 0.008 ^b
	4	0.431 ± 0.012 ^{abc}	0.164 ± 0.102 ^b	0.229 ± 0.050 ^a	0.174 ± 0.051 ^{bc}	0.035 ± 0.032 ^a	0.005 ± 0.001 ^d	0.805 ± 0.005 ^a	0.669 ± 0.011 ^a	0.252 ± 0.064 ^{ab}	0.374 ± 0.017 ^{ab}
	5	0.388 ± 0.043 ^{abc}	0.092 ± 0.072 ^{ab}	0.146 ± 0.083 ^{ab}	0.147 ± 0.026 ^{abc}	0.022 ± 0.013 ^a	0.011 ± 0.007 ^{bc}	0.725 ± 0.080 ^{ab}	0.465 ± 0.205 ^{bc}	0.215 ± 0.036 ^{bc}	0.402 ± 0.22 ^a
	6	0.418 ± 0.024 ^{abc}	0.052 ± 0.010 ^{ab}	0.225 ± 0.054 ^{ab}	0.198 ± 0.026 ^a	0.005 ± 0.002 ^a	0.008 ± 0.003 ^d	0.761 ± 0.039 ^a	1.025 ± 0.255 ^a	0.282 ± 0.034 ^a	0.288 ± 0.069 ^a
Quinoa	1	0.224 ± 0.041 ^{fg}	0.016 ± 0.004 ^b	0.022 ± 0.008 ^{ab}	0.048 ± 0.025 ^c	0.008 ± 0.001 ^a	0.017 ± 0.001 ^{ab}	0.473 ± 0.060 ^{cd}	0.095 ± 0.075 ^{cd}	0.058 ± 0.042 ^{cd}	0.021 ± 0.015 ^c
	2	0.269 ± 0.016 ^{def}	0.021 ± 0.004 ^b	0.028 ± 0.002 ^{ab}	0.046 ± 0.009 ^{bc}	0.009 ± 0.000 ^a	0.017 ± 0.001 ^{ab}	0.530 ± 0.014 ^{bc}	0.150 ± 0.000 ^{bcd}	0.053 ± 0.019 ^{cd}	0.035 ± 0.008 ^c
	3	0.327 ± 0.008 ^{def}	0.021 ± 0.001 ^b	0.052 ± 0.001 ^{ab}	0.074 ± 0.026 ^{bcd}	0.009 ± 0.000 ^a	0.018 ± 0.000 ^a	0.624 ± 0.001 ^b	0.235 ± 0.007 ^{bcd}	0.095 ± 0.050 ^{cd}	0.057 ± 0.015 ^c
	4	0.396 ± 0.035 ^{bcd}	0.094 ± 0.070 ^{ab}	0.144 ± 0.085 ^{ab}	0.165 ± 0.009 ^{ab}	0.022 ± 0.013 ^a	0.011 ± 0.007 ^{cd}	0.755 ± 0.050 ^a	0.465 ± 0.205 ^{bc}	0.244 ± 0.008 ^{ab}	0.100 ± 0.24 ^{cd}
	5	0.360 ± 0.028 ^{abc}	0.082 ± 0.009 ^{ab}	0.138 ± 0.008 ^{ab}	0.140 ± 0.007 ^{abc}	0.023 ± 0.001 ^a	0.012 ± 0.001 ^{cd}	0.728 ± 0.004 ^a	0.322 ± 0.143 ^{bcd}	0.209 ± 0.007 ^{bc}	0.299 ± 0.053 ^{ab}
	6	0.440 ± 0.023 ^{ab}	0.077 ± 0.025 ^{ab}	0.225 ± 0.001 ^a	0.193 ± 0.005 ^a	0.008 ± 0.004 ^a	0.007 ± 0.001 ^{cd}	0.781 ± 0.020 ^a	0.764 ± 0.062 ^a	0.280 ± 0.001 ^a	0.382 ± 0.095 ^a

Each value is Mean ± SD of the 3 individual observations.
Means in the same column sharing a same superscript letter are not significantly different and determined by DMRT test ($p < 0.05$).

TABLE 4 Growth parameter, proximate composition and productivity of fish.

Growth and proximate parameters	Aquaponics system		
	Pearl millet	Finger millet	Quinoa
Initial no of fish	20.00 ± 0.00 ^a	20.00 ± 0.00 ^a	20.00 ± 0.00 ^a
Final no of fish	17.33 ± 1.15 ^a	17.67 ± 0.58 ^a	17.33 ± 0.58 ^a
Initial weight/fish (g)	34.67 ± 3.06 ^a	34.33 ± 2.08 ^a	33.67 ± 1.53 ^a
Final weight/ fish (g)	350.69 ± 6.04 ^a	345.17 ± 8.39 ^a	347.58 ± 10.34 ^a
Weight gain / fish (g)	316.02 ± 9.01 ^a	310.83 ± 9.07 ^a	313.92 ± 10.34 ^a
Total fish weight (kg)	6.07 ± 0.32 ^a	6.10 ± 0.17 ^a	6.03 ± 0.35 ^a
Feed intake (g)	425.00 ± 15.00 ^a	430.00 ± 8.66 ^a	430.14 ± 11.85 ^a
FCR	1.35 ± 0.04 ^a	1.38 ± 0.06 ^a	1.37 ± 0.08 ^a
Survival rate (%)	86.67 ± 5.77 ^a	88.33 ± 2.89 ^a	86.67 ± 2.89 ^a
Moisture (%)	75.00 ± 0.46 ^a	74.79 ± 0.29 ^a	75.50 ± 0.78 ^a
Ash (%)	11.19 ± 0.30 ^a	11.06 ± 0.18 ^a	10.89 ± 0.47 ^a
Protein (%)	49.62 ± 1.22 ^a	48.76 ± 1.13 ^a	49.58 ± 1.33 ^a
Fat (%)	1.71 ± 0.30 ^a	1.58 ± 0.18 ^a	1.46 ± 0.07 ^a
Fiber (%)	21.85 ± 0.84 ^a	22.60 ± 0.53 ^a	22.71 ± 0.39 ^a
Carbohydrate (%)	16.12 ± 1.89 ^a	16.01 ± 2.03 ^a	15.36 ± 1.28 ^a

Each value is Mean ± SD of the 3 individual observations.

Means in the same row sharing a same superscript letter are not significantly different and determined by DMRT test ($p < 0.05$).

TABLE 5 Growth parameters and productivity performance of experimental plants.

Growth parameters	Pearl millet	Finger millet	Quinoa
Initial Plants	75.00 ± 0.00 ^a	75.00 ± 0.00 ^a	75.00 ± 0.00 ^a
Final Plants	68.67 ± 2.31 ^a	69.00 ± 2.65 ^a	69.33 ± 0.58 ^a
Total length (cm)	140.33 ± 4.73 ^a	105.33 ± 5.51 ^c	128.67 ± 7.51 ^b
Shoot length (cm)	115.33 ± 3.51 ^c	84.33 ± 4.04 ^c	103.00 ± 7.21 ^b
Root length (cm)	25.00 ± 2.00 ^a	21.00 ± 2.00 ^b	25.67 ± 2.08 ^a
Survival rate (%)	91.56 ± 3.08 ^a	92.00 ± 3.53 ^a	92.44 ± 0.77 ^a
Total grain Yield (gm)	1218.33 ± 59.23 ^a	1185.00 ± 62.65 ^b	973.33 ± 20.21 ^c
Yield/plant (gm)	17.25 ± 0.53 ^a	14.62 ± 1.12 ^b	17.57 ± 0.79 ^a
Feed input (Kg)	3.51 ± 0.18 ^b	4.31 ± 0.13 ^a	3.75 ± 0.36 ^b
Plant biomass WB (kg)	5.43 ± 0.42 ^a	3.38 ± 0.33 ^b	3.58 ± 0.27 ^b
FCR ^{plant} (%)	0.65 ± 0.02 ^a	1.28 ± 0.15 ^b	1.06 ± 0.18 ^b

Each value is Mean ± SD of the 3 individual observations.

Means in the same row sharing a same superscript letter are not significantly different and determined by DMRT test ($p < 0.05$).

potassium, magnesium, manganese, iron, cobalt, sodium, and zinc contents differed significantly among crops ($p < 0.05$). For calcium and phosphorus, finger millet exhibited significantly higher values,

while quinoa showed significantly higher concentrations of potassium, magnesium, manganese, iron, cobalt, and zinc. Sodium content differed significantly, with pearl millet recording higher values compared to finger millet and quinoa, which did not differ significantly from each other.

