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Aquaponics as a climate-smart technology for sustainable food production: A comparison with conventional production system in United Arab Emirates

Drishya Nishanth | Mariam H. S. Alshamsi | Alreem M. K. A. Alkaabi | Aysha H. A. AlKaabi | Shamma H. K. Alnuaimi | Chythra Somanathan Nair | Abdul Jaleel

Department of Integrative Agriculture, College of Agriculture and Veterinary Medicine, United Arab Emirates University, Al Ain, United Arab Emirates

Correspondence
Abdul Jaleel, Department of Integrative Agriculture, College of Agriculture and Veterinary Medicine, United Arab Emirates University, Al Ain, P.O. Box 15551, United Arab Emirates.
Email: abdul.jaleel@uaeu.ac.ae

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Abstract

This research aimed to standardize the growth of two commonly cultivated herbs in the United Arab Emirates, basil (*Ocimum basilicum* L.) and coriander (*Coriandrum sativum* L.), within an aquaponic system. The study compared a recirculatory aquaponic system (RAS) with static aquaculture systems (for fish performance) and irrigated greenhouse cultivation systems (for herb performance). The project assessed growth, element composition, and aquaponic efficacy to determine the viability of aquaponics for these herbs. In the soilless (aquaponic) system, both herbs exhibited significantly enhanced growth parameters, including plant height, root length, leaf count, and fresh and dry weights, compared to conventional soil-based cultivation. This growth enhancement was attributed to the additional nutrients derived from fish waste in the aquaponic system. Furthermore, plants displayed significantly higher element levels, highlighting the effectiveness of aquaponics in nutrient delivery. Notably, the aquaponic system demonstrated

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superior antioxidant activity in both herbs. The study also revealed remarkable water use efficiency in the aquaponic system, with water savings exceeding 90% compared to conventional methods. These findings establish the efficiency and sustainability of aquaponic systems over traditional food production approaches, particularly in arid regions such as the United Arab Emirates. Utilizing an aquaponic system for these commonly cultivated herbs resulted in improved growth and resource efficiency, affirming its viability as an environmentally sustainable and efficient method of food production in desert climates.

KEYWORDS
aquaponics, climate-smart farming, food security, sustainable agriculture

1 | INTRODUCTION

As per the FAO statistics, an increase in food production by 50% by 2050 will be required to feed an additional 2 billion people (FAO, 2017a; FAO, 2017b). In this aspect, the current trends in agricultural yield improvements will not be sufficient (Fitton et al., 2019). The current practices in agriculture use a great volume of water to produce food crops worldwide. There is a growing trend toward shifting to zero-fertilizer usage in agriculture. Scientists and experts in the field are stressing the need to shift to sustainable food production techniques. Most of them are cost-effective, but initial investments seem to be very high. Another main problem with these types of production systems is water usage, which will not be a feasible option for countries in arid regions.

Food production depends on natural resources such as availability of arable land, water, energy, and nutrients (Conijn et al., 2018). At present, these resources are getting depleted at an alarming rate that their rate of degradation is several times more than their rate of regeneration (Van Vuuren et al., 2010). The non-availability of agricultural resources makes food production very difficult for the ever-increasing global population. The SDG (Sustainable Development Goals) Goal 2 outlines the importance of feeding the growing global population, which is projected to rise to 10 billion by 2050 (UN, 2017). The rural population is shrinking due to urbanization, and rural labor force constitutes a major portion of agricultural labor (Santos, 2016). Food production faces other challenges such as degradation of land, loss of biodiversity, climate change, and pollution (Bajželj et al., 2014). According to the World Bank Report in 2018 (WorldBank, 2018), one-third of the global land area is put to agricultural use. Yet less than 10% of this area is arable. More forests or natural ecosystems cannot be converted to agricultural lands as this may have many adverse effects such as loss of biodiversity, erosion, natural calamities and so on. Agricultural practices have already degraded and contaminated natural resources worldwide (Garnett, 2011).

In the Middle East, the area available for agriculture is limited. Soil salinity is one major issue. Water scarcity is another issue. The water resources necessary to grow food in the region were depleted long ago (Allan, 1997). Most countries in the region rely on methods such as desalinization to meet the increasing demands (Sowers et al., 2011). In countries such as the United Arab Emirates (UAE), less arable land with most of the fields being under arid and semi-arid zones with little to no rainfall makes it difficult for conventional production systems to meet the ever-increasing food demand. The rational use of water in agriculture is of prime significance as agricultural water usage is costlier than ever. One of the best alternatives for this high-water usage is to change to integrated agriculture production systems, such as recirculating aquaponics. Many recent studies have highlighted the importance of

aquaponics as an alternative plant production system. However, not many studies have been conducted in the UAE and the Gulf region. The arability of the land, soil salinity, and water scarcity make aquaponics one of the best alternatives for plant production in these regions.

Many recent studies have highlighted the importance of aquaponics as an alternative plant production system. Non-soil-based production systems are becoming popular for food production (Abusin & Mandikiana, 2020). Aquaponics is expected to help in meeting some of the SDG goals (Abusin & Mandikiana, 2020). Aquaponics has more benefits when compared to hydroponics and aquaculture systems working separately (Blidariu & Grozea, 2011). Aquaponics is a soilless system of plant production that combines aquaculture and hydroponics (Rakocy et al., 2006). The basic idea behind an aquaponic system consists of three kinds of living organisms: fish, beneficial bacteria, and plants; their interrelations are highly complex and interdependent (Kloas et al., 2015; Love, Fry, et al., 2015; Tisdell, 1999; Tyson et al., 2011). The fish waste generated after the fish eats the fish feed is converted to nutrients for the plant by the bacteria harboring in the biofilters (Rakocy et al., 2011). Standardization of a production system for Nile tilapia (*Oreochromis niloticus*) has already been performed (Rakocy et al., 2006). Research conducted worldwide has proven that aquaponic system of cultivation is possible for a wide variety of vegetable crops. Standardization of vegetable crop production has not yet been done due to the variations in growth patterns and difference in the marketable produce (Ferrarezi & Bailey, 2019). In the current scenario, water availability is the most important limiting factor for food production (Hoekstra et al., 2012; Hoekstra & Mekonnen, 2012). The gap between food demand and food supply is increasing day by day. Aquaponic systems are almost waste-free and have minimum effects on the soil and environment (König et al., 2016). A RAS recycles water, and there is minimum water usage. Thus, such systems have a great potential to be used as an alternative way of food production to feed the increasing world population. In an aquaponic system, the major source of nutrients is the fish feed (Delaide et al., 2017; Schmautz et al., 2017). Fish feed is the major source of nitrogen, phosphorous, potassium, iron, manganese, and zinc (Delaide et al., 2017). Tap water is the major source for elements such as magnesium, calcium, sulfur, boron, and copper (Delaide et al., 2017). After fish feed is added, major part of it is eaten by the fish and excreted as soluble and solid feces (Goddek et al., 2019). Some part of the feed decays in the tank (Schneider et al., 2005). Nitrification is a two-step process wherein ammonia generated from the fish feed and feces is first converted to nitrites. Nitrites are then converted to plant-available form, nitrates. Both the steps in the nitrification process are administered by bacteria harboring in the biofilters. Fish can utilize about 15% of phosphorous and 7% of K contained in the fish feed (Rafiee & Saad, 2005).

One of the most important decisions when it comes to aquaponics is the selection of the fish species. Plants get nutrients from the waste generated by the fish. Thus, careful selection of the species is very important for the successful functioning of an aquaponic system. The selection of fish species depends on the climate and location. The size of the tanks is decided by the stocking density of fish. Often, farmers must make a choice between edible fish and ornamental fish species. When it comes to large-scale commercial aquaponic units, the production of both fish and plants should meet the local market demands (Goddek et al., 2019). Choice of fish species that generate less waste is very important. There should be a balanced fish-to-plant ratio for a successful coupled aquaponic system (Goddek et al., 2019). Fish such as tilapia, catfish, carp, koi, goldfish, barramundi, and various other ornamental fish species are common choices for an aquaponic unit due to their ability to adjust and to survive to the conditions (Yavuzcan Yildiz et al., 2017). The suitability of Nile tilapia (*O. niloticus*) has been investigated in many studies. Nile tilapia has been used as a model fish species with different plant species in different studies (Al-Hafedh et al., 2008; Diem et al., 2017; Simeonidou et al., 2012; Subramanian, 2020). Tilapia is a popular choice for aquaponic units in the desert environment as it can survive in a wide range of water conditions (Subramanian & Belal, 2022).

