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Optimizing Basil Aquaponics: Divergent Advantages of Nutrient Film and Deep-Water Culture Systems

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ABSTRACT

Aquaponics, a symbiotic integration of aquaculture and hydroponics, represents a closed-loop cultivation paradigm that augments resource-use efficiency and sustainability in modern crop production. Basil (*Ocimum basilicum* L.), a premium culinary and medicinal herb frequently adopted as a model species in aquaponic cultivation, has been investigated extensively in relation to nutrient and irrigation regimes; nevertheless, direct comparisons of plant performance under distinct system architectures remain scarce. Here, we present the first comprehensive evaluation of basil growth dynamics within nutrient film technique (NFT) and deep-water culture (DWC) aquaponics, assessed at two phenological stages (40 and 70 days after sowing, DAS). A factorial experimental framework was implemented to quantify fish growth, basil biomass, water-use efficiency (WUE), pigment profiles and biochemical attributes. Our findings demonstrate that NFT consistently conferred superior WUE, exhibiting increases of 45% and 49% relative to DWC at 40 and 70 DAS, respectively. In contrast, the DWC system fostered enhanced fish productivity, basil biomass accumulation, chlorophyll and carotenoid enrichment, and metabolite profiles, particularly pronounced at 70 DAS. Both designs exhibited a stage-dependent decline in WUE, with reductions of 12.2% and 14.4% for NFT and DWC, respectively. Collectively, these results underscore the divergent functional advantages of NFT and DWC aquaponics and deliver critical insights for tailoring system design to maximize basil productivity and resource efficiency in water-limited agroecosystems.

1 | Introduction

The United Arab Emirates (UAE) lies within an arid to hyper-arid climatic belt, characterized by extremely limited precipitation, where water scarcity constitutes the foremost constraint to agricultural production (Ammar 2022). According to World Bank data, the average annual precipitation in the UAE from 1991 to 2020 was about 78 mm (≈3.1 inches), highlighting its extreme dry conditions (World Bank 2023). Although agriculture remains the single largest consumer of freshwater resources, its contribution to the national gross domestic product (GDP) is marginal, accounting for < 1% (Ammar 2022). The country's total GDP in 2023 stood at ~$514.13 billion nominally, highlighting the relatively minor economic role of the agricultural sector (Worldometers 2025). The challenge is further compounded by inherently poor soil quality, with only about 13% of cultivated land classified as moderately suitable for agricultural activities (Abdelfattah 2013). To sustain domestic demand, the country relies heavily on nonconventional water sources, predominantly seawater desalination and

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treated wastewater reuse (Murad 2010). However, projections indicate that by 2030, groundwater reserves may face near-complete depletion, intensifying the urgency to adopt alternative water resources for agriculture (Shahin and Salem 2015). Superimposed upon this structural limitation, climate change has exacerbated regional water stress, while the UAE's elevated greenhouse gas (GHG) emissions have further aggravated environmental vulnerabilities (Ajaj et al. 2019). Food security is an equally pressing concern: with nearly 90% of its food supply imported, the nation remains acutely vulnerable to fluctuations in global supply chains and international market volatility (Ammar 2022; Degefa 2022). This reliance underscores the strategic imperative of enhancing local food production capacity. Accordingly, the UAE government has prioritized the development of resilient alternative food production systems, including soilless cultivation and controlled-environment agriculture (CEA), as part of a broader vision to mitigate dependency on imports (Al Qaydi 2016). These initiatives are embedded within comprehensive policy frameworks such as the National Strategy for Food Security 2051, and are operationalized through institutional mechanisms like the Emirates Council for Food Security, both of which aim to bolster domestic agricultural output and safeguard long-term food sovereignty (Al-Qodsi et al. 2024).