3.6 Proximate and mineral composition of the crops stems and leaves

The proximate composition and mineral nutrient content of stems and leaves of pearl millet, finger millet, and quinoa cultivated under aquaponic conditions are presented in Table 7. Dry matter and moisture content did not differ significantly among the three crops, as indicated by shared superscript letters. In contrast, ash content differed significantly among crops ($p < 0.05$), with finger millet exhibiting significantly higher values than quinoa and pearl millet. Protein content also showed significant variation, with finger millet recording significantly higher values, while quinoa exhibited significantly lower values compared to the other crops. Acid detergent fiber (ADF) content differed significantly among treatments, with quinoa showing significantly lower values than pearl millet and finger millet, whereas neutral detergent fiber (NDF) content did not differ significantly among crops. Fat content showed minor but significant variation, with quinoa exhibiting significantly higher values compared to the other treatments. DPPH radical scavenging activity differed significantly among crops ($p < 0.05$), with pearl millet showing significantly higher values, followed by finger millet and quinoa (Table 7).

Significant differences were also observed in macro- and micro-nutrient concentrations among crops. Sodium, magnesium, potassium, phosphorus, sulfur, manganese, iron, cobalt, copper, molybdenum, and zinc contents differed significantly among treatments ($p < 0.05$), whereas calcium content did not show significant variation among crops. For most minerals, finger millet and quinoa differed significantly from pearl millet, as indicated by distinct superscript letters within rows.

4 Discussion

4.1 System performance and water quality

The present study confirms the suitability of aquaponic systems for operation under arid climatic conditions, as demonstrated by the maintenance of water quality parameters within ranges supportive of both plant and fish performance. The similar temporal trends observed across all crop treatments indicate that water quality dynamics were primarily driven by system maturation, rather than crop-specific effects. Progressive increases in total dissolved solids (TDS), electrical conductivity (EC), and nutrient concentrations particularly ammonia and nitrate reflect the gradual accumulation of dissolved constituents derived from fish waste and organic matter mineralization. Concurrently, the gradual decline in pH is characteristic with increasing nitrification activity and nutrient loads within the system, underscoring the dynamic nature of nutrient cycling in recirculating aquaponic environments.

Temperature, a critical regulator of metabolic and microbial processes in aquaponics, remained stable throughout the experimental period and aligned well with optimal ranges reported for aquaponic

TABLE 6 Proximate and minerals composition of the millets and quinoa grains.

Analyses	Nutrients	Pearl millet	Finger millet	Quinoa
Biochemical composition (%)	Dry matter	8.30 ± 0.53 ^c	10.97 ± 0.21 ^a	9.16 ± 0.18 ^b
	Moisture	10.27 ± 0.57 ^{ab}	7.70 ± 0.56 ^b	11.36 ± 0.65 ^a
	Ash	5.37 ± 0.45 ^a	1.80 ± 0.36 ^c	2.11 ± 0.27 ^b
	Protein	12.20 ± 0.30 ^b	12.50 ± 0.36 ^b	13.08 ± 0.37 ^a
	ADF	11.87 ± 0.50 ^c	17.87 ± 2.25 ^a	13.86 ± 0.58 ^b
	NDF	61.53 ± 0.96 ^a	59.50 ± 2.43 ^b	61.63 ± 1.53 ^a
	Fat	3.35 ± 0.31 ^a	2.85 ± 0.79 ^c	3.20 ± 0.35 ^b
	DPPH*	60.16 ± 5.56 ^a	42.54 ± 0.44 ^b	33.24 ± 3.19 ^c
Macro and micro minerals composition (mg/g)	Ca	23.12 ± 1.02 ^c	109.25 ± 1.95 ^a	69.25 ± 1.75 ^b
	P	72.40 ± 6.50 ^b	90.70 ± 5.10 ^a	39.55 ± 2.80 ^c
	K	22.67 ± 1.47 ^c	35.00 ± 0.90 ^b	84.88 ± 2.13 ^a
	Mg	3.85 ± 0.35 ^c	6.08 ± 0.31 ^b	17.15 ± 0.35 ^a
	Mn	0.23 ± 0.03 ^c	2.40 ± 0.45 ^b	3.85 ± 0.25 ^a
	Fe	1.29 ± 0.04 ^c	1.56 ± 0.10 ^b	4.60 ± 0.15 ^a
	Co	0.09 ± 0.01 ^b	0.08 ± 0.02 ^b	0.58 ± 0.02 ^a
	Na	5.45 ± 0.35 ^a	3.95 ± 0.25 ^b	3.30 ± 0.40 ^b
	Zn	0.17 ± 0.02 ^c	0.45 ± 0.03 ^b	1.45 ± 0.10 ^a

Each value is Mean ± SD of the 3 individual observations.

Means in the same row sharing a same superscript letter are not significantly different and determined by DMRT test ($p < 0.05$).

TABLE 7 Proximate and minerals composition of the cultivated millet and Quinoa crops (Stem and leaves).

Analyses	Nutrients	Pearl millet	Finger millet	Quinoa
Biochemical composition (%)	Dry matter	86.60 ± 1.84 ^a	87.50 ± 1.84 ^a	88.40 ± 0.85 ^a
	Moisture	11.80 ± 0.42 ^a	11.75 ± 0.78 ^a	11.61 ± 0.84 ^a
	Ash	22.55 ± 2.05 ^c	26.10 ± 2.12 ^a	24.50 ± 2.26 ^b
	Protein	7.75 ± 0.35 ^b	8.10 ± 1.27 ^a	7.20 ± 0.99 ^c
	ADF	31.70 ± 2.83 ^a	30.55 ± 2.47 ^a	28.55 ± 2.62 ^b
	NDF	49.90 ± 4.53 ^a	49.35 ± 4.03 ^a	46.20 ± 4.24 ^a
	Fat	0.87 ± 0.08 ^{ab}	0.86 ± 0.07 ^{ab}	0.90 ± 0.08 ^a
	DPPH*	46.27 ± 1.56 ^a	24.43 ± 2.21 ^b	21.22 ± 3.11 ^c
Macro and micro minerals composition (mg/g)	Na	43.46 ± 5.15 ^{ab}	37.31 ± 3.77 ^b	48.61 ± 5.29 ^a
	Mg	140.98 ± 19.66 ^{ab}	129.10 ± 10.51 ^b	160.63 ± 6.18 ^a
	Ca	74.88 ± 16.80 ^a	72.21 ± 6.49 ^a	91.68 ± 2.29 ^a
	K	549.58 ± 109.92 ^{ab}	620.23 ± 60.19 ^a	439.66 ± 41.61 ^b
	P	172.74 ± 35.93 ^{ab}	202.39 ± 21.86 ^a	136.81 ± 3.50 ^b
	S	93.96 ± 24.63 ^{ab}	76.76 ± 13.94 ^b	118.59 ± 3.49 ^a
	Mn	226.19 ± 62.34 ^{ab}	301.28 ± 45.81 ^a	163.85 ± 15.95 ^b
	Fe	301.66 ± 8.30 ^b	415.14 ± 40.59 ^a	293.36 ± 2.30 ^b
	Co	0.29 ± 0.01 ^b	0.37 ± 0.03 ^a	0.32 ± 0.02 ^b
	Cu	38.07 ± 8.33 ^{ab}	45.90 ± 5.39 ^a	29.74 ± 0.47 ^b
	Mo	4.54 ± 0.44 ^{ab}	5.47 ± 0.46 ^a	4.10 ± 0.57 ^{ab}
	Zn	11.34 ± 2.01 ^{ab}	13.63 ± 1.43 ^a	9.33 ± 0.45 ^b

Each value is Mean ± SD of the 3 individual observations.

Means in the same row sharing a same superscript letter are not significantly different and determined by DMRT test ($p < 0.05$).

systems, supporting efficient fish metabolism and plant growth (Maulini et al., 2022; Deswati et al., 2022; Jayaprakash et al., 2022). Dissolved oxygen concentrations were similarly maintained at levels adequate for Nile tilapia culture, facilitating effective feed utilization and overall fish health, consistent with earlier findings (Tran-Duy et al., 2012; Gichana et al., 2019).