The cultivation of a wide variety of plant crops under coupled aquaponics has been reported. Herbs can be easily grown in an aquaponic system as their nutrient requirements are less. Plants with medium or high nutritional requirements such as tomato or strawberry might require the addition of additional nutrients externally (Somerville et al., 2014). Lettuce is a crop that has been cultivated successfully in aquaponics for a long time (Subramanian, 2020). Somerville (Somerville et al., 2014) also noted that crops such as cauliflower, broccoli, pepper, peas, beans, and cabbage can also be cultivated under the aquaponic system. Other crops can also be cultivated, and testing of new crop species is being reported worldwide (Knaus & Palm, 2017; Sace & Fitzsimmons, 2013).

Basil (*Ocimum basilicum*) belongs to the Lamiaceae family and is widely cultivated. It is a herb that is native to the African and Asian tropical regions. Basil is cultivated as a medicinal plant. Dried basil is used as a spice and condiment. Basil has been used in traditional medicine as a remedy for diarrhea, headache, cough, and so on (Simon et al., 1984). It was also used against insect bites and skin problems (Waltz, 2001).It is a common ingredient in dental and oral products (Simon & Chadwick, 1984). Basil extracts have many antimicrobial, antinematodal, and insecticidal properties (Zheljazkov et al., 2008). These reasons make it a popular ingredient in the food, pharmaceutical, and perfume industry (Pushpangadan & George, 2012). Basil is a herb that is commonly cultivated in the soil. It is a summer crop and requires well-drained moist soil. It is widely cultivated throughout the world. Basil can be cultivated under the aquaponic system (Love, Uhl, & Genello, 2015). Basil is a good choice for this type of production system due to its fast growth and economic value (Rakocy et al., 2003).

Coriander (*Coriandrum sativum*) belongs to the Apiaceae family. It is also known as cilantro. All parts of this plant are edible though the seeds and leaves are the most widely used plant parts. It is a popular herb used in many cuisines worldwide. Coriander is a rich source of vitamin A and vitamin K. It has many antioxidants and minerals in it. Coriander is a herb that can be successfully cultivated under soil and aquaponic systems as it has low nutritional requirements (Somerville et al., 2014). The nutrients from the fish alone will be enough to sustain the growth of this herb in aquaponics.

Although the production of leafy greens through aquaponics is established, the production of herbs that are used in day-to-day life is not yet explored in this system. In UAE, herbs and spices such as basil and coriander are used in daily life. These are important herbs, and a significant proportion of the currently used herbs are being imported from various countries. The main hindrance in cultivating these herbs locally in the UAE is that they need huge quantities of water for their successful field establishment and growth. The incidence of pests and diseases is another problem in their cultivation. Therefore, this study focuses on establishing a standardization protocol for the cultivation of these herbs through a sustainable and less water used system, namely, recirculated aquaponics with a simultaneous comparison with greenhouse cultivation. Their nutritional composition and quality are also evaluated at the end of the study.

2 | MATERIALS AND METHODS

2.1 | Study location

The study was conducted in Falaj Hazza Experimental Farm of the College of Agriculture and Veterinary Medicine, UAEU, in Al Ain city, 160 km East of Abu Dhabi, the capital city of the United Arab Emirates, co-ordinate latitude and longitude of 24.2191° N and 55.7146° E, with ambient lighting, average daily temperature of 19.2–26.4°C, and relative humidity of 40%–60%.

2.2 | Seed collection

The packed seeds of basil (*O. basilicum*) and coriander (*C. sativum*) were obtained from standard growers and certified seed merchandisers in Al Ain, UAE. For Greenhouse experiment, the seeds of both the plants were sown in pots filled with peat moss and soil mixture and watered daily. The plants were given all the regular cultivation practices. For aquaponic tank, the seeds of both basil and coriander were sown in moisturized rockwool cubes, placed in plastic containers, and sprayed with water every day. The well-grown plants were then transplanted to rockwool slabs.

2.3 | Fish species and experimental setup

For the present study, we used two different types of fish, tilapia (*O. niloticus*) and common catfish (*Clarias batrachus*). The fish fingerlings were obtained from Aquaculture Experimental Station, Falaj Hazza, CAVM, UAEU.

Fingerlings of fish tilapia and common catfish with an average weight of 5 g were used for the study. The fish introduced were fed with standard fish feed (from ARASCO feeds) three times a day as per the recommended dosage. The commercial fish feed nutritional composition is provided in Table 1. The layout of fish production was categorized into six different groups: Group I: tilapia + basil, Group II: tilapia + coriander, Group III: catfish + basil, Group IV: catfish + coriander, Group V: tilapia, and Group VI: catfish.

2.4 | Recirculatory aquaponic unit

For the experiment, a model RAS was established by a standard method (UN., 2017). The system consisted of one fish tank, one biofilter tank, three plant culture troughs with the styrofoam sheet for plant cultivation, and a sump tank with a submersible aquarium pump for water recirculation in the designed aquaponic system. The total system volume of the aquaponic system is given in Table 2, and Figure 1 shows the aquaponic system set up by the continuous aeration system for aquaculture tank and plant cultivation troughs.

2.5 | Plant growth setup in aquaponic and greenhouse system

Plants were grown in rockwool in aquaponic system. Different stages of plant growth setup in aquaponic system is shown in Figure 2. The seeds of both basil and coriander were sown in pots filled with peat moss and soil mixture and watered daily. The plants were given all the regular cultivation practices (Figure 3).

TABLE 1 Feed's proximate composition used in the study to feed tilapia and catfish.

Moisture (%)	Protein (%)	Fiber (%)	Fat (%)	Ash (%)	NFE (%)
4.78 ± 0.10	35.21 ± 0.30	3.41 ± 0.10	3.25 ± 0.18	10.07 ± 0.30	43.06 ± 0.19

TABLE 2 Total system volume of the aquaponic system.

Tanks	Water volume (in m^3)	Number of tanks
Fish tank	8.06	4
Biofilter	0.785	4
Cultivation tank/trough	9.67	4
Re-pumping tank	0.32	4

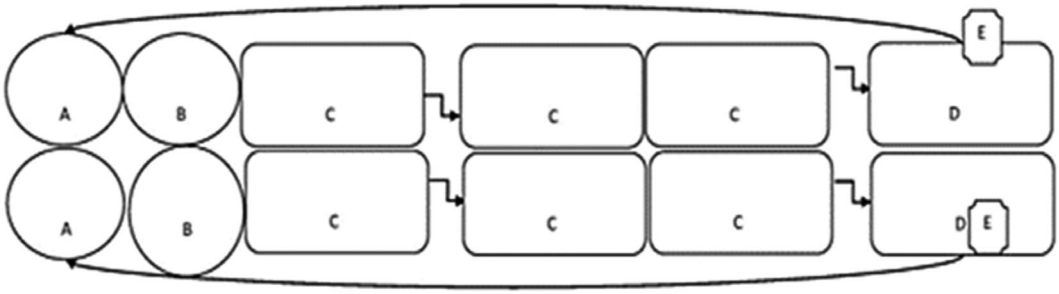


FIGURE 1 Aquaponic setup. (a) fish tank, (b) biofilter, (c) plants, (d) pump, (e) electrical sump.