Aquaponics has emerged as a rapidly advancing paradigm of sustainable food production, particularly well-suited for water-scarce and arid environments where it is increasingly recognized as a climate-smart agricultural innovation aligned with the United Nations Sustainable Development Goals (Oliveira et al. 2020; Ibrahim et al. 2023). Operating as a recirculating, closed-loop system, aquaponics integrates aquaculture with hydroponics, achieving water-use efficiencies (WUE) reported to reach nearly 90% (Nishanth et al. 2024; Nair et al. 2025). Such efficiency underscores its value in arid and semi-arid regions, where conventional agriculture is severely constrained by freshwater scarcity. Beyond water conservation, aquaponic systems substantially reduce reliance on synthetic fertilizers, as nutrient recycling and biological interactions within the system regulate both plant nutrition and pest dynamics. By coupling aquaculture with soilless plant cultivation, aquaponics has been shown to enhance crop performance and enrich nutritional quality in high-value herbs such as basil and coriander (Nishanth et al. 2024). The potential for elevated productivity is further evidenced by integrated trials, where systems co-cultivating tilapia and cucumber achieved yields of up to 3.2 tons of cucumber and 0.5 tons of tilapia within a compact production module (Subramanian and Bilal 2022). Moreover, aquaponics transcends its role as a production technique to become a model for urban innovation. Its incorporation into sustainable housing designs demonstrates its promise as a localized food production strategy for densely populated cities with limited land resources (Mohanan et al. 2023). Localized studies conducted within the UAE context have demonstrated aquaponics' remarkable suitability to desert climates. Trials growing basil and coriander in closed aquaponic systems yielded significantly higher biomass, nutrient uptake and antioxidant activity, while achieving over 90% water savings compared to conventional soil-based agriculture (Nishanth et al. 2024). These attributes position aquaponics as a transformative approach to sustainable intensification, offering a multifaceted response to the dual challenges of food security and water scarcity in vulnerable agro-ecosystems.

Basil (*Ocimum basilicum* L. [*O. basilicum*]), a premium culinary and aromatic herb of the Lamiaceae family, commands significant global demand, positioning it as an ideal candidate for CEA (Modarelli et al. 2023). The species exhibits remarkable adaptability, thriving under both conventional soil-based systems and advanced soilless cultivation techniques. The species also exhibits marked agronomic plasticity across cultivation modes: beyond conventional soils, basil performs robustly in soilless systems, tolerating stringent hydroponic conditions (e.g., low phosphorus with elevated salinity) under proper nutrient management, and showing strong growth and functional responses in aquaponics relative to hydroponics (Germano et al. 2022). Accumulating evidence demonstrates that basil production in hydroponic and aquaponic systems not only enhances resource-use efficiency but also reduces environmental burdens relative to traditional cultivation (Geldenhuys 2024; Mourantian et al. 2023). Adoption of such innovative growing practices contributes to lowering the carbon footprint of basil production while maintaining high yield stability and quality consistency (Modarelli et al. 2023). Aquaponic cultivation further eliminates the dependence on synthetic fertilizers, since nutrient availability is sustained through biological nutrient cycling, thereby coupling ecological sustainability with production efficiency (Modarelli et al. 2023; Geldenhuys 2024). Collectively, these attributes highlight the promise of aquaponics as a robust and sustainable production strategy for basil in both densely populated urban centres and resource-limited arid regions. Basil has become a widely studied model species in aquaponics owing to its high market value, relatively modest nutrient demands and short life cycle, which permits multiple successive harvests within a single growing season (Rodgers et al. 2022). Comparative evaluations of basil grown in aquaponic, hydroponic and conventional soil-based systems have examined parameters such as biomass accumulation, photosynthetic efficiency and nutrient assimilation (Walters and Currey 2015; Mourantian et al. 2023). These studies consistently report that aquaponic cultivation can yield superior outcomes, with basil exhibiting increased biomass accumulation, greater dry matter content, and, in some cases, enhanced phytochemical attributes when compared to alternative production methods (Mourantian et al. 2023). Importantly, basil performance is not uniform across aquaponic systems; design configurations play a decisive role in determining growth efficiency and yield outcomes (Walters and Currey 2015). Consequently, system architecture represents a critical determinant of productivity, reinforcing the necessity for rigorous evaluations of design-specific impacts on basil physiology and water-use dynamics.

Despite the growing prominence of aquaponics as a sustainable food production strategy, systematic evaluations of crop performance across distinct system designs remain scarce. In particular, no prior study has directly compared the growth trajectories of basil under alternative aquaponic configurations, as most existing research has concentrated on aquaponic–hydroponic comparisons. Basil has been extensively studied in aquaponic cultivation, including both NFT and DWC systems, but direct comparative assessments of plant growth, pigment

profiles, biochemical attributes and WUE across these distinct system architectures remain scarce. The gap is especially critical in arid regions such as the UAE, where system architecture can strongly influence both water- and nutrient-use efficiency. Understanding how plant growth responses vary between designs and across developmental stages is therefore essential for tailoring resource-efficient production strategies. Moreover, comparative assessments at key phenological stages such as 40 and 70 days after sowing (DAS) offer the potential to identify periods of peak productivity and sustainability benefits. The 40 DAS stage represents mid-growth, when basil plants are well established and vegetative growth is active. The 70 DAS stage corresponds to near maturity, when plants reach maximum biomass and quality for harvest. Accordingly, the present study was undertaken to conduct a rigorous evaluation of fish growth, basil growth performance, physiological responses and nutrient composition along with overall system performance, under two contrasting aquaponic designs—deep-water culture (DWC) and nutrient film technique (NFT), at both 40 and 70 DAS.