The observed pH range throughout the study was favourable for fish, plants, and nitrifying bacteria, highlighting the stability of key biological processes within the system (Mori et al., 2021). The gradual increase in TDS and EC across all crop treatments is characteristic of maturing closed-loop aquaponic systems, where nutrient accumulation can support sustained plant productivity when maintained within acceptable thresholds (Fabula et al., 2023).

Nitrogen dynamics further confirmed effective system functioning. Ammonia concentrations remained within tolerable limits for tilapia, indicating efficient biofiltration, although the increasing trend toward the later stages of the experiment emphasizes the importance of scaling biofilter capacity in response to rising biomass and nutrient loading (Maulini et al., 2022). The accumulation of nitrate over time reflects active nitrification and adequate nitrogen availability for plant uptake, consistent with observations reported by Tórz et al. (2021). Importantly, nitrite concentrations remained well below toxic thresholds for fish, confirming stable nitrification and minimal risk of nitrite-induced stress (Abdelfattah et al., 2022).

Micronutrient availability, particularly iron, improved progressively during the study period. Iron deficiency is a well-documented limitation in aquaponic systems due to precipitation and reduced solubility (Kasozi et al., 2019). The observed increase in iron concentration suggests effective supplementation and improved micronutrient availability (Subramanian et al., 2025), which is essential for chlorophyll synthesis and overall plant vigour, particularly in cereal and millet crops (Manwaring et al., 2016).

The present study identified a broad range of macro- and micro-nutrients in aquaponic water, underscoring the efficiency of nutrient cycling inherent to integrated aquaponic systems. These findings are consistent with earlier reports documenting the presence of trace and essential minerals in aquaponics water derived from fish effluents (Delaide, 2017; Roosta and Hamidpur, 2011; Rakocy et al., 2004a,b; Pantanella et al., 2012; Subramanian et al., 2025). The integration of recirculating aquaculture with hydroponic plant production creates a mutually beneficial environment in which fish waste is transformed into plant-available nutrients, while plant uptake and associated microbial processes contribute to water purification for fish (Nicoletto et al., 2018; Gichana et al., 2019; Okomoda et al., 2022).

Nutrient cycling in aquaponics is driven by complex biological and chemical interactions, primarily mediated by microorganisms. Fish feed consumption results in the excretion of ammonia and solid waste (Bittsanszky et al., 2016; Lobanov et al., 2021), which is subsequently oxidized to nitrite and nitrate by nitrifying bacteria within the biofilter (Eck et al., 2019). Plants preferentially absorb nitrate and other dissolved nutrients, thereby reducing nitrogenous waste concentrations and maintaining water quality suitable for fish culture (Schmautz et al., 2016; Maucieri et al., 2018). This closed-loop recirculation substantially reduces freshwater use and minimizes the discharge of nutrient-rich effluents into the environment (Yogev et al., 2016; Wei et al., 2019).

Both macro- and micronutrients play critical roles in supporting plant physiological processes within aquaponic systems.

Macronutrients such as nitrogen, phosphorus, potassium, calcium, magnesium, and sulphur are essential for growth and metabolic functions, while micronutrients including iron, manganese, zinc, copper, boron, molybdenum, and chlorine are required in smaller quantities but are equally vital for enzymatic activity, photosynthesis, and overall plant health (Lobanov et al., 2021; Al-Tawaha et al., 2021; Nozzi et al., 2018). Deficiencies or imbalances in these nutrients can adversely affect crop performance.

Nutrient availability in aquaponic systems is influenced by several interacting factors, including fish feed composition, stocking density, plant species, system design, and water quality management (Yang et al., 2020; Bittsanszky et al., 2016). Consistent with previous studies, the present findings support observations that nitrate levels in well-managed aquaponic systems are generally sufficient for plant growth, whereas other nutrients particularly potassium, calcium, magnesium, and iron may become limiting if not appropriately supplemented (Nicoletto et al., 2018; Bittsanszky et al., 2016). These complexities highlight the importance of a comprehensive understanding of nutrient transformations and mineral dynamics within aquaponics. While challenges related to nutrient imbalances and long-term water quality management persist, continued research and technological innovation are contributing to the development of more efficient and sustainable aquaponic practices (Goddek et al., 2017).

Overall, these findings demonstrate that careful management of water quality parameters can sustain balanced aquaponic production under arid conditions. While system performance remained stable, the gradual accumulation of dissolved solids and nitrogenous compounds highlights the necessity for continuous monitoring and adaptive management to ensure long-term sustainability.

4.2 Fish productivity

Fish growth performance and survival are key indicators of aquaponic system functionality, as they directly reflect water quality stability, nutrient cycling efficiency, and overall system health. In the present study, Nile tilapia reared in aquaponic systems integrated with pearl millet, finger millet, and quinoa exhibited consistently high survival rates, indicating favorable rearing conditions across all treatments (Table 3). Survival remained above commonly reported thresholds for healthy aquaponic systems, aligning with earlier findings that emphasize the importance of stable water quality and low physiological stress in integrated systems (Yildiz et al., 2017). The marginally higher survival observed in the finger millet-based system may reflect subtle differences in nutrient uptake dynamics and system balance, may be associated with minor differences in system nutrient dynamics, although survival did not differ significantly among treatments.

Fish growth performance further supports the effectiveness of the aquaponic systems. Substantial weight gain and final body weights were achieved across all treatments, demonstrating that the integrated millet-based systems supported robust fish biomass production. Comparable growth trends have been reported in well-managed aquaponic and recirculating aquaculture systems, where adequate dissolved oxygen, stable temperature, and effective biofiltration promote efficient nutrient assimilation and growth (Sujatha and Bhat, 2015; Gichana et al., 2019). Although slight variation in final weights was observed among treatments, these differences were not statistically significant, suggesting that crop type did not adversely influence fish growth under the prevailing system conditions.

Feed intake patterns provide additional insight into fish metabolic activity and system nutrient dynamics. Fish in the finger millet-based system exhibited slightly higher feed consumption, which may indicate increased metabolic demand or marginally enhanced environmental conditions supporting active feeding behaviour (Lall and Tibbetts, 2009; Nageswari et al., 2022). Despite this variation, all systems demonstrated efficient utilization of feed inputs, as reflected by low feed conversion ratio (FCR) values across treatments. Efficient FCR is a key indicator of sustainability in aquaponic and aquaculture systems, as it reflects effective conversion of feed into fish biomass with minimal waste generation (Besson et al., 2020; Colt and Semmens, 2022; Kagali et al., 2025). The consistently low FCR values observed in this study highlight the capacity of aquaponic systems to support efficient fish production while simultaneously supplying nutrients for plant growth. Similar findings have been reported in integrated aquaponic systems, where balanced nutrient recycling reduces feed losses and enhances overall system efficiency (Danner et al., 2019; Shaw et al., 2022). The absence of significant differences in FCR among treatments further indicates that integration with different millet crops did not compromise feed efficiency or fish performance.

The proximate composition of fish carcasses did not differ significantly among treatments, indicating that integration with different millet crops did not influence fish body composition. Comparable moisture, protein, fat, ash, fiber, and carbohydrate contents across systems suggest consistent nutrient assimilation and metabolic regulation under uniform aquaponic conditions. The high protein content observed in all treatments reflects the favourable nutritional quality of tilapia produced in aquaponics and is consistent with values reported for fish reared under optimal feeding regimes and environmental conditions. The uniformity in carcass composition further indicates that dietary inputs and system management were effectively standardized across treatments.

Fish meat exhibited the highest protein concentration, demonstrating efficient conversion of dietary protein into muscle tissue and underscoring the nutritional value of aquaponically produced fish (Ghaly et al., 2013). The commercial feed provided adequate protein levels to support optimal growth, while the presence of substantial protein content in fish sludge suggests incomplete dietary protein utilization and highlights its potential for recovery or repurposing within integrated systems (Lall and Kaushik, 2021). Fat content was highest in fish meat, contributing to its energy value and reflecting efficient lipid metabolism, as commonly reported in tilapia cultured under balanced nutritional and environmental conditions (Khalili and Sampels, 2018).

Overall, the results demonstrate that millet-based aquaponic systems can sustain high fish survival, robust growth, efficient feed utilization, and consistent carcass quality. The absence of significant differences among treatments highlights the flexibility of aquaponic systems to accommodate diverse crop species without compromising fish performance. These findings reinforce the potential of aquaponics as a resilient and sustainable food production strategy, particularly well suited for regions where efficient resource utilization and system stability are critical.