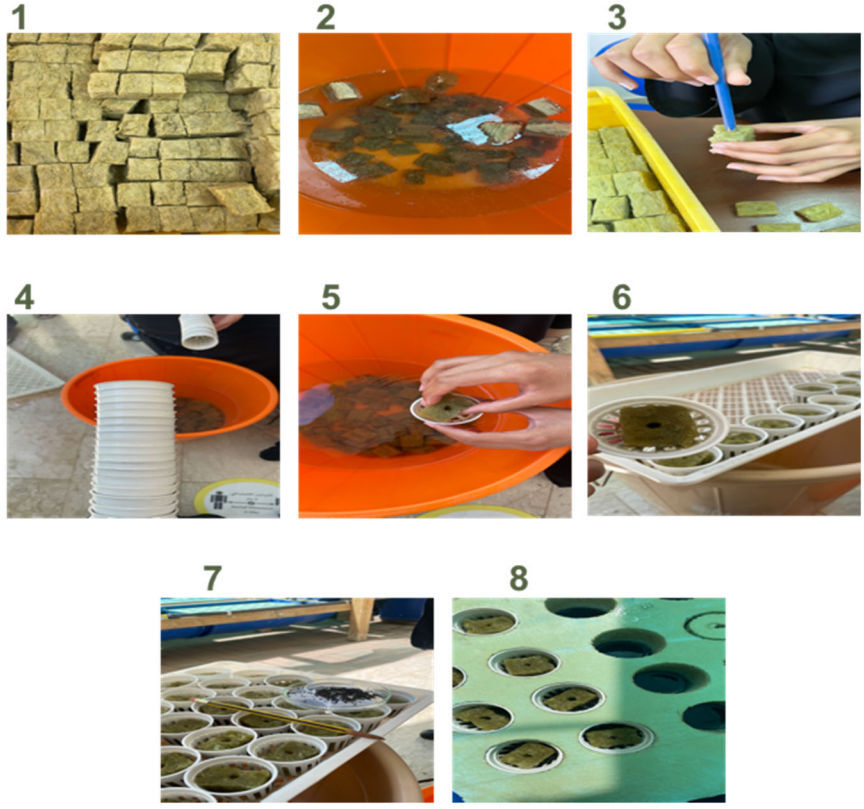


FIGURE 2 Stages of plant growth setup in aquaponic system: (1) rockwool cubes (2.0 cm × 2.0 cm × 2.0 cm), (2) separation, (3) plastic containers, (3) plants transplanting in a Rockwool slabs, (6, 7, and 8) connection to the aquaponic system.

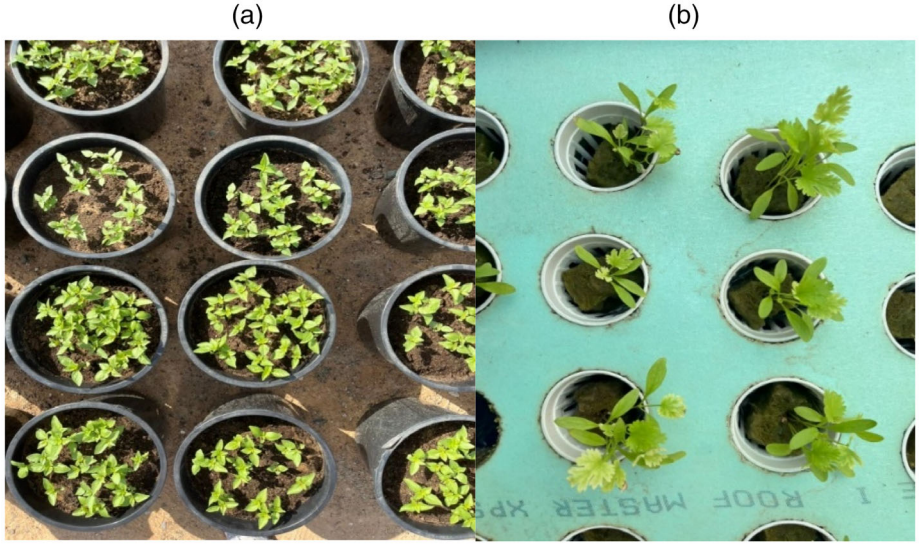


FIGURE 3 (a) Plant grown under greenhouse conditions. (b) Plant grown in rockwool under aquaponic system.

2.6 | Water quality parameters

During the experiment, regular monitoring and analysis of water samples from each system were conducted on a weekly basis. The water quality parameters of pH, temperature, electrical conductivity, total dissolved solids (TDS), NH_3, NO_3^-, and NO_2^- were measured using specific instruments. The pH, temperature, and electrical conductivity were measured using a HACH HQD portable meter (Make: HACH; Model: HQ 40d). The TDS was measured using a HACH TDS meter Pocket pro™ (HACH; Model: DR 900).

2.7 | Water use efficiency

Water use efficiency for each system was calculated. This was accomplished by recording the total water consumption in each system. Based on the results, the water consumption per day (in L) was calculated for each system.

2.7.1 | Hydraulic retention time (HRT)

Hydraulic retention time (HRT) of the aquaponic system was also calculated using the following formula given by Leicester et al. (Leicester et al., 2020):

$$\text{HRT} = \text{volume of tank}/\text{influent flow rate}.$$

2.8 | Fish growth parameters

Fish growth was analyzed for both tilapia and catfish on a regular basis. The parameters such as number of fish introduced to the tanks, weight of fish (kg), weight gain (kg), average weight/fish (kg), consumed feed (kg), feed conversion ratio (FCR) (%), and mortality rate (%) of fish were calculated and tabulated.

2.9 | Plant growth parameters

The coriander plants and basil plants were harvested at 45 days after sowing (DAS). Both species of plants were then evaluated for their length (leaf to root), shoot length, root length, total weight, shoot weight, leaf weight, and average leaf number per plant. The height of both basil and coriander plants was measured from the soil surface to the tip of the shoot. The values were then expressed in "cm." The plant root lengths were also expressed in "cm" as the length from the point of first cotyledonary node to the tip of the longest root. The number of fully opened and developed leaves per plant was counted and expressed as the number of leaves per plant. The plants were first washed with tap water. The fresh weight was then determined using an electronic balance (expressed in grams). The plants were then dried at 60°C for 48 h in a hot air oven. The plant dry weight and the root dry weight were then measured in grams.

2.10 | Estimation of photosynthetic pigments

Chlorophyll and carotenoid were extracted from the leaves and estimated by the method of Arnon (Arnon, 1949). Anthocyanin was extracted and estimated from the flowers by the method of Beggs and Wellmann (Beggs &

Wellmann, 1985). Xanthophyll was extracted and estimated from fresh plant tissues by the method of Neogy et al. (Neogy et al., 2001). The results were then expressed as milligrams/gram of FW.

2.11 | Biochemical analysis

2.11.1 | Biochemical composition analysis in cultivated plants

The estimation of protein content was conducted using the Bradford method, as described by Bradford (Bradford, 1976). A standard curve was generated utilizing bovine serum albumin (BSA) as the reference protein. This curve was subsequently employed to quantify the protein content, with the outcomes being reported in milligrams per gram of dry weight. The estimation of total phenols was conducted using the method developed by Malick and Singh (Malick & Singh, 1980). The quantification of total phenols was conducted by employing a standard curve that was constructed by utilizing various quantities of gallic acid. The quantification of free proline was conducted using the methodology proposed by Bates et al. (Bates et al., 1973).

2.12 | Element analysis

Simultaneous determination of major elements and trace metals in plant samples was performed by the method of ICP-OES (Inductively Coupled Plasma Optical Emission Spectroscopy). The prepared mixed calibration standard solutions (Merck) were aspirated to construct calibration curves for each element. Calibration check standard solutions (Romil) was aspirated, and the value was recorded. The prepared sample solutions were aspirated, and the concentration from the calibration curve was determined. Ash content analysis was performed by weighing 0.5 g of the sample. It was then placed in a crucible. The crucible with the sample was then placed in a furnace and ignited at 550°C. The weight difference was then recorded.

2.13 | Antioxidant activity studies

For the preparation of the extract, ten times the volume of methanol was added to one part of the powdered plant sample. After overnight spinning, the solution was filtered and dried in a hot air oven at 50°C for 24 h. The dried extract obtained was then dissolved in 10% dimethyl sulfoxide. The resulting extract was then stored for later analysis.

The ABTS (2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid)) radical scavenging activity of the samples was measured using the method of Wolfenden and Willson (Wolfenden & Willson, 1982). The ABTS+ solution was prepared by the addition of 7 mM ABTS solution and 140 mM potassium persulfate solution and incubated in the dark for 16 h. The ABTS+ solution was diluted with ethanol to make an absorbance of 0.70 ± 0.02 at 734 nm. The extract (10 µL) and 290 µL of freshly prepared ABTS+ solution was added to the 96-well plate and incubated at 25°C for 6 min. The absorbance was read at 734 nm. The standard curve was generated with Trolox (1 mM), which was linear between 0 and 800 µM. The results were then expressed as % inhibition or µmolTE/g of sample as described by Aldhanhani et al. (Aldhanhani et al., 2022).

DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging assay was performed by the method of Brand-Williams et al. (Brand-Williams et al., 1995). Stock solutions of DPPH were prepared by dissolving 24 mg of DPPH in 100 mL methanol. The solution was then shaken in a sonicator for 20 min. The working solution was then prepared by

diluting 20 mL of stock solution with 80 mL methanol (5X dilution). Trolox (1 mM) was used to make the standard curve, which was linear between 0 and 800 μM.

2.14 | Statistical analysis

Statistical analysis was performed using one-way analysis of variance (ANOVA) followed by Duncan's multiple range test (DMRT). The values are mean ± SD for nine samples in each group. P values ≤0.05 were considered as significant.

3 | RESULTS

3.1 | Water quality parameters

The present study conducted a weekly analysis of various water parameters to evaluate the quality of water in an aquaponic system of plants. Internal observations of the system were analyzed to determine the water quality parameters. Data of weekly average water quality parameters of soilless (aquaponics) system are given in Table 3. The water temperature exhibited fluctuations between 22°C and 25°C during the analysis, as indicated in Table 4. Among the parameters examined, the highest dissolved oxygen levels were observed in the fish-growing systems. The levels of water temperature, dissolved oxygen, pH, TDS, EC, NH_3, NO_3^-, and NO_2^- demonstrated variations during different intervals of the aquaponic system. Based on existing literature, the recommended pH ranges for tilapia fish, plants, and nitrifying bacteria are 6 to 9, 5.5 to 6, and 7 to 8, respectively. Therefore, it can be inferred that maintaining a pH of 7 would be a suitable compromise for aquaponics.

3.2 | Water use efficiency

The water consumption rates in both aquaponic and soil systems were calculated for the entire study period, and the results indicated that the daily average water consumption rates in the greenhouse system were much higher than those of the aquaponic systems (Figure 4). Average daily system volume discharge from the aquaponic system is given in Table 5.

3.2.1 | Hydraulic retention time

HRT of the aquaponic system was calculated using the following formula: HRT = volume of tank/influent flow rate.

Total volume of tank = 18.83 cubic m.

Influent flow rate = 544.32cubic m per day.

The calculated HRT is 0.34 h or 20.4 min.

3.3 | Fish growth parameters

Fish growth was analyzed for both tilapia and catfish on a regular basis. The parameters such as number of fish introduced to the tanks, weight of fish (kg), weight gain (kg), average weight/fish (kg), consumed feed (kg), feed conversion ratio (FCR) (%), and mortality rate (%) of fish were calculated and tabulated (Table 6).

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TABLE 3 Weekly average water quality parameters of aquaponic system.

System	Weeks	Dissolved oxygen (mg/L)	pH	TDS (ppm)	EC (mV)	NH_3 (mg/l)	NO_3^- (mg/l)	NO_2^- (mg/l)
Exp I (Jan–Feb)	1	5.01 ± 0.04	7.02 ± 0.04	310.11 ± 1.122	18.22 ± 0.05	0.14 ± 0.02	4.91 ± 0.02	0.41 ± 0.01
	2	5.27 ± 0.04	6.77 ± 0.03	384.25 ± 1.25	20.00 ± 0.05	0.22 ± 0.04	7.85 ± 0.04	0.18 ± 0.02
	3	4.02 ± 0.03	6.52 ± 0.03	314.98 ± 0.71	22.11 ± 0.05	0.21 ± 0.04	13.00 ± 0.05	0.12 ± 0.03
	4	3.09 ± 0.02	6.99 ± 0.03	390.22 ± 1.41	25.74 ± 0.03	0.17 ± 0.03	20.14 ± 0.06	0.14 ± 0.03
	5	4.02 ± 0.03	6.85 ± 0.04	398.25 ± 1.04	40.00 ± 0.12	0.05 ± 0.02	20.11 ± 0.04	0.17 ± 0.03
	6	3.88 ± 0.03	6.88 ± 0.02	384.55 ± 1.52	32.01 ± 0.04	0.11 ± 0.04	21.14 ± 0.05	0.19 ± 0.04
	7	3.77 ± 0.02	6.99 ± 0.05	398.41 ± 0.98	32.00 ± 0.05	0.47 ± 0.03	19.00 ± 0.04	0.17 ± 0.01
	8	5.02 ± 0.04	7.01 ± 0.05	387.87 ± 0.99	41.00 ± 0.15	0.77 ± 0.04	20.14 ± 0.06	0.21 ± 0.04

TABLE 4 Water parameters of the aquaponic system at the beginning and end of the study period.

	At the beginning			At the end		
Parameters	**U1**	**U2**	**U3**	**U1**	**U2**	**U3**
pH	7.80	7.10	7.20	7.42	7.21	7.32
Temperature (°C)	21.6	20.7	20.2	29.2	28.3	27.9
NH_3	0.25	0.5	0.25	0.25	0.25	0.25
NO_2^- (ppm)	0	0	0	0	0	0.5
NO_3^- (ppm)	5	0	0	5	0.25	5
DO (mg/L)	5.01	5.0	5.0	4.0	4.03	4.32
EC (mV)	1.40	0.515	0.524	1.35	0.518	0.544
TDS (ppm)	879	322	322	780	395	374

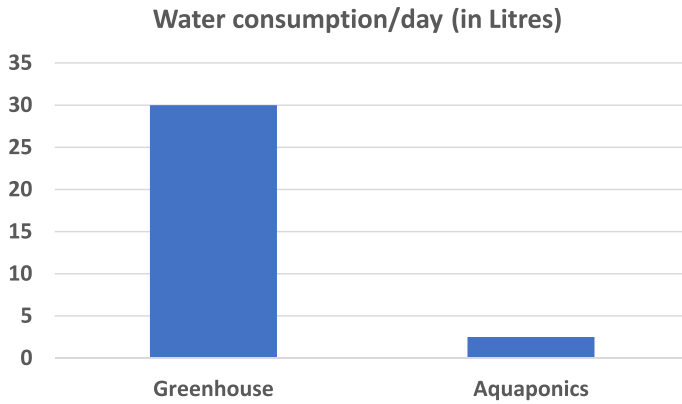


FIGURE 4 Water consumption rates expressed as consumption/day (in liters) in different systems of cultivation.

TABLE 5 Average daily system volume discharge from the aquaponic system.

Tank	Water volume (in m^3)	Average discharge volume (m^3)
Fish tank	8.06	0.24
Bio-filter	0.785	0.024
Cultivation tank/trough	9.67	0.29
Re-pumping tank	0.32	0.0096

3.4 | Plant growth parameters

3.4.1 | Morphological parameters

The growth performance of basil and coriander plants in both aquaponic and soil systems was monitored over time in the present study. The results indicated that both plant species exhibited an increase in height as they grew since their introduction to the respective systems. The maximum height of both plants was achieved at the end of the experimental period. A comparison of plant growth between aquaponic and greenhouse systems revealed a reduced height for both basil and coriander in the latter (as shown in Table 7). The mean plant height of basil in the aquaponic

TABLE 6 Fish growth rate, weight increment and feed consumption in different growth systems.

System	Months	Number of fish	Weight of fish (kg)	Weight gain (kg)	Average weight/ fish (kg)	Consumed feed (kg)	FCR (%)	Mortality rate (%)
Group I	Initial	50	0.7	0	0.014	0	0	0
	2 months	44	3.26	2.56	0.074	5.48	2.14	12
Group II	Initial	50	0.68	0	0.013	0	0	0
	2 months	41	3.74	3.06	0.091	5.44	1.78	18
Group III	Initial	50	0.91	0	0.02	0	0	0
	2 months	41	3.85	2.94	0.09	5.3	1.80	18
Group IV	Initial	50	0.7	0	0.014	0	0	0
	2 months	43	5.47	4.77	0.12	8.8	1.84	14
Group V	Initial	50	0.77	0	0.154	0	0	0
	2 months	38	3.02	2.25	0.79	6.00	2.67	24
Group VI	Initial	50	0.75	0	0.015	0	0	0
	2 months	39	4.26	3.51	0.11	5.88	1.68	22

Note: Group I: tilapia + basil, Group II: tilapia + coriander, Group III: catfish + basil, Group IV: catfish + coriander, Group V: tilapia, and Group VI: catfish; FCR: feed conversion rate.