2 | Materials and Methods

2.1 | Study Location

The experiment was carried out inside a polycarbonate greenhouse at Falaj Hazza Research Station, College of Agriculture and Veterinary Medicine, United Arab Emirates University (UAEU), Al Ain, Abu Dhabi, UAE. Al Ain, located to the east of Abu Dhabi, is characterized by a desert climate with pronounced aridity. The region experiences average daily temperatures ranging from 19°C to 27°C, with ambient natural lighting and a mean relative humidity of 40%–60%. These environmental conditions were maintained inside the greenhouse to ensure consistent temperature and humidity throughout the experiment.

2.2 | Fish Species

Nile tilapia (*Oreochromis niloticus* (*O. niloticus*)) was selected as the aquaculture component of the aquaponic system. Fingerlings with an average initial weight of ~5 g were procured from the Aquaculture Experimental Research Station, Falaj Hazza, Al Ain, UAE. The fish were reared at a stocking density of 50 individuals/system (NFT and DWC), corresponding to an equal biomass input across treatments to ensure comparability of nutrient availability for plant uptake. Fish were fed a standard commercial diet three times daily, at 2.5% of their body weight and formulated to meet species-specific nutritional requirements. The proximate composition of the feed is presented in Table 1.

2.3 | Experimental Setup

Basil (*O. basilicum*) seedlings were cultivated under two aquaponic system configurations: the NFT and DWC. The plants were evaluated at two developmental stages 40 and 70 DAS to assess treatment effects across growth phases. Seeds were germinated in rockwool cubes, and seedlings at the 3–4 leaf stage were transplanted into net pots for system establishment. In the NFT system, seedlings were positioned in slightly inclined polyvinyl chloride (PVC) channels that facilitated the recirculation of a thin film of nutrient-enriched water derived from the aquaculture tanks. A total of 115–120 plants were grown in the NFT channels, as the thin flowing water film allows each plant to thrive with a relatively small water volume. The design allowed for partial root exposure to air, thereby ensuring adequate oxygen availability throughout the experimental period. In contrast, the DWC system utilized floating rafts that suspended the basil plants in reservoirs containing 15–30 cm of nutrient-rich water. The DWC system supported a total of 80 plants because each plant required a larger water volume to maintain root submersion and nutrient uptake. Aeration was maintained using air stones to provide continuous oxygenation of the root zone. The number of plants remained the same at both 40 and 70 DAS in each system, although plant size and water-nutrient demand increased as the basil developed. In both systems, nutrient supply originated from the fish culture water, thereby integrating aquaculture effluents into plant production. The primary objective of the experiment was to compare WUE, growth dynamics, nutrient uptake and overall system performance between NFT and DWC configurations across two growth stages. System parameters were continuously monitored for 10 weeks, with weekly measurements of pH, dissolved oxygen (DO, $mg\,L^{-1}$), electrical conductivity (EC, $dS\,m^{-1}$), total dissolved solids (TDS, ppm), ammonia ($mg\,L^{-1}$), nitrite ($mg\,L^{-1}$) and nitrate ($mg\,L^{-1}$) concentrations.

2.4 | The Recirculatory Aquaponic Unit

A recirculatory aquaponic system (RAS) was established to facilitate a comparative evaluation of basil growth under the NFT and DWC configurations. Each system comprised two subsystems corresponding to different cultivation durations (40 DAS and 70 DAS), resulting in a total of four treatments. Each subsystem consisted of a fish tank, a canister filter incorporating both mechanical and biological filtration, a submersible water pump for recirculation, and air stones to maintain DO levels through continuous aeration. While the overall system architecture was standardized, the plant cultivation method differed between treatments. In the DWC configuration, basil roots were fully submerged in a nutrient-enriched solution, whereas in the NFT configuration, a shallow film of water continuously

TABLE 1 | Proximate composition of the formulated fish diet used in the study, indicating the relative proportions of key nutritional components.