4.3 Crop performance and suitability

Crop growth performance and suitability in the aquaponic system were evaluated using multiple plant growth indices, including plant

length components, survival rate, grain yield, feed input, biomass production, and plant feed conversion ratio (FCR^{Plant}). Overall, the consistently high survival rates observed for pearl millet, finger millet, and quinoa indicate that the aquaponic system successfully maintained favourable growing conditions for all crops, including adequate nutrient availability, oxygenation, and pH stability. High survival across treatments suggests that the system effectively supported plant establishment and sustained growth, consistent with previous reports highlighting the resilience of aquaponic systems in providing stable environments for diverse crops (Leimu and Fischer, 2008; Yang and Kim, 2019).

Significant differences in plant growth characteristics among the three crops highlight species-specific responses to aquaponic conditions. Pearl millet exhibited the greatest total and shoot length, followed by quinoa, whereas finger millet showed comparatively lower growth. Shoot and total plant length are key indicators of photosynthetic capacity and biomass accumulation, while root length is closely associated with nutrient uptake efficiency in soilless systems (Yep and Zheng, 2019; Abd Ghani et al., 2023). The longer root systems observed in pearl millet and quinoa suggest enhanced nutrient acquisition, while their greater shoot development likely contributed to improved photosynthetic performance and biomass production (Baligar et al., 2001; Richards, 2000). In contrast, the shorter roots and shoots of finger millet may have limited its capacity to fully exploit available nutrients and light, resulting in comparatively reduced growth.

Grain yield, a primary indicator of crop productivity, varied significantly among treatments. Pearl millet and quinoa produced higher grain yields than finger millet, indicating superior conversion of available nutrients into harvestable biomass. In aquaponic systems, grain yield reflects both plant nutrient-use efficiency and the effectiveness of nutrient cycling within the system (Lobanov et al., 2021; Ibrahim et al., 2023). The higher yields observed for pearl millet and quinoa are consistent with their more developed root and shoot systems, which likely facilitated greater nutrient uptake and allocation to reproductive growth (Fageria and Moreira, 2011; Abd Ghani et al., 2023). These results suggest that pearl millet and quinoa are particularly well suited for aquaponic cultivation when the goal is to maximize productivity under space- and resource-limited conditions.

Feed input is a critical factor influencing both plant and fish performance in aquaponic systems, as it directly determines nutrient availability while also affecting water quality and operational costs (Rakocy, 2012; Goulding et al., 2008). In this study, finger millet required higher feed input than pearl millet and quinoa, yet produced lower grain yield. This pattern indicates lower nutrient-use efficiency for finger millet compared to the other crops (Arvanitoyannis and Kassaveti, 2008; Gupta et al., 2017). Correspondingly, pearl millet and quinoa exhibited lower FCR^{Plant} values, reflecting more efficient conversion of nutrient inputs into plant biomass. Lower FCR^{Plant} values are particularly desirable for sustainable aquaponic production, as they indicate reduced resource consumption per unit of yield (Fry et al., 2018; Ranjan et al., 2019).

In contrast, the higher FCR^{Plant} observed for finger millet suggests less efficient nutrient conversion, likely associated with its comparatively smaller root and shoot systems, which may have constrained nutrient uptake and utilization. Taken together, these findings indicate that while all three crops can be successfully cultivated in aquaponic systems, pearl millet and quinoa demonstrate better growth performance, yield potential, and nutrient-use efficiency. These traits make them more suitable candidates for aquaponic production, particularly in arid and resource-limited environments where maximizing productivity and sustainability is essential.

4.4 Nutritional enhancement: nutrient dynamics and crop nutritional performance in aquaponic systems

The mineral nutrient composition of aquaponic effluent water highlights the dynamic and progressive nature of nutrient cycling within integrated aquaponic systems. Across all three crop-based systems, macro- and micronutrient concentrations increased over time, reflecting the continuous input of fish-derived nutrients and the maturation of biological processes such as mineralization and nitrification. The lack of pronounced crop-specific differences in water mineral profiles suggests that nutrient availability was largely regulated by system-level processes rather than differential plant uptake, corroborating earlier findings that aquaponic water chemistry is strongly influenced by feed inputs, fish metabolism, and microbial activity (Rakocy et al., 2004a,b; Goddek et al., 2016). The steady enrichment of essential nutrients including calcium, potassium, magnesium, phosphorus, and trace elements indicates that the aquaponic system functioned as a continuously replenished nutrient reservoir capable of supporting cereal and pseudo-cereal crops under arid conditions.

This enhanced nutrient availability in the effluent water was reflected in the nutritional composition of harvested grains, demonstrating clear species-specific nutrient assimilation patterns. Quinoa grains exhibited higher protein content and elevated levels of key micronutrients such as iron, zinc, magnesium, and potassium, consistent with previous reports identifying quinoa as a nutritionally dense pseudo-cereal (FAO & CIRAD, 2015; Manoharan et al., 2026). Finger millet grains were particularly rich in calcium and phosphorus, reinforcing their well-documented role as an important dietary source of minerals, especially calcium. In contrast, pearl millet showed higher ash content and antioxidant activity (DPPH), suggesting greater mineral accumulation and enhanced oxidative stress protective capacity. These findings emphasize the influence of crop genotype on nutrient partitioning and grain nutritional quality, even under a uniform aquaponic nutrient environment.

Analysis of vegetative tissues revealed distinct nutrient allocation patterns among crops. Stems and leaves contained substantially higher concentrations of macro and micronutrients than grains, particularly potassium, calcium, magnesium, iron, and manganese, confirming that vegetative biomass acts as a major nutrient sink in aquaponic systems. Finger millet leaves accumulated higher levels of calcium, phosphorus, and iron, while quinoa vegetative tissues were enriched in potassium, magnesium, and sulfur. Pearl millet leaves exhibited comparatively higher antioxidant activity, suggesting species-specific stress responses or secondary metabolite synthesis. These observations align with previous studies indicating that leafy biomass from aquaponic crops can serve as a nutritionally valuable by-product for fodder or functional applications, especially in integrated crop-livestock systems.

Biochemical composition further highlighted the nutritional potential of aquaponically grown millets. Dry matter content, an indicator of nutrient density, was highest in finger millet, followed by quinoa and pearl millet, while relatively similar values across crops indicate that aquaponics supported efficient growth and biomass accumulation. Moisture content varied among species, with quinoa exhibiting higher moisture suitable for fresh

consumption, whereas the lower moisture content of finger millet favours storage stability and processing (Boxall et al., 2002; Poonia et al., 2024). Pearl millet showed higher ash content, reflecting its richer mineral profile, while quinoa recorded the highest protein content, consistent with its characterization as a source of high-quality, balanced protein (Soares et al., 2019; Afzal et al., 2023). Notably, finger millet leaves contained higher protein levels among vegetative tissues, indicating efficient nitrogen assimilation and protein synthesis in leafy biomass.

Dietary fiber content, expressed as ADF and NDF, varied among crops, reflecting structural and physiological adaptations to arid environments. Finger millet exhibited higher ADF, while pearl millet and quinoa showed higher NDF, consistent with previous reports on millet resilience under water-limited conditions (Sharma et al., 2024). Fat content was highest in pearl millet grains, supporting its role as an energy-dense cereal, whereas finger millet aligned with low-fat dietary preferences and quinoa displayed a balanced lipid profile. Antioxidant activity followed a similar crop-specific pattern, with pearl millet showing the highest DPPH activity, likely linked to its adaptation to environmental stress and associated accumulation of bioactive compounds (Chaudhary et al., 2023; Nidhee et al., 2023).

The macro and micronutrient composition of both grains and leaves further confirms the nutritional superiority of aquaponically grown millets compared to conventional cultivation. Millets are already recognized for their richness in dietary fiber, phytochemicals, and essential minerals (Hymavathi et al., 2020; Arya and Bisht, 2022; Nidhee et al., 2023), and the enhanced mineral content observed under aquaponic conditions suggests additional nutritional benefits driven by nutrient-rich recirculating water.

Collectively, these findings demonstrate that aquaponic systems not only maintain stable nutrient cycling in water but also support the production of nutritionally differentiated crops under arid conditions. Quinoa emerged as a strong candidate for protein and micronutrient enrichment, finger millet for calcium-rich grains and protein-dense leafy biomass, and pearl millet for antioxidant-rich outputs. These complementary attributes highlight the value of diversified crop integration in aquaponics to enhance food and nutritional security while maximizing resource use efficiency. Future research should focus on elucidating the mechanisms underlying enhanced mineral uptake, optimizing nutrient management strategies for targeted nutritional outcomes, and further improving the sustainability and multifunctionality of aquaponic production systems in arid and semi-arid regions.