TABLE 7 Plant growth parameters in different systems of cultivation.

	Aquaponic system		Greenhouse system	
Growth parameters	Basil	Coriander	Basil	Coriander
Total plant height (cm)	67.41 ± 9.82^{a}	34.05 ± 7.24^{a}	65.54 ± 9.32^{b}	29.18 ± 5.27^{b}
Root length (cm)	28.11 ± 5.44^{a}	21.14 ± 4.32^{a}	23.90 ± 4.94^{b}	17.11 ± 3.25^{b}
Leaves (No.)	111.00 ± 23.01^{a}	33.00 ± 7.01^{a}	102.74 ± 28.20^{b}	29.00 ± 17.36^{b}
Total wet weight (g)	47.11 ± 13.60^{a}	18.20 ± 3.25^{a}	43.84 ± 12.12^{b}	15.11 ± 10.21^{b}
Total dry weight (g)	4.99 ± 1.60^{a}	2.35 ± 0.71^{a}	3.80 ± 1.26^{b}	2.01 ± 0.67^{a}
Root dry weight (g)	0.76 ± 0.33^{a}	0.47 ± 0.32^{a}	0.45 ± 0.20^{b}	0.29 ± 0.21^{b}

Note: In each group, the values are shown as the mean ± SD of nine samples. When applying the DMRT, values that do not have the same superscript (a, b) differ significantly at $p < 0.05$.

system was 67.41 cm, while in the greenhouse, it was 65.54 cm. Similarly, the mean plant height of coriander was 34.05 cm in the aquaponic system, whereas it was only 29.18 cm in the greenhouse.

The results indicated an increase in root length with age for both plant species in both systems. A comparison of the root length between the two systems showed a decreased root length in the soil system as compared to the aquaponic system (as depicted in Table 7). The average root length of basil was 23.90 cm under the greenhouse system and 28.11 cm under the aquaponic system, while the mean root length of coriander was 21.14 cm in the aquaponic system and only 17.11 cm under the greenhouse system. Additionally, the number of leaves for both coriander and basil plants increased with age in both aquaponic and greenhouse systems. However, a comparison of the number of leaves between the two systems revealed a reduced number of leaves in the greenhouse system as compared to the aquaponic system (as shown in Table 7).

3.4.2 | Photosynthetic pigments

Estimation of chlorophyll "a" content was done for both basil and coriander herbs by randomly selecting samples from both aquaponic and greenhouse systems. The outcomes are given in Figure 5 and Figure 6. The chlorophyll "a" content for basil was considerable higher in the plants grown in the greenhouse system (0.45 mg/g FW). A similar trend was also noticed in the case of coriander plants wherein the greenhouse-grown plants exhibited a higher chlorophyll "a" content (0.81 mg/g FW). The enhancement in the chlorophyll "a" content was statistically significant for both herbs in the greenhouse systems.

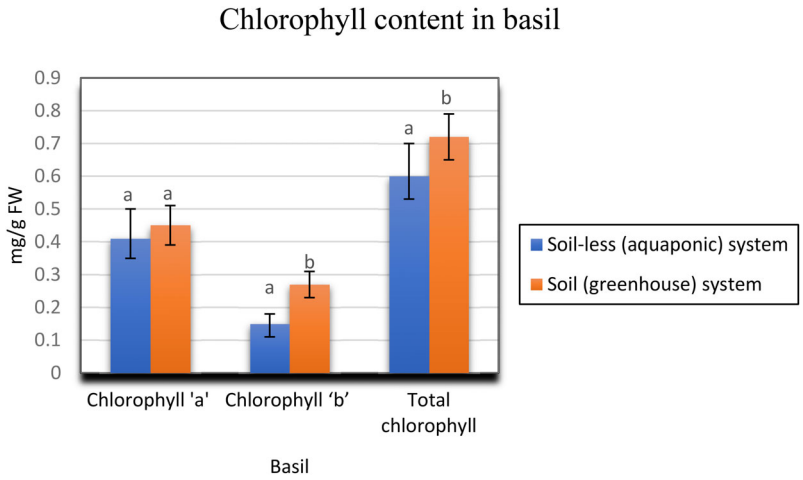


FIGURE 5 Chlorophyll content in basil (Ocimum basilicum). Values are given as mean ± SD of nine experiments in each group. Values that are not sharing a common superscript (a,b) differ significantly at $p \leq 0.05$ (DMRT).

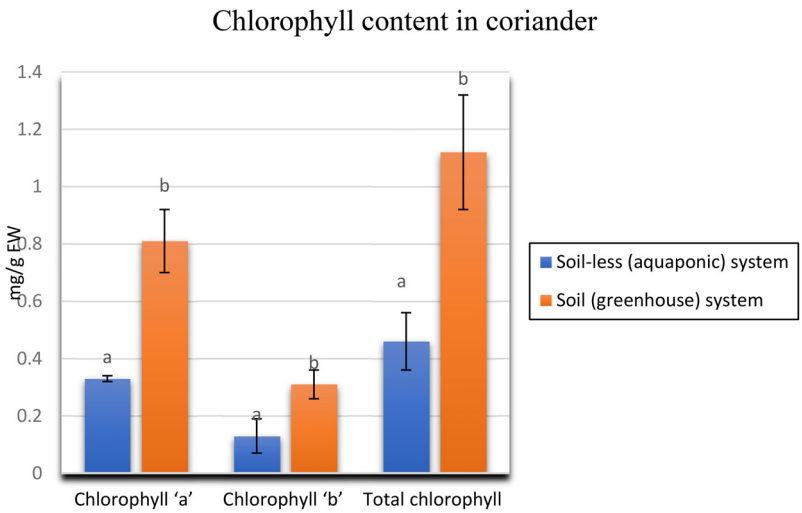


FIGURE 6 Chlorophyll content in coriander (*Coriandrum sativum*). Values are given as mean ± SD of nine experiments in each group. Values that are not sharing a common superscript (a,b) differ significantly at $p \leq 0.05$ (DMRT).

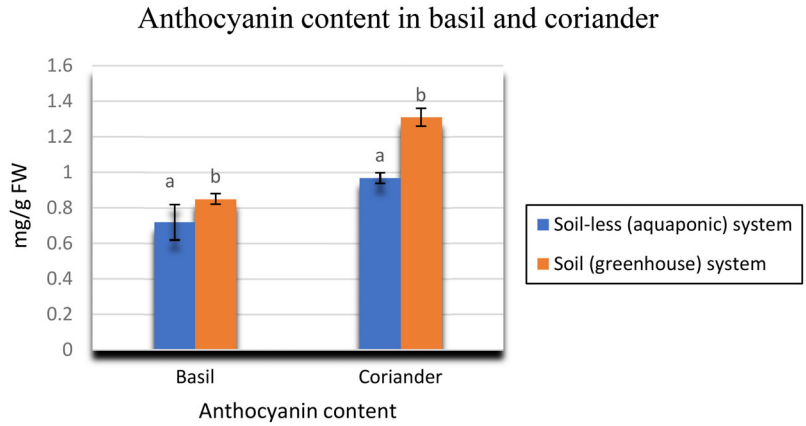


FIGURE 7 Anthocyanin content in *Ocimum basilicum* and *Coriandrum sativum*. Values are given as mean ± SD of nine experiments in each group. Values that are not sharing a common superscript (a,b) differ significantly at $p \leq 0.05$ (DMRT).

Moreover, the plants from the greenhouse system also showed a higher concentration of chlorophyll "b" for both basil and coriander. For basil, the chlorophyll "b" concentration was 0.15 mg/g FW in aquaponics, while it was 0.27 mg/g FW in greenhouse. Similarly, the concentration of chlorophyll "b" for coriander plants was only 0.13 mg/g FW in the aquaponic system, while it was 0.31 mg/g FW for the plants under the greenhouse system.