Moisture (%)	Protein (%)	Fibre (%)	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

Note: Data adapted from Nishanth et al. (2024).

TABLE 2 | Total system volumes of the deep-water culture (DWC) and nutrient film technique (NFT) aquaponic configurations.

System type	Component	Number of units	Volume per unit (m^3)	Total volume (m^3)
DWC	Fish tank	2	0.38483	0.76966
	Canister filter	2	0.01	0.02
	Plant bed	2	0.30	0.60
	Sump	2	0.25	0.50
DWC total				1.88966
NFT	Fish tank	2	0.38483	0.76966
	Canister filter	2	0.01	0.02
	Plant bed	2	0.17725	0.35450
	Sump	2	0.20	0.40
NFT total				1.54416

Note: The table summarizes the volumetric capacity of individual components (fish tanks, canister filters, plant beds and sumps), along with their respective unit numbers, volumes and cumulative totals for each system design.

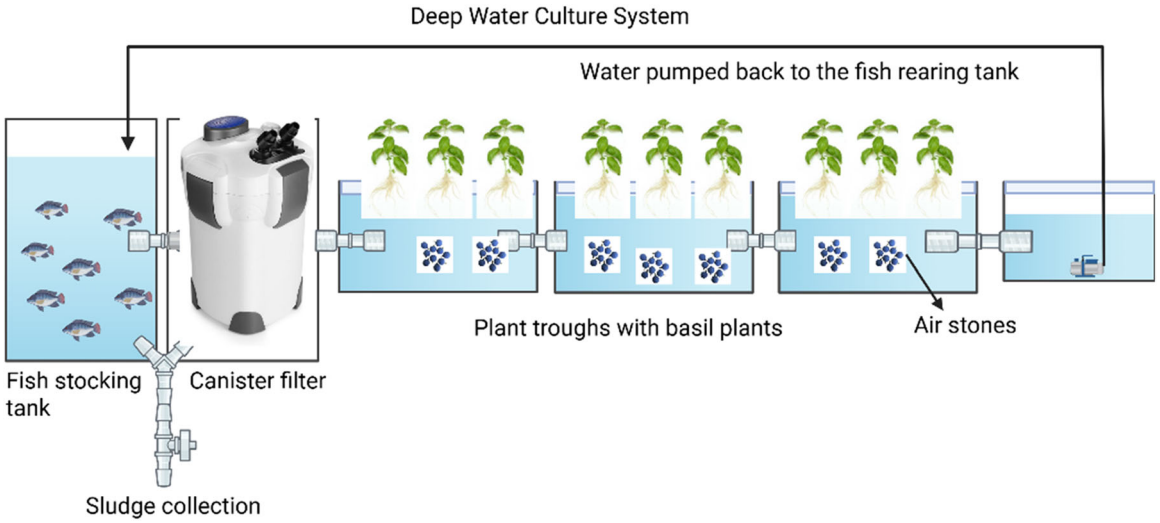


FIGURE 1 | Schematic representation of the deep-water culture (DWC) aquaponic system used in the study. The design consists of a fish rearing tank connected to a canister filter unit incorporating both mechanical and biological filtration, with sludge collected at the outlet. Nutrient-rich effluent water is continuously circulated into plant troughs holding basil seedlings suspended on floating rafts, where roots remain fully immersed. Aeration was maintained by air stones to ensure adequate dissolved oxygen levels. After nutrient uptake by plants, the water was recirculated back into the fish tank, thereby completing the closed-loop configuration.

circulated across the root surface, leaving part of the roots exposed to air for oxygenation. To ensure experimental consistency, identical fish stocking densities were maintained in both NFT and DWC systems, thereby eliminating potential confounding effects arising from unequal nutrient availability. Table 2 presents the system volumes for each configuration, while schematic representations of the NFT and DWC setups are provided in Figures 1 and 2.