5 Conclusion

This study reveals that the potential of aquaponic systems for the sustainable cultivation of pearl millet, finger millet, and quinoa integrated with tilapia culture. Over the six-month experimental period, the system maintained favourable water quality and mineral nutrient levels, supporting healthy growth and performance of both fish and plants. Tilapia exhibited high survival rates (86–88%) and substantial weight gain across all treatments, with slightly improved performance observed in the finger millet-based system.

Plant growth and yield responses varied among crops, with pearl millet, finger millet, and quinoa exhibiting distinct performance in terms of total plant length, grain yield, and nutrient-use efficiency. The aquaponic system also supported the production of nutritionally valuable grains, with each crop exhibiting distinct nutritional advantages: quinoa showed higher calcium and magnesium contents, finger millet was enriched in iron and zinc, and pearl millet exhibited the highest antioxidant activity. These differences highlight the importance of crop selection in optimizing nutritional outputs from aquaponic systems.

Effective nutrient cycling was a key feature of the system, as evidenced by the effective utilization of fish-derived inputs including fish feed, organic supplements, fish biomass, and fish sludge for plant nutrition. The ability to simultaneously produce quality grains while maintaining fish health underscores the suitability of aquaponics as a resource-efficient and environmentally sustainable food production strategy, particularly in water-limited and arid regions.

Overall, the findings suggest that integrating millets and quinoa into aquaponic systems can contribute to enhanced food security and nutritional quality while reducing dependence on conventional soil-based agriculture. Further research is warranted to optimize crop-specific management protocols, assess long-term system sustainability, and evaluate aquaponic performance under varying environmental and operational conditions.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Ethics statement

The manuscript presents research on animals that do not require ethical approval for their study.

Author contributions

SA: Data curation, Methodology, Conceptualization, Writing – original draft. RS: Investigation, Writing – review & editing, Methodology. DN: Writing – review & editing. SC: Writing – review & editing. RM: Writing – review & editing. AJ: Writing – review & editing, Project administration, Investigation, Supervision, Funding acquisition.

References

- Abdelfattah, I., El-Saied, F. A., Almedolab, A. A., and El-Shamy, A. M. (2022). Biosorption as a perfect technique for purification of wastewater contaminated with Ammonia. *Appl. Biochem. Biotechnol.* 194, 4105–4134. doi: 10.1007/s12010-021-03794-4
- Abd Ghani, R., Omar, S., Jolánkai, M., Tarnawa, Á., Khalid, N., Kassai, M. K., et al. (2023). Response of shoot and root growth, yield, and chemical composition to nutrient concentrations in soybean varieties grown under soilless and controlled environment conditions. *Agriculture* 13:1925. doi: 10.3390/agriculture13101925

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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- Adler, P. R., Harper, J. K., Takeda, F., Wade, E. M., and Summerfelt, S. T. (2000). Economic evaluation of hydroponics and other treatment options for phosphorus removal in aquaculture effluent. *HortScience* 35, 993–999. doi: 10.21273/hortsci.35.6.993

- Adolf, V. I., Shabala, S., Andersen, M. N., Razzaghi, F., and Jacobsen, S. E. (2012). Varietal differences of quinoa's tolerance to saline conditions. *Plant Soil* 357, 117–129. doi: 10.1007/s11104-012-1133-7