Furthermore, the total chlorophyll content for basil plants was found to be higher for plants grown under the greenhouse system (0.72 mg/g FW) as compared to the aquaponic ones (0.6 mg/g FW). A comparable pattern was also observed in the case of coriander plants. The total chlorophyll content was 0.46 mg/g FW for the aquaponic plants and 1.12 mg/g FW for the greenhouse plants.

The anthocyanin content (Figure 7) was higher for basil plants grown under the greenhouse system (0.85 mg/g FW) than for the plants grown under aquaponics (0.72 mg/g FW). Similarly, the concentration of anthocyanin was higher for greenhouse-cultivated coriander plants 0.97 mg/g FW for the aquaponic plants, while it was 1.31 mg/g FW for the greenhouse plants. Overall, the highest anthocyanin concentration was observed in the greenhouse-cultivated coriander plants.

The highest concentration of xanthophyll pigment was recorded for the coriander plants grown under the greenhouse system (Figure 8). The aquaponically grown coriander plants recorded an average concentration of 1.78 mg/g FW. Similarly, for basil, the concentration of xanthophyll was 2.6 mg/g FW for the greenhouse plants, whereas it was only 1.78 mg/g FW for the aquaponic plants.

3.4.3 | Biochemical analysis

Protein content of the plants under investigation was measured in percentage (%). In the case of basil, there was only a slight variation in the protein content between the greenhouse plants and the aquaponic plants (Table 8). However, the protein % was higher for the greenhouse plants (18.7%) than for the aquaponic plants (18%). When it comes to coriander (Table 6), the protein percentage showed a significant increase for the aquaponic plants (21.9%). It was only 15.5% for the greenhouse plants.

Total phenol was measured as mg gallic acid equivalent per g of fresh weight of the samples. The trend was like that of protein for basil plants (Table 8). The greenhouse plants (12.58 mg GAEq g^{-1} FW) had a higher concentration of total phenol than the aquaponic plants (10.09 mg GAEq g^{-1} FW) for basil. In the case of coriander, the trend was opposite. It was 6.30 mg GAEq g^{-1} FW for the aquaponic plants and 5.55 mg GAEq g^{-1} FW for the greenhouse plants.

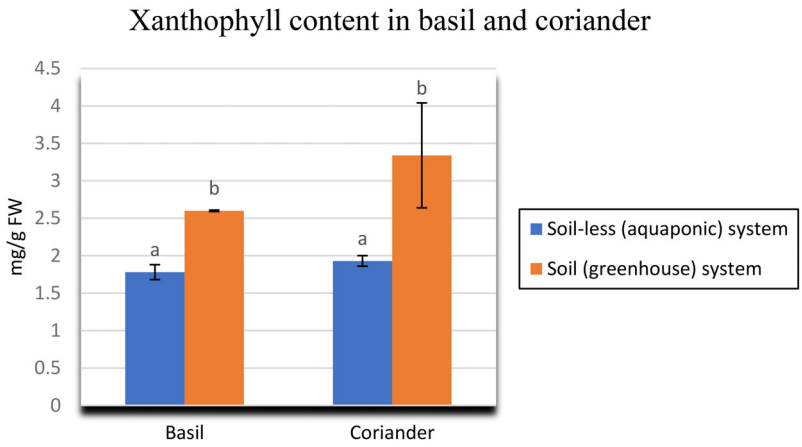


FIGURE 8 Xanthophyll content in *Ocimum basilicum* and *Coriandrum sativum*. Values are given as mean ± SD of nine experiments in each group. Values that are not sharing a common superscript (a,b) differ significantly at $p \leq 0.05$ (DMRT).

TABLE 8 Biochemical parameters of *Ocimum basilicum* and *Coriandrum sativum* in aquaponic and greenhouse systems.

	Aquaponic system		Greenhouse system	
Biochemical parameters	**Basil**	**Coriander**	**Basil**	**Coriander**
Protein (%)	18.7 ± 2.3^{a}	21.9 ± 2.6^{a}	18.0 ± 2.07^{a}	15.1 ± 1.5^{b}
Total phenol (mg GAEq g^{-1} FW)	10.09 ± 4.06^{a}	6.30 ± 0.7^{a}	12.58 ± 1.32^{b}	5.55 ± 1.53^{b}
Free proline (proline/g of FW)	6.8 ± 0.64^{a}	8.63 ± 1.2^{a}	25 ± 2.2^{b}	3.95 ± 0.9^{b}

Note: In each group, the values are shown as the mean ± SD of nine samples. When applying the DMRT, values that do not have the same superscript (a, b) differ significantly at $p < 0.05$.

Free proline was measured per gram of fresh weight of the samples. In the case of the basil plants, there was a significant increase in free proline (25.0 proline/g of FW) for the greenhouse plants, while it was only 6.8 proline/g of FW for the aquaponic plants. When it comes to coriander (Table 8), the free proline content was only 3.95 proline/g of FW for the greenhouse plants, while it was 8.63 proline/g of FW for the aquaponically grown plants.

3.4.4 | Micro and macroelements

The analysis of macroelements and microelements for both herbs from both systems was performed at the end of the study. The macroelements were measured in percentage (%), while the microelements were measured in parts per million (ppm). As evident from Table 9, the macroelement concentrations were generally higher for aquaponically grown basil plants. The concentration of phosphorous (0.74%) was higher for the greenhouse basil plants. The concentration of all the macroelements (Table 9) was higher for aquaponically grown coriander plants. The aquaponic plants showed an increased microelement concentration for basil and coriander when compared to the greenhouse plants (Tables 9 and 10). The cobalt concentration (0.6 ppm) was similar for both greenhouse plants and aquaponic plants in the case of basil. For coriander plants, the cobalt concentration was slightly higher than for greenhouse plants (0.5 ppm).

TABLE 9 Macroelements (%) and microelements (ppm) for *Ocimum basilicum* under aquaponic and greenhouse systems at the end of the growth period.

Elements	Growth systems	
Macroelements (%)	**Aquaponics**	**Greenhouse**
Nitrogen (N)	5.0 ± 0.38[a]	4.88 ± 0.33[b]
Phosphorus (P)	0.84 ± 0.09[a]	0.74 ± 0.07[b]
Potassium (K)	1.0 ± 0.42[a]	0.9 ± 0.15[b]
Magnesium (Mg)	0.44 ± 0.09[a]	0.4 ± 0.02[a]
Calcium (Ca)	2.12 ± 0.8[a]	2.61 ± 0.15[b]
Sulfur (S)	0.25 ± 0.06[a]	0.24 ± 0.04[b]
Microelements (*ppm*)		
Sodium (Na)	87.7 ± 14.4[a]	73.3 ± 5.4[b]
Cobalt (Co)	0.6 ± 0.14[a]	0.6 ± 0.13[a]
Copper (Cu)	17.6 ± 1.4[a]	13.2 ± 6.3[b]
Iron (Fe)	82.8 ± 7.9[a]	77.3 ± 7.1[b]
Manganese (Mn)	95.9 ± 10.9[a]	81.8 ± 4.7[b]
Zinc (Zn)	54.0 ± 5.4[a]	59.3 ± 4.6[b]

Note: In each group, the values are shown as the mean ± SD of nine samples. When applying the DMRT, values that do not have the same superscript (a, b) differ significantly at $p < 0.05$.

3.4.5 | Antioxidant activity studies

The DPPH radical scavenging activity was measured in units of μmol Trolox equivalent/g of sample. It is clear from Table 10 that the Trolox equivalent/g of the sample was higher for the aquaponic plants for both basil (48.80) and coriander (26.52) in comparison with the greenhouse-grown ones (Table 11).

ABTS radical scavenging assay is another method to measure the antioxidant activity in plant samples. As evident from Table 11, the aquaponic plants of both basil and coriander showed higher antioxidant activity than the greenhouse plants.