2.5 | Water Quality Parameters

Water quality was systematically monitored throughout the experimental period at weekly intervals to ensure optimal conditions for both plant and fish growth. The parameters recorded included pH, DO, EC, TDS, temperature and nitrogenous compounds—namely ammonia (NH_3), nitrite (NO_2^-) and nitrate (NO_3^-). A digital pH metre was employed to measure the pH while nitrogen compounds were quantified using a HACH Fish Farming Test Kit. EC and TDS were measured using a portable waterproof EC/TDS metre. DO was maintained through aeration by air stones in both systems, with concentrations verified during weekly monitoring. WUE was assessed at 6 weeks (40 DAS) and 10 weeks (70 DAS) in both NFT and DWC systems. WUE was calculated following the classical definition of Briggs and Shantz (1913), expressed as the ratio of total plant biomass to the volume of water consumed during the growth period:

$$\text{WUE (g/L)} = \text{Total Biomass Yield (g)/Total water used (L)}.$$

2.6 | Fish Growth Parameters

The influence of aquaponic system design (NFT and DWC) on Nile tilapia growth was assessed by systematically monitoring key

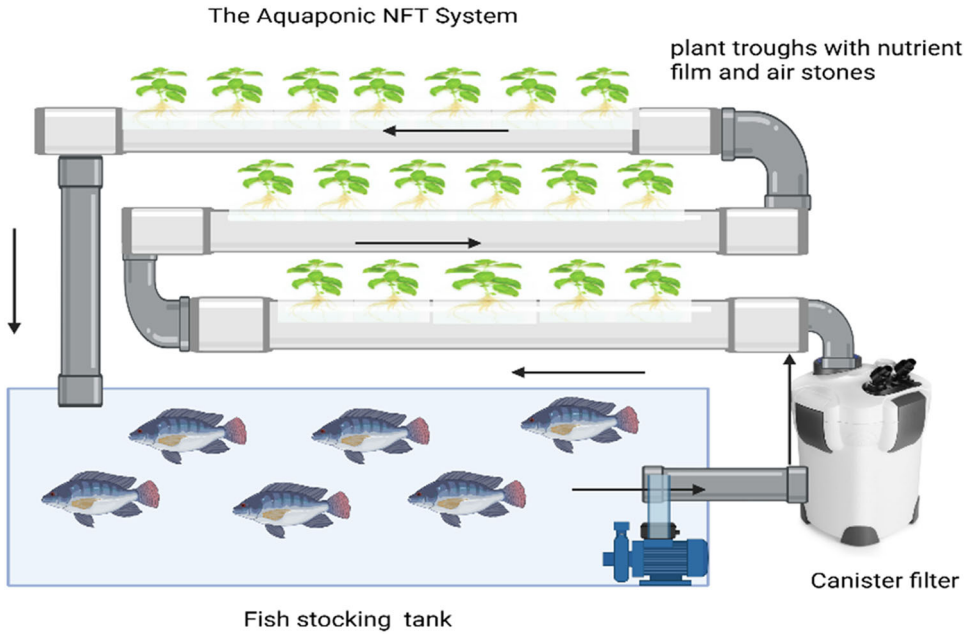


FIGURE 2 | Schematic representation of the nutrient film technique (NFT) aquaponic system employed in the study. The design comprises a fish rearing tank connected to a canister filter for mechanical and biological filtration, followed by recirculation of nutrient-rich water through slightly inclined PVC channels containing basil plants in net pots. A thin film of water continuously flowed along the root surface, supplemented by air stones to maintain oxygenation. Excess water was returned to the fish tank, thereby ensuring a closed-loop cycle of nutrient exchange between aquaculture and plant subsystems.

performance indicators throughout the experimental period. At the onset, the number of fish stocked and their collective initial biomass (kg) were recorded. As the trial progressed, data on final biomass (kg), mean individual weight (g), total weight gain (g) and average weight per fish (g) were collected to quantify growth trends. Several performance indices were calculated to evaluate system efficiency, including feed conversion ratio (FCR, %), specific growth rate (SGR, %), thermal growth coefficient (TGC, standardized to 24.5°C) and mortality (%). Weight gain and SGR served as indicators of overall growth efficiency, while FCR provided insight into feed utilization, reflecting the proportion of feed effectively converted into fish biomass. TGC was used to normalize growth performance relative to fish size and environmental temperature, and mortality rates were monitored as a measure of tilapia adaptability to the aquaponic environment. The SGR was calculated according to the modified formula proposed by Crane et al. (2020):

$$\text{SGR}\,(\%/\text{day}) = \left(e^{\log W_f^{-\log} W_i/T)-1}\right) \times 100$$

where W_f = final weight (g), W_i = Initial weight (g), T = period (days), e = the base of the natural logarithm.