- Afzal, I., Haq, M. Z. U., Ahmed, S., Hirich, A., and Bazile, D. (2023). Challenges and perspectives for integrating quinoa into the Agri-food system. *Plants* 12:3361. doi: 10.3390/plants12193361
- Al-Tawaha, A. R., Wahab, P. E. M., Jaafar, H. B., Zuan, A. T. K., Hassan, M. Z., and Al-Tawaha, A. R. (2021). Yield and nutrients leaf content of butterhead lettuce (*Lactuca sativa*) in response to fish nutrient solution in a small scale of aquaponic systems. *Ecological Engineering Environmental Technology* 22:85. doi: 10.12912/27197050/141524
- AOAC (2005) in *Official method of analysis*, eds. H. William and George W. L. Jr., 18th ed (Gaithersburg, Maryland, USA: Association of Officiating Analytical Chemists, Published by, AOAC International).
- APHA (1998). *Standard methods for the examination of water and wastewater*. 20th Edn. Washington, DC: American Public Health Association, American Water Works Association and Water Environmental Federation.
- APHA (2005). *Standard methods for the examination of water and wastewater*. 21st Edn. Washington DC: American Public Health Association/American Water Works Association/Water Environment Federation.
- Armanda, D. T., Guinée, J. B., and Tukker, A. (2019). The second green revolution: innovative urban agriculture's contribution to food security and sustainability – a review. *Glob. Food Sec.* 22, 13–24. doi: 10.1016/j.gfs.2019.08.002
- Arvanitoyannis, I. S., and Kassaveti, A. (2008). Fish industry waste: treatments, environmental impacts, current and potential uses. *Int. J. Food Sci. Technol.* 43, 726–745. doi: 10.1111/j.1365-2621.2006.01513.x
- Arya, C., and Bisht, A. (2022). “Small millets: path to food and nutrition security” in *Small millet grains: The superfoods in human diet* (Singapore: Springer Nature Singapore), 161–190. doi: 10.1007/978-981-16-9306-9_8
- Baby, T., Raheem, M. A. U., Kumar, V. S., Gokari, P., Yadav, A., and Kaur, A. (2023). Pearl millet (*Pennisetum glaucum*) production in the 21st century. *The Pharma Innovation* 12, 2045–2047. doi: 10.22271/tpi.2023.v12.i2y.18694
- Baligar, V. C., Fageria, N. K., and He, Z. L. (2001). Nutrient use efficiency in plants. *Commun. Soil Sci. Plant Anal.* 32, 921–950. doi: 10.1081/CSS-100104098
- Baßmann, B., Harbach, H., Weißbach, S., and Palm, H. W. (2018). Effect of plant density in coupled aquaponics on the welfare status of African catfish, *Clarias gariepinus*. *J. World Aquacult. Soc.* 51, 183–199. doi: 10.1111/jwas.12574
- Besson, M., Komen, H., Rose, G., and Marc, V. (2020). The genetic correlation between feed conversion ratio and growth rate affects the design of a breeding program for more sustainable fish production. *Genet. Sel. Evol.* 52, 5–10. doi: 10.1186/s12711-020-0524-0
- Bittsanszky, A., Gyulai, G., Junge, R., Schmutz, Z., and Komives, T. (2016). “Plant protection in ecocycle-based agricultural systems: aquaponics as an example” in *Presented at the 28th international plant protection congress. August 24–27, 2016* (Berlin, Germany).
- Boxall, R. A., Brice, J. R., Taylor, S. J., and Bancroft, R. D. (2002). “Crop postharvest, science and technology, volume 1, principles and practice” in *Crop post-harvest: Science and technology*, eds. P. Golob, G. Farrell and E. Orchard (Oxford, UK: Blackwell Science Ltd), 141–204. doi: 10.1002/9780470751015.ch5
- Buzby, K. M., and Lin, L. S. (2014). Scaling aquaponic systems: balancing plant uptake with fish output. *Aquac. Eng.* 63, 39–94. doi: 10.1016/j.aquaeng.2014.09.002
- Chaudhary, N., Kumar, R., and Walia, S. (2023). Functional composition, physiological effect and agronomy of future food quinoa (*Chenopodium quinoa* Willd.): a review. *J. Food Compos. Anal.* 118:105192. doi: 10.1016/j.jfca.2023.105192
- Colt, J., and Semmens, K. J. (2022). Computation of feed conversion ratio (FCRplant) and plant-fish mass ratio (PFRM) for aquaponic systems. *Aquac. Eng.* 98:102260. doi: 10.1016/j.aquaeng.2022.102260
- Danner, R. I., Mankasingh, U., Ananthawat-Jonsson, K., and Thorarinsdottir, R. I. (2019). Designing aquaponic production systems towards integration into greenhouse farming. *Water* 11:2123. doi: 10.3390/w11102123
- Delaide, B. 2017 A study on the mineral elements available in aquaponics, their impact on lettuce productivity and the potential improvement of their availability. [Doctoral dissertation]. Université de Liège, Gembloux Agro-Bio Tech, Communauté française de Belgique. Available online at: <https://orbi.uliege.be/bitstream/2268/216289/1/Thesis%20AP%20Boris%20Delaide.pdf>
- Deswati, D., Elsa, Y., Safni, S., Norita, T. O., and Pardi, H. (2022). Development methods in aquaponics systems using biofloc to improve water quality (ammonia, nitrite, nitrate) and growth of tilapia and samhong mustard. *Int. J. Environ. Anal. Chem.* 102, 7824. doi: 10.1080/03067319.2020.1839437
- Dhanushkodi, V., Thanga Hemavathy, A., Shenbagavalli, S., Sangeetha, S., Anitha, R., and UmaMaheshwar, T. (2023). A review on nutritional properties and health benefits of finger millet. *Int. J. Plant Soil Sci.* 35, 753–761. doi: 10.9734/ijppss/2023/v35i183342
- Eck, M., Körner, O., and Ijjakli, M. H. (2019). “Nutrient cycling in aquaponics systems” in *Aquaponics food production systems*, eds. S. Goddek, A. Joyce, B. Kotzen and G. M. Burnell (Cham: Springer), 231–246. doi: 10.1007/978-3-030-15943-6_9
- Effendi, H., Wahyuningsih, S., and Wardiatno, Y. (2017). The use of nile tilapia (*Oreochromis niloticus*) cultivation wastewater for the production of romaine lettuce (*Lactuca sativa* L. var. longifolia) in water recirculation system. *Appl. Water Sci.* 7, 3055–3063. doi: 10.1007/s13201-016-0418-z
- Fabula, J. G., Gavino, H. F., Sace, C. F., Cinense, M. M., Sicat, E. V., and Abucay, J. S. (2023). Growing conditions and system productivity in a closed-loop aquaponic system under varying stocking density. *J. Ecol. Eng.* 24, 25–39. doi: 10.12911/2298993/162210
- Fageria, N. K., and Moreira, A. (2011). The role of mineral nutrition on root growth of crop plants. *Adv. Agron.* 110, 251–331. doi: 10.1016/B978-0-12-385531-2.00004-9
- FAO. (2018). The state of food security and nutrition in the world. Building climate resilience for food security and nutrition. Rome: FAO. The Food and Agriculture organization of the United Nations. Available online at: <http://www.fao.org/3/I9553EN/i9553en.pdf> (Accessed 20 May 2024).
- FAO & CIRAD. (2015). State of the art report on quinoa around the world in 2013; by Bazile, D., Bertero, D., and Nieto, C., eds. Rome. FAO Santiago, Chile CIRAD Montpellier, France.
- Fedoroff, N. V., Battisti, D. S., Beachy, R. N., Cooper, P. J. M., Fischhoff, D. A., Hodges, C. N., et al. (2010). Radically rethinking agriculture for the 21st century. *Science* 327, 833–834. doi: 10.1126/science.1186834
- Filep, R. M., Diaconescu, Ș., Costache, M., Stavrescu-Bedivan, M.-M., Bădulescu, L., and Nicolae, C. G. (2016). Pilot aquaponic growing system of carp (*Cyprinus carpio*) and basil (*Ocimum basilicum*), agriculture and agricultural science Procedia 10, 255–260. doi: 10.1016/j.aaspro.2016.09.062
- Fry, J. P., Mailloux, N. A., Love, D. C., Milli, M. C., and Cao, L. (2018). Feed conversion efficiency in aquaculture: do we measure it correctly? *Environ. Res. Lett.* 13:024017. doi: 10.1088/1748-9326/aaa273
- Ghaly, A. E., Ramakrishnan, V. V., Brooks, M. S., Budge, S. M., and Dave, D. (2013). Fish processing wastes as a potential source of proteins, amino acids and oils: a critical review. *J. Microb. Biochem. Technol.* 5, 107–129. doi: 10.4172/1948-5948.1000110
- Gichana, Z., Liti, D., Wakibia, J., Ogello, E., Drexler, S., Meulenbroek, P., et al. (2019). Efficiency of pumpkin (*Cucurbita pepo*), sweet wormwood (*Artemisia annua*) and amaranth (*Amaranthus dubius*) in removing nutrients from a smallscale recirculating aquaponic system. *Aquac. Int.* 27, 1767–1786. doi: 10.1007/s10499-019-00442-x
- Goddek, S. (2017). *Opportunities and challenges of multi-loop aquaponic systems*. [thesis]. Wageningen, the Netherlands: Wageningen University. 170. doi: 10.18174/412236
- Goddek, S., Espinal, C. A., Delaide, B., Ijjakli, M. H., Schmutz, Z., Wuertz, S., et al. (2016). Navigating towards decoupled aquaponic systems: a system dynamics design approach. *Water* 8:303. doi: 10.3390/w8070303
- Goldstein, B., Hauschild, M., Fernández, J., and Birkved, M. (2016). Urban versus conventional agriculture, taxonomy of resource profiles: a review. *Agron. Sustain. Dev.* 36:19. doi: 10.1007/s13593-015-0348-4
- Gold, V. M. (1999). *Sustainable agriculture: Definitions and terms. Special reference briefs series no. SRB 99-02*. Beltsville, MD: National Agricultural Library.
- Goulding, K., Jarvis, S., and Whitmore, A. (2008). Optimizing nutrient management for farm systems. *Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci.* 363, 667–680. doi: 10.1098/rstb.2007.2177
- Graber, A., and Junge, R. (2009). Aquaponic systems: nutrient recycling from fish wastewater by vegetable production. *Desalination* 246, 147–156. doi: 10.1016/j.desal.2008.03.048
- Greenfield, A., Becker, N., McIlwain, J., Fotedar, R., and Bornman, J. F. (2018). Economically viable aquaponics? Identifying the gap between potential and current uncertainties. *Rev. Aquac.* 11, 848–862. doi: 10.1111/raq.12269
- Gupta, S. M., Arora, S., Mirza, N., Pande, A., Lata, C., Puranik, S., et al. (2017). Finger millet: a “certain” crop for an “uncertain” future and a solution to food insecurity and hidden hunger under stressful environments. *Front. Plant Sci.* 8:643. doi: 10.3389/fpls.2017.00643
- Hassan, Z. M., Sebola, N. A., and Mabelebele, M. (2021). The nutritional use of millet grain for food and feed: a review. *Agric Food Secur.* 10:16. doi: 10.1186/s40066-020-00282-6
- Hymavathi, T., Roberts, T. P., Jyothsna, E., and Sri, V. T. (2020). Proximate and mineral content of ready to use minor millets. *Int. J. Chem. Stud.* 8, 2120–2123. doi: 10.22271/chemi.2020.v8.i2af.9065
- Ibrahim, L. A., Shaghaleh, H., El-Kassar, G. M., Abu-Hashim, M., Elsadek, E. A., and Alhaj Hamoud, Y. (2023). Aquaponics: a sustainable path to food sovereignty and enhanced water use efficiency. *Water* 15:4310. doi: 10.3390/w15244310
- Jayaprakash, K., Muthuselvam, M., Devi, K. N., Santhanam, P., Kumar, S. D., Gunabal, S., et al. (2022). Standardization of the novel aquaponic system for the production of Tilapia fish *Oreochromis niloticus* integrated with millet (*Brassica nigra*) and mustard (*Pennisetum glaucum*) plant: a sustainable approach to reduce the water scarcity through recirculating aquaculture system. *Research Square*. doi: 10.21203/rs.3.rs-1885517/v1
- Kagali, R. N., Ogila, K. O., Mbogo, K. O., Orina, P. S., and Opiyo, M. A. (2025). Performance efficiency of selected medium culture and raft systems for waste removal in a small-scale aquaponics production system. *Aquac. Res.* 36:68908. doi: 10.1155/are/3668908
- Kasoz, N., Abraham, B. J., Kaiser, H., and Wilhelmi, B. 2021 The complex microbiome in aquaponics: significance of the bacterial ecosystem Ann. Microbiol. 71:1 doi: 10.1186/s13213-020-01613-5
- Kasoz, N., Tandlich, R., Fick, M., Kaiser, H., and Wilhelmi, B. (2019). Iron supplementation and management in aquaponic systems: a review. *Aquacult. Rep.* 15:100221. doi: 10.1016/j.aqrep.2019.100221
- Khalili, T. S., and Sampels, S. (2018). Nutritional value of fish: lipids, proteins, vitamins, and minerals. *Rev. Fish. Sci. Aquac.* 26, 243–253. doi: 10.1080/23308249.2017.1399104