4 | DISCUSSION

4.1 | Water quality parameters

Maintaining optimal water quality is of paramount importance when striving to establish equilibrium among the needs of fish, plants, and bacteria within the aquaponic system's RAS components (Subramanian, 2020). It is imperative to maintain the correct temperature to facilitate the optimal growth of the selected fish species and plants within the system (Filep et al., 2016). According to Kohinoor (Kohinoor, 2000) and Anita and Pooja (Anita & Pooja, 2013), the suitable temperature range for fish culture falls in the range 18.5–32.9°C and 15–30°C, respectively. The temperature in the aquaponic system kept fluctuating between 22 and 25 ° C, which was in favor of the fish culture. Dissolved oxygen (DO) holds vital significance as it serves a crucial role in distinguishing various water masses (Ibrahim & Ramzy, 2013). Furthermore, it is essential for the aerobic nitrifying bacteria, which require oxygen for the production of nitrate (NO_3^-) (Henriksen et al., 1981). The DO concentration was highest in week 2 of analysis (5.27 mg/L) but remained within acceptable limits as per the findings of Lloyd (Lloyd, 1992). TDS is an indicator

TABLE 10 Macroelements (%) and microelements (ppm) for *Coriandrum sativum* under aquaponic and greenhouse systems at the end of the growth period.

Elements	Growth systems	
Macroelements (%)	**Aquaponics**	**Greenhouse**
Nitrogen (N)	6.0 ± 0.38[a]	4.08 ± 0.33[b]
Phosphorus (P)	0.64 ± 0.08[a]	0.71 ± 0.06[b]
Potassium (K)	1.1 ± 0.41[a]	0.88 ± 0.16[b]
Magnesium (Mg)	0.47 ± 0.09[a]	0.5 ± 0.03[b]
Calcium (Ca)	3.01 ± 0.9[a]	2.9 ± 0.16[a]
Sulfur (S)	0.35 ± 0.06[a]	0.21 ± 0.03[b]
Microelements (*ppm*)		
Sodium (Na)	87.7 ± 14.4[a]	73.3 ± 5.4[b]
Cobalt (Co)	0.5 ± 0.14[a]	0.5 ± 0.12[a]
Copper (Cu)	19.6 ± 1.5[a]	18.2 ± 4.5[b]
Iron (Fe)	72.8 ± 6.8[a]	71.2 ± 6.1[b]
Manganese (Mn)	89.1 ± 11.9[a]	77.8 ± 3.7[b]
Zinc (Zn)	44.0 ± 4.4[a]	41.3 ± 3.1[b]

Note: In each group, the values are shown as the mean ± SD of nine samples. When applying the DMRT, values that do not have the same superscript (a, b) differ significantly at $p < 0.05$.

TABLE 11 DPPH and ABTS radical scavenging activity (μmol Trolox equivalent/g of sample) by *Ocimum basilicum* and *Coriandrum sativum* plants grown under aquaponic and greenhouse systems.

Antioxidant activity	Herb	Aquaponic system	Greenhouse system
DPPH	Basil	48.80 ± 3.58[a]	24.05 ± 2.14[b]
	Coriander	26.52 ± 9.8[a]	11.31 ± 1.15[b]
ABTS	Basil	350.51 ± 200[a]	281.63 ± 165.37[b]
	Coriander	544.19 ± 60.18[a]	241.8 ± 72.05[b]

Note: In each group, the values are shown as the mean ± SD of nine samples. When applying the DMRT, values that do not have the same superscript (a, b) differ significantly at $p < 0.05$.

of the deteriorating water quality in an aquaponic system. Any value greater than 500 ppm is detrimental to fish and plant health (Wibowo et al., 2019). In our study, the TDS value was within the range of 300–400 ppm throughout the study period. According to literature, a pH of 7 is an ideal compromise for an aquaponic system (Gosh & Chowdhury, 2019). The nitrification process depends on the pH of the system, and a pH below 6 almost stops the nitrification process (Nelson, 2008). A pH range of 6.5–7 was maintained throughout the study, indicating that the pH was tolerable to all three components of the system. Fish generates waste in the form of ammonia. Ammonia is a waste product produced by fish. Nitrosomonas bacteria first turn ammonia into nitrite. Nitrobacter bacteria then change nitrite into nitrate. Nitrates are the form of nitrogen that plants absorb. The nitrogen cycle's crucial nitrification process turns ammonia from its reduced form to its oxidized form, nitrate (Prosser, 1990). The plants absorb nitrogen in this form. Nitrogen in the form of nitrites is toxic to fish even in very small amounts (Thangam, 2014). It is clear from our study that the levels of ammonia and nitrite were within what fish and plants could tolerate. Therefore, the fish and plants in our study were not negatively affected by the levels of ammonia and nitrite present in the environment.

4.1.1 | Water use efficiency

The data presented in Figure 4 illustrate a remarkable disparity in water consumption between the aquaponic system and the greenhouse system. In fact, the aquaponic system exhibits an extraordinary water-saving capacity, conserving over 90% of water compared to its greenhouse counterpart. This substantial reduction in water usage aligns closely with the findings of earlier research, particularly a study conducted by AlShrouf (AlShrouf, 2017). Furthermore, investigation conducted by Monsees (Monsees et al., 2019) also supports the notion that forward-looking methods such as aquaponics possess substantial potential for significantly curtailing water consumption in agriculture, potentially achieving reductions of up to 60%. These outcomes underscore the environmentally sustainable and water-efficient nature of aquaponic systems in the realm of food production.

4.1.2 | Hydraulic retention time

A short period of 0.34 h was the calculated HRT of the aquaponic system. According to Wallace-Springer et al. (Wallace-Springer et al., 2022) and Shete et al. (Shete et al., 2016), short HRT in aquaponics boosts water use efficiency by improving nutrient uptake by plants, reducing water loss, ensuring adequate oxygen supply, and preventing nutrient buildup, leading to a more efficient and productive system.

4.2 | Fish growth parameters

The analysis of weight gain in both catfish and tilapia within the aquaculture and aquaponic systems yielded noteworthy insights. Notably, catfish exhibited the highest weight gain when raised in the catfish + coriander aquaponic unit, with an impressive increase of 87.2%. On the other hand, tilapia demonstrated the most substantial weight gain when cultivated alongside coriander, boasting an 81.81% increase. Following closely, the tilapia + basil unit showed a significant weight gain of 78.52%, while tilapia in isolation exhibited a commendable weight gain of 74.5%. These findings align with prior research, specifically a study conducted by Ariadi et al. (Ariadi et al., 2020), which highlighted the positive impact of Kailan (*Brassica oleracea*) and Pakcoy (*B. rapa*) plants on the growth rate and feed conversion ratio of tilapia. Moreover, our study sheds light on the elevated mortality rates observed in the aquaculture environment, where tilapia faced a 24% mortality rate, and catfish experienced a 22% mortality rate.

Building upon these results, it is pertinent to reference a study by Oladimeji et al. (Oladimeji et al., 2020), which evaluated the performance of a catfish–pumpkin aquaponic system in comparison with recirculatory and static aquaculture systems. Their findings concurred with ours, emphasizing the enhanced efficiency of fish production within an aquaponic system. In summary, our study provides further support for existing research, particularly in the context of fish growth, while highlighting the potential advantages of aquaponics over traditional aquaculture methods.

4.3 | Plant growth parameters

In our research, we observed that both basil and coriander plants experienced increased growth in height after being introduced into the aquaponic system. This was not just limited to height; other growth indicators such as root length, leaf count, and the weight of the plants (both in dry and wet conditions) showed significant improvements in plants cultivated within the aquaponic setup compared to those grown in a greenhouse. The key factor at play here is nitrogen, which is essential for the vegetative growth of plants (Raven et al., 1986). It is reasonable to infer that the additional nutrients, particularly nitrogen, made available to the plants in the aquaponic system played a pivotal role in their heightened growth. This pattern aligns with findings from Savidov's research (Savidov, 2005), which demonstrated that crops such as cucumbers and tomatoes achieved superior yields when cultivated in aquaponic

systems as opposed to hydroponic ones. In essence, our findings underscore the importance of nutrient availability, notably nitrogen, in enhancing plant growth within aquaponic systems. This strengthens the case for aquaponics as a promising approach for efficient and sustainable crop cultivation.

4.4 | Photosynthetic pigments

The chlorophyll "a" and chlorophyll "b" content in both basil and coriander plants was found to be elevated in the greenhouse system. This observation aligns closely with the findings of a prior study conducted by Albadwawi et al. (Albadwawi et al., 2022) involving basil plants. Similarly, the concentration of the xanthophyll pigment was notably higher in greenhouse-grown basil and coriander plants. This trend was also observed in the case of anthocyanin pigment in both basil and coriander.