The FCR (%) was calculated using the formula of Colt and Semmens (2022):

$$\text{FCR}(\%) = \text{Fed feed (kg)/Weight gain of animal (kg)} \times 100.$$

The TGC was calculated using the formula by Bolger and Connolly (1989):

$$\text{TGC} = [(W_f)^{1/3} - (W_i)^{1/3}/(T \times t)] \times 1000$$

where W_f = final weight (g), W_i = initial weight (g), T = period (days), t = mean temperature (in °C).

Mortality rate (%) was calculated using the formula:

$$\text{Mortality}\ (\%) = \text{Number of fish dead/Initial number of fish} \times 100.$$

2.7 | Plant Growth Parameters

Basil (*O. basilicum*) growth was monitored under both NFT and DWC systems and recorded at two developmental stages: 6 weeks (40 DAS) and 10 weeks (70 DAS). Growth assessments included plant length (leaf tip to root tip, cm), shoot length (cm), root length (cm), total fresh weight (g), shoot dry weight (g) and root dry weight (g). Plant length was determined as the distance from the uppermost leaf tip to the base of the root system, whereas shoot length was measured as the vertical distance from the collar region to the apical meristem. Root length was quantified from the stem base to the tip of the longest root. Fresh biomass was determined immediately after harvesting. Subsequently, plant samples were oven-dried at 60°C for 48 h in a hot-air oven until constant weight was achieved. Dry biomass of both shoots and roots was then recorded in grams.

2.8 | Plant Photosynthetic Pigments

The concentrations of major photosynthetic pigments chlorophyll a, chlorophyll b, total chlorophyll, carotenoids and

xanthophylls were quantified according to the spectrophotometric protocol described by Wellburn (1994). At each sampling time, fully expanded leaves were collected from five plants per treatment combination. Fresh leaf tissue was homogenized, and pigments were extracted in an appropriate solvent until complete leaching was achieved. Absorbance values were recorded at their respective wavelengths using a UV–visible spectrophotometer, and pigment concentrations were calculated using standard equations. Results were expressed on a fresh weight basis as milligrams per gram (mg g^{-1} FW).

2.9 | Biochemical Analysis

A comprehensive suite of biochemical assays was performed to characterize the physiological responses of basil plants cultivated under the NFT and DWC aquaponic systems. Protein content was estimated by the Bradford assay (Bradford 1976), in which Coomassie Brilliant Blue G-250 dye was used to form a protein–dye complex, and bovine serum albumin served as the standard curve reference. Antioxidant potential was initially assessed through quantification of total phenolic content (TPC) and total flavonoid content (TFC). TPC was determined following the Folin–Ciocalteu method described by Singleton and Rossi (1965), wherein gallic acid served as the calibration standard and results were expressed as mg gallic acid equivalents (GAE) per g dry weight. TFC was quantified according to the aluminium chloride colorimetric method of Chang et al. (2002), using quercetin as the reference compound and values expressed as mg quercetin equivalents (QE) per g dry weight. Essential oil profiles were examined to capture compositional variations between system designs. Oils were extracted from fresh basil leaves via hydrodistillation and subsequently analyzed using gas chromatography–mass spectrometry according to the method of Adams (2007). Individual compounds were identified by comparison with spectral libraries and retention indices. Oxidative stress responses were evaluated by assaying enzymatic antioxidants. Peroxidase (POD) and catalase (CAT) activities were measured using the spectrophotometric protocol of Chance and Maehly (1955), with enzyme activity expressed as units per mg protein. Finally, non-enzymatic antioxidant capacity was assessed using two complementary radical scavenging assays: the DPPH (2,2-diphenyl-1-picrylhydrazyl) assay following Brand-Williams et al. (1995) and the ABTS (2,2′-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid)) assay as outlined by Re et al. (1999). Both assays quantified the percentage inhibition of radicals by plant extracts. Macro- and micronutrient concentrations—including nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), zinc (Zn) and manganese (Mn)—were determined using inductively coupled plasma–optical emission spectroscopy, following the standardized plant tissue digestion and analysis protocol described by Jones (2001).

2.10 | Statistical Analysis

All experimental data are expressed as mean ± standard deviation (SD), calculated from five biological replicates per treatment. To determine the effects of aquaponic system architecture and developmental stage on the recorded variables, a two-way analysis of variance (ANOVA) was employed. The independent factors were system design (NFT vs. DWC) and DAS (40 vs. 70). Because each factor consisted of only two levels, additional post hoc multiple comparison tests were deemed unnecessary. Statistical significance was accepted at a probability threshold of $p < 0.05$, corresponding to a 95% confidence interval. For assessing and graph plotting, SigmaPlot 12 (Microcal Software) was operated to calculate the statistical variations.