- König, B., Janker, J., Reinhardt, T., Villarroel, M., and Junge, R. (2018). Analysis of aquaponics as an emerging technological innovation system. *J. Clean. Prod.* 180, 232–243. doi: 10.1016/j.jclepro.2018.01.037
- König, B., Junge, R., Bittsánszky, A., Villarroel, M., and Kömives, T. (2016). On the sustainability of aquaponics. *Ecocycles* 2, 26–32. doi: 10.19040/ecocycles.v2i1.50
- Kumar, A., Tomer, V., Kaur, A., Kumar, V., and Gupta, K. (2018). Millets: a solution to agrarian and nutritional challenges. *Agric. Food Secur.* 7:31. doi: 10.1186/s40066-018-0183-3
- Lall, S. P., and Kaushik, S. J. (2021). Nutrition and metabolism of minerals in fish. *Animals* 11:2711. doi: 10.3390/ani11092711
- Lall, S. P., and Tibbetts, S. M. (2009). Nutrition, feeding, and behavior of fish. *Exot. Anim. Pract.* 12, 361–372. doi: 10.1016/j.cvex.2009.01.005
- Leimu, R., and Fischer, M. (2008). A Meta-analysis of local adaptation in plants. *PLoS One* 3:e4010. doi: 10.1371/journal.pone.0004010
- Lennard, W. A., and Leonard, B. V. (2006). A comparison of three different hydroponic sub-systems (gravel bed, floating and nutrient film technique) in an aquaponic test system. *Aquac. Int.* 14, 539–550. doi: 10.1007/s10499-006-9053-2
- Lobanov, V., Combot, D., Pelissier, P., Labbé, L., and Joyce, A. (2021). Improving plant health through nutrient remineralization in Aquaponic systems. *Front. Plant Sci.* 12:683690. doi: 10.3389/fpls.2021.683690
- Madigan, M., Martinko, J. M., and Parker, J. (2003). *Brock biology of microorganisms*. 10th Edn. Upper Saddle River, NJ: Prentice Hall.
- Manikaran, S., and Nidhi. (2022). Millets: food for future. Just agriculture (a multidisciplinary e newsletter) Vol. 2, 1–3. <https://justagriculture.in/files/newsletter/2022/august/25.%20Millets%20-%20Food%20for%20Future.pdf>
- Manoharan, R., Asthana, S., Somanathan, N. C., Gokhale, T., Nishanth, D., Jaleel, A., et al. (2026). Exploring the hidden treasure in arid regions: pseudocereals as sustainable, climate-resilient crops for food security. *Front. Plant Sci.* 16:1756967. doi: 10.3389/fpls.2025.1756967
- Manwaring, H. R., Bligh, H. F., and Yadav, R. (2016). The challenges and opportunities associated with biofortification of Pearl millet (*Pennisetum glaucum*) with elevated levels of grain Iron and zinc. *Front. Plant Sci.* 7:1944. doi: 10.3389/fpls.2016.01944
- Maucieri, C., Nicoletto, C., Junge, R., Schmautz, Z., Sambo, P., and Borin, M. (2018). Hydroponic systems and water management in aquaponics: a review. *Ital. J. Agron.* 13:1012. doi: 10.4081/ija.2017.1012
- Maulini, R., D. S., and O. A. (2022). Monitoring of pH, Amonia (NH₃) and temperature parameters Aquaponic water in the 4.0 revolution era. IOP conference series: 2nd international conference on agriculture and applied science (ICoAAS 2021). *Earth Environ. Sci.* 1012:012087. doi: 10.1088/1755-1315/1012/1/012087
- Mori, J., Erickson, K., and Smith, R. L. (2021). Predictive modeling of pH in an aquaponics system using Bayesian and non-Bayesian linear regression to inform system maintenance. *ACS Agric. Sci. Technol.* 1, 400–406. doi: 10.1021/acscagtech.1c00112
- Mujica, A., Jacobsen, S.-E., and Izquierdo, J. (2001). “Resistencia a factores adversos de la quinoa” in *Quinoa (Chenopodium quinoa Willd.) - Ancestral cultivo andino, alimento del presente y futuro*. eds. A. Mujica, S.-E. Jacobsen, J. Izquierdo and J. P. Marathe (Santiago, Chile: FAO, UNA-Puno, CIP), 162–183.
- Murphy, K., and Matanguihan, J. (2012). *Quinoa: Improvement and sustainable production*. Hoboken, NJ: Wiley-Blackwell, 256 <https://www.wiley.com/Quinoa%3A+Improvement+and+Sustainable+Production-p-9781118628058>.
- Nageswari, P., Verma, A. K., Gupta, S., Jeyakumari, A., and Chandrakant, M. H. (2022). Optimization of stocking density and its impact on growth and physiological responses of *Pangasianodon hypophthalmus* (Sauvage, 1878) fingerlings reared in finger millet based biofloc system. *Aquaculture* 551:737909. doi: 10.1016/j.aquaculture.2022.737909
- Nair, C. S., Alsudain, M. B. H., Manoharan, R., Nishanth, D., Subramanian, R., Manga, A., et al. (2024). Sandponics: a sustainable agriculture solution for food security and resource efficiency in arid regions. *J. Sustain. Agric. Environ.* 3:e70033. doi: 10.1002/sae2.70033
- Nair, C. S., Junge, R., Manoharan, R., Nishanth, D., Subramanian, R., Ahmed, Z. F. R., et al. (2025). Marine aquaponics for arid and coastal resilience: closing loops in saline food systems. *Aquacult. Rep.* 45:103123. doi: 10.1016/j.aqrep.2025.103123
- Nicoletto, C., Maucieri, C., Mathis, A., Schmautz, Z., Komives, T., Sambo, P., et al. (2018). Extension of aquaponic water use for NFT baby-leaf production: mizuna and rocket salad. *Agronomy* 8:75. doi: 10.3390/agronomy8050075
- Nidhee, S., and Purnima, S. (2023). Analysis of the proximate composition, mineral content and antioxidant compound of pearl millet flour. *Int. J. Home Sci.* 9, 304–306.
- Nishanth, D., Al-Shamsi, M., Alkaabi, A. M. K. A., AlKaabi, A. H. A., Alnuaimi, S. H. K., Nair, C. S., et al. (2024). Aquaponics as a climate-smart technology for sustainable food production: a comparison with conventional production system in United Arab Emirates. *J. World Aquacult. Soc.* 55, 1–24. doi: 10.1111/jwas.13049
- Nishanth, D., Nair, C. S., Manoharan, R., Subramanian, R., Salim, I., Maqsood, S., et al. (2025). Current technologies for nutrient recovery in aquaponic systems: a review. *Front. Sustain. Food Syst.* 9:1681638. doi: 10.3389/fsufs.2025.1681638
- Nozzi, V., Graber, A., Schmautz, Z., Mathis, A., and Junge, R. (2018). Nutrient management in aquaponics: comparison of three approaches for cultivating lettuce, mint and mushroom herb. *Agronomy* 8:27. doi: 10.3390/agronomy8030027
- Okomoda, V. T., Oladimeji, S. A., Solomon, S. G., Olufegba, S. O., Ogah, S. I., and Ikhwannuddin, M. (2022). Aquaponics production system: a review of historical perspective, opportunities, and challenges of its adoption. *Food Sci. Nutr.* 11, 1157–1165. doi: 10.1002/fsn3.3154
- Palm, H. W., Knaus, U., Appelbaum, S., Goddek, S., Strauch, S. M., Vermeulen, T., et al. (2018). Towards commercial aquaponics: a review of systems, designs, scales and nomenclature. *Aquac. Int.* 26, 813–842. doi: 10.1007/s10499-018-0249-z
- Pantarella, E., Cardarelli, M., Colla, E., Rea, G., and Marcucci, A. (2012). Aquaponics vs. hydroponics: Production and quality of lettuce crop. *Acta Hort.* 927, 887–894. doi: 10.17660/ActaHortic.2012.927.109
- Poonia, A., Bhardwaj, A., and Sai, N. C. S. (2024). “Quinoa” in *Cereals and nutraceuticals* (Singapore: Springer Nature Singapore), 209–250. doi: 10.1007/978-981-97-2542-7
- Radhakrishnan, S. (2020). A pilot study on the lettuce and cucumber mixed cultivation in a recirculated aquaponics system. *Innovations Agriculture* 3:e32827. doi: 10.25081/ia.2020.v4.2197
- Radhakrishnan, S., and Belal, I. E. H. (2022). Growth and yield of cucumber and tilapia fish in aquaponics under UAE climatic condition. *Innovations Agriculture* 5:e32842. doi: 10.25081/ia.2022.v5.001
- Rakocy, J., Bailey, D. S., Thoman, E. S., and Shultz, R. C. (2004a). Intensive tank culture of Tilapia with a suspended, bacterial based, treatment process, Proceedings of 6th international symposium on Tilapia in aquaculture, R. B. Mair, G.C. Bolivar and K. Fitzsimmons, pp. 584–596, Manila, Philippines.
- Rakocy, J. E. (2012). “Aquaponics: integrating fish and plant culture” in *Aquaculture Production Systems*. Editor J. H. Tidwell (John Wiley & Sons), vol. 1, 344–386. doi: 10.1002/9781118250105.ch14
- Rakocy, J. E., Masser, M. P., and Losordo, T. M. (2006). *Recirculating aquaculture tank production systems: Aquaponics integrating fish and plant culture, recirculating aquaculture tank production systems: Aquaponics-integrating fish and plant culture*, vol. 454. United States: SRAC Publication, 1–16.
- Rakocy, J. E., Shultz, R. C., Bailey, D. S., Thoman, E. S., and Nicholseditor, M. A. (2004b). Aquaponic production of tilapia and basil: Comparing a batch and staggered cropping system. International Society for Horticultural Science. *Acta Hort.* 648, 63–69. doi: 10.5555/20043111305
- Ranjan, R., Yadav, R., Kumar, A., and Mandal, S. N. (2019). Contributing traits for nitrogen use efficiency in selected wheat genotypes and corollary between screening methodologies. *Acta Agric. Scand. Sect. B Soil Plant Sci.* 69, 588–595. doi: 10.1080/09064710.2019.1623302
- Richards, R. A. (2000). Selectable traits to increase crop photosynthesis and yield of grain crops. *J. Exp. Bot.* 51 Spec No, 447–458. doi: 10.1093/jexbot/51.suppl_1.447
- Roosta, H. R., and Hamidpour, M. (2011). Effects of foliar application of some macro- and micro-nutrients on tomato plants in aquaponic and hydroponic systems. *Sci. Hortic.* 129, 396–402. doi: 10.1016/j.scienta.2011.04.006
- Sachdev, N., Goomer, S., Singh, L. R., Pathak, V. M., Aggarwal, D., and Chowhan, R. K. (2023). Current status of millet seed proteins and its applications: a comprehensive review. *Appl. Food Res.* 3:100288. doi: 10.1016/j.afres.2023.100288
- Salam, M. A., Asadujjaman, M., and Rahman, M. S. (2013). Aquaponics for improving high density fish pond water quality through raft and rack vegetable production. *World J. Fish. Mar. Sci.* 5, 251–256. doi: 10.5829/idosi.wjms.2013.05.03.7274
- Santos, M. J. P. L. (2016). Smart cities and urban areas—aquaponics as innovative urban agriculture. *Urban Forestry Urban Greening* 20, 402–406. doi: 10.1016/j.ufug.2016.10.004
- Schmautz, Z., Loeu, F., Liebisch, F., Graber, A., Mathis, A., Griessler Bulc, T., et al. (2016). Tomato productivity and quality in aquaponics: comparison of three hydroponic methods. *Water* 8:533. doi: 10.3390/w8110533
- Serna Saldivar, S.O., and Hernández, D.S. (2020). Dietary Fiber in cereals, legumes, Pseudocereals and other seeds. In: J. Welti-Chanes, S. Serna-Saldivar, O. Campanella and V. Tejeda-Ortizgo (eds) Science and Technology of Fibers in food systems. Food Engineering Series. Springer, Cham. doi: 10.1007/978-3-030-38654-2_5
- Sharma, V., Singh, A., and Thakur, M. (2024). “Millets: biology, Classification & Applications” in *World sustainability series*. ed. T. Monika (Cham, Switzerland: Springer International Publishing, Springer Nature Switzerland AG 2024).
- Shaw, C., Knopf, K., and Kloas, W. (2022). Fish feeds in aquaponics and beyond: a novel concept to evaluate protein sources in diets for circular multitrophic food production systems. *Sustainability* 14:4064. doi: 10.3390/su14074064
- Shete, A. P., Verma, A. K., Chadha, N. K., Prakash, C., and Chandrakant, M. H. (2015). A comparative study on fish to plant component ratio in recirculating aquaponic system with common carp and mint. *J. Env. Bio. Sci.* 29: 323–329.
- Soares, J. C., Santos, C. S., Carvalho, S. M. P., Manuela, M. P., and Marta, M. V. (2019). Preserving the nutritional quality of crop plants under a changing climate: importance and strategies. *Plant Soil* 443, 1–26. doi: 10.1007/s11104-019-04229-0
- Subramanian, R., Nair, C. S., Manoharan, R., Nishanth, D., El-Haroun, E., and Jaleel, A. (2025). Integrated nutrient and feeding optimization strategies in aquaponics for sustainable urban food production and water conservation. *Front. Sustain. Food Syst.* 9:1681782. doi: 10.3389/fsufs.2025.1681782
- Sujatha, S., and Bhat, R. (2015). Resource use and benefits of mixed farming approach in arecanut ecosystem in India. *Agric. Syst.* 141, 126–137. doi: 10.1016/j.agry.2015.10.005