Interestingly, our results diverge from those reported in earlier research conducted by Sankhalkar et al. (Sankhalkar et al., 2019), where Okra (*Abelmoschus esculentus*) and moong (*Vigna radiata*) displayed higher chlorophyll content in soilless systems as compared to traditional soil-based systems. Additionally, a contrasting outcome was also noted in a study by Mullis and Reyes (Mullis & Reyes, 2019), which found no significant difference in chlorophyll content between basil plants grown in soilless and soil-based systems. These discrepancies highlight the complexity of plant responses to different cultivation methods and emphasize the need for further investigation in this area.

4.5 | Biochemical analysis

The analysis of protein content indicated that basil and coriander plants cultivated through aquaponics exhibited a greater percentage of protein content compared to alternative cultivation methods. This observation is in line with the findings of Albadwawi et al. (Albadwawi et al., 2022) who reported that basil raised in an aquaponic setting demonstrated an elevated protein content when contrasted with basil grown in a greenhouse, thereby confirming earlier research outcomes.

However, the assessment of phenol content yielded mixed results within our study. Aquaponically grown basil plants demonstrated reduced phenol content, whereas coriander plants displayed augmented phenol levels. According to a previous study conducted by Braglia et al. (Braglia et al., 2022), parsley (*Petroselinum crispum*) and basil (*O. basilicum*) plants showed a higher phenolic content in soil on a fresh basis, while the results were opposite when the assay was done on a dry basis. This study is in support of the above-mentioned study as the aquaponically grown coriander showed higher phenolic content. The results were opposite for basil wherein the soil plants had more phenolic activity. Thus, we can conclude that the antioxidant levels of plants in both soil and soilless systems are high. Plants can be grown in both the systems without compromising on their antioxidant levels.

Proline accumulation serves as a responsive mechanism to both biotic and abiotic stressors (Verbruggen & Hermans, 2008) and serves as an indicator of salt-induced stress (Meloni et al., 2001). In our investigation, basil plants grown in a greenhouse system displayed an elevated concentration of free proline, implying potential stress responses in this context. Conversely, coriander plants nurtured in soil-based systems showcased a higher concentration of free proline, signifying an alternate response to stress factors. These discrepancies underscore the intricate manners in which plants react to distinct growth environments and stressors, emphasizing the necessity for further research in this realm.

4.6 | Microelements and macroelements

4.6.1 | Macroelements

Both basil and coriander aquaponic plants in the current study had higher nitrogen concentrations than greenhouse plants. For the element's potassium and calcium, a comparable pattern was seen. For coriander grown in aquaponic

systems, the phosphorus concentration was higher. The concentration of phosphorus was higher in the greenhouse-grown basil plants. In aquaponics, fish is the primary source of nutrients (Roosta & Hamidpour, 2013). The aquaculture effluents are phosphorous and nitrogen-rich (Cerozi & Fitzsimmons, 2017). The bacteria in the biofilters convert these effluents into forms that are useful to plants. In aquaponics, the flow of nitrogen to the plants is constant (Wongkiew et al., 2017). Thus, the current study supports each of the earlier studies that were mentioned. This highlights the importance of understanding the nitrogen cycle in aquaponic systems and how it can be optimized for plant growth.

Regarding magnesium concentration, there was no discernible difference between basil plants grown in aquaponic and greenhouse systems. Coriander grown in aquaponics had a magnesium content that was significantly higher than that of plants grown in a greenhouse. The concentration of sulfur was the same. The basil grown in aquaponic systems contained less sulfur than plants grown in greenhouses. This suggests that the aquaponic system may have a different nutrient profile or uptake mechanism compared to traditional greenhouse systems, which could have implications for the nutritional content and flavor of the basil.

4.6.2 | Microelements

Microelement concentrations were measured in parts per million (ppm). For basil, aquaponically grown plants exhibited higher levels of sodium, cobalt, and zinc compared to soil-cultivated counterparts. Copper concentrations showed no significant difference between aquaponic and soil-grown basil. Interestingly, aquaponically grown basil had lower iron and manganese levels. In contrast, coriander plants from aquaponic systems showed significantly higher concentrations of sodium, cobalt, manganese, and zinc, with copper levels remaining consistent between aquaponic and greenhouse coriander. Notably, aquaponically grown coriander had lower iron content. It is important to note that micronutrient supply is often insufficient in aquaponic systems (Bittsánszky et al., 2016), consistent with previous studies. This aligns with Kasozi et al.'s research (Kasozi et al., 2019), highlighting the essential role of iron in plant photosynthesis and cellular functions, as well as its significance in fish cellular processes. Typically, aquaponic systems lack sufficient iron (Kasozi et al., 2019), as evidenced by our study, where aquaponically cultivated basil and coriander had lower iron content compared to their greenhouse counterparts.

Ashing is the first step in element analysis. Ashing helps in determining the mineral content in plants, after the complete combustion or oxidation of organic matter (Harris & Marshall, 2017). The ash content for both basil and coriander plants were more in the aquaponic system than in the soil system, indicating that the element content in aquaponically produced plants is higher than for plants produced in the soil system.

4.7 | Antioxidant assay

In our study, we utilized both the DPPH and ABTS+ assays to assess the antioxidant activity of basil and coriander cultivated in both traditional soil-based systems and innovative soilless aquaponic systems. We measured antioxidant activity based on dry weight to ensure consistency and accuracy in our comparisons. Our findings align with a prior investigation conducted by Braglia et al. (Braglia et al., 2022), which discovered that dill and basil plants exhibited higher antioxidant activity in soil when assessed on a fresh basis, with contrasting results when the assessment was conducted on a dry weight basis. Our study corroborates Braglia et al.'s (Braglia et al., 2022) findings, as we observed that aquaponically grown basil and coriander plants displayed elevated antioxidant activities.

Therefore, we can confidently conclude that the antioxidant levels in plants from soilless systems are comparable to those in soil-based systems. This suggests that cultivating crops aquaponically does not compromise their antioxidant activities. Our research underscores the viability of aquaponic cultivation methods for maintaining or even enhancing the antioxidant properties of these crops, further emphasizing the potential of aquaponics in sustainable agriculture.

5 | CONCLUSION

In conclusion, this research was conducted to standardize aquaponic production of basil and coriander plants in the UAE, utilizing edible fish species such as tilapia and catfish. The objective was also to compare the growth and quality of these plants with conventional greenhouse cultivation methods under the unique climatic conditions of the region. The study yielded promising results for the adoption of aquaponics as a sustainable agricultural practice in the UAE. Basil and coriander plants cultivated through aquaponics demonstrated impressive growth rates and exhibited superior quality compared to those grown conventionally in greenhouses. The efficient nutrient cycling within the aquaponic system, facilitated by fish waste conversion through beneficial bacteria, played a pivotal role in these outcomes. Additionally, the study revealed the water-saving potential of aquaponics, conserving over 90% of water compared to greenhouse cultivation. This water efficiency aligns with global sustainability goals and addresses pressing concerns related to water scarcity in arid regions such as the UAE.

Moreover, the elevated chlorophyll pigment concentrations and favorable biochemical parameters, such as increased protein content and antioxidant activity, underscore the health and nutritional benefits of crops produced through aquaponics. The analysis of macro- and microelement concentrations further confirmed the viability of aquaponics, with plant nutrient levels comparable to those grown conventionally. This suggests that aquaponically produced crops maintain their nutritional integrity.

Furthermore, the study highlighted the growth potential of fish in aquaponic systems, making it a viable alternative to traditional aquaculture. The analysis of water quality parameters emphasized the efficient nutrient cycling process in aquaponics, contributing to its sustainability. In a country like the UAE, where arable land is limited, and water resources are precious, aquaponics emerges as a sustainable and resource-efficient method of food production. The ability to cultivate essential herbs such as basil and coriander locally reduces dependency on imports, conserves vital resources, and enhances food security.

This research underscores the significant potential of aquaponics in the UAE and other regions facing similar challenges. By harnessing the advantages of aquaponic systems, nations can transition toward sustainable food production, mitigate water scarcity concerns, and contribute to long-term food security and resource conservation.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

Abdul Jaleel https://orcid.org/0000-0002-2513-764X

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