- Suwannatrai, K., Namwongsa, K., Phanomkhet, N., Tawil, S., and Roschat, W. (2023) Analysis of the Nile Tilapia fish's (*Oreochromis niloticus* L.) proximate composition in Sakon Nakhon province, Thailand. *Cre. Sci.* 15: 251073. doi: 10.55674/cs.v15i2.251073
- Timmons, M. B., Ebeling, J. M., Wheaton, F. W., Summerfelt, S. T., and Cayuga, B. J. (2002). *Recirculating aquaculture systems*. 2nd Edn. Ithaca: Cayuga Aqua Adventures.
- Tórz, A., Burda, M., Pólgesek, M., Sadowski, J., and Nędzarek, A. (2021). Biochemical transformations of nitrogen compounds in the integrated multi-trophic aquaculture the using media filled beds in plant cultivation. *Aquaculture* 533:736141. doi: 10.1016/j.aquaculture.2020.736141
- Tran-Duy, A., van Dam, A. A., and Schrama, J. W. (2012). Feed intake, growth and metabolism of Nile tilapia (*Oreochromis niloticus*) in relation to dissolved oxygen concentration. *Aquac. Res.* 43, 730–744. doi: 10.1111/j.1365-2109.2011.02882.x
- UN. (2018). United Nations, Department of Economic and Social Affairs, Population Division. World urbanization prospects: The 2018 revision. United Nations. Available online at: <https://population.un.org/wup/assets/WUP2018-Report.pdf>
- Wei, Y., Li, W., An, D., Li, D., Jiao, Y., and Wei, Q. (2019). Equipment and intelligent control system in aquaponics: a review. *IEEE Access* 7, 169306–169326. doi: 10.1109/ACCESS.2019.2953491
- Yang, T., and Kim, H. (2019). Nutrient management regime affects water quality, crop growth, and nitrogen use efficiency of aquaponic systems. *Sci. Hortic.* 256:108619. doi: 10.1016/j.scienta.2019.108619
- Yang, T., and Kim, H.-J. (2020). Characterizing nutrient composition and concentration in tomato-, basil-, and lettuce-based aquaponic and hydroponic systems. *Water* 12:1259. doi: 10.3390/w12051259
- Yep, B., and Zheng, Y. (2019). Aquaponic trends and challenges – a review. *J. Clean. Prod.* 228, 1586–1599. doi: 10.1016/j.jclepro.2019.04.290
- Yıldız, H. Y., Robaina, L., Pirhonen, J., Mente, E., Domínguez, D., and Parisi, G. (2017). Fish welfare in aquaponic systems: its relation to water quality with an emphasis on feed and faeces—a review. *Water* 9:13. doi: 10.3390/w9010013
- Yogev, U., Barnes, A., and Gross, A. (2016). Nutrients and energy balance analysis for a conceptual model of a three loops off grid, aquaponics. *Water* 8:589. doi: 10.3390/w8120589