3 | Results

3.1 | Water Quality Remained Stable in Both NFT and DWC Systems

Water quality was continuously monitored at weekly intervals throughout the experimental period, and the recorded values for NFT and DWC systems are presented in Tables 3 and 4. In

TABLE 3 | Weekly water quality parameters of the nutrient film technique (NFT) aquaponic system.

Week	pH	Temperature (°C)	Dissolved oxygen (DO, mg/L)	Electrical conductivity (EC, mS/cm)	Ammonia (mg/L)	Nitrite (mg/L)	Nitrate (mg/L)	TDS (ppm)
Week 1	6.89 ± 0.03	24.75	5.15 ± 0.2	0.91 ± 0.03	0.19 ± 0.04	0.40 ± 0.01	3.33 ± 0.31	417.45 ± 6.13
Week 2	7.05 ± 0.03	24.30	5.05 ± 0.12	0.88 ± 0.05	0.20 ± 0.01	0.15 ± 0.03	7.57 ± 0.81	445.67 ± 4.69
Week 3	7.31 ± 0.39	24.46	5.11 ± 0.13	0.86 ± 0.02	0.18 ± 0.01	0.25 ± 0.04	14.63 ± 1.10	427.32 ± 2.80
Week 4	6.95 ± 0.05	24.93	5.05 ± 0.10	0.92 ± 0.05	0.35 ± 0.02	0.15 ± 0.05	17.46 ± 1.31	515.83 ± 4.28
Week 5	6.81 ± 0.09	24.71	5.14 ± 0.19	0.93 ± 0.04	0.49 ± 0.04	0.19 ± 0.01	19.71 ± 1.4	479.36 ± 2.28
Week 6	6.85 ± 0.03	24.65	5.23 ± 0.25	0.86 ± 0.03	0.56 ± 0.02	0.13 ± 0.02	21.99 ± 0.70	452.97 ± 3.47
Week 7	6.92 ± 0.05	24.72	5.72 ± 0.11	0.91 ± 0.01	0.66 ± 0.01	0.11 ± 0.01	19.97 ± 1.21	441.61 ± 23.7
Week 8	7.08 ± 0.06	24.80	5.61 ± 0.25	0.87 ± 0.01	0.69 ± 0.03	0.19 ± 0.03	23.51 ± 1.73	429.78 ± 4.42
Week 9	7.12 ± 0.02	24.94	5.58 ± 0.13	0.93 ± 0.05	0.81 ± 0.01	0.21 ± 0.01	26.48 ± 0.92	455.42 ± 2.56
Week 10	6.97 ± 0.03	25.01	5.83 ± 0.20	0.97 ± 0.03	0.87 ± 0.01	0.17 ± 0.02	30.05 ± 0.76	469.85 ± 3.35

Note: Values include pH, temperature (°C), dissolved oxygen (DO, mg L^{-1}), electrical conductivity (EC, mS cm^{-1}), ammonia (NH_3–N, mg L^{-1}), nitrite (NO_2^-–N, mg L^{-1}), nitrate (NO_3^-–N, mg L^{-1}) and total dissolved solids (TDS, ppm) recorded throughout the experimental period.

TABLE 4 | Weekly water quality parameters of the deep-water culture (DWC) aquaponic system.

Week	pH	Temperature (°C)	Dissolved oxygen (DO, mg/L)	Electrical conductivity (EC, mS/cm)	Ammonia (mg/L)	Nitrite (mg/L)	Nitrate (mg/L)	TDS (ppm)
Week 1	6.89 ± 0.02	24.91	6.11 ± 0.15	0.91 ± 0.04	0.22 ± 0.02	0.15 ± 0.03	4.13 ± 0.15	463.45 ± 4.08
Week 2	7.01 ± 0.04	24.56	5.88 ± 0.10	0.82 ± 0.03	0.31 ± 0.04	0.23 ± 0.02	9.83 ± 0.35	432.13 ± 2.61
Week 3	6.90 ± 0.15	24.73	5.75 ± 0.26	0.88 ± 0.02	0.31 ± 0.02	0.19 ± 0.01	17.73 ± 0.60	440.06 ± 3.12
Week 4	6.86 ± 0.17	25.64	5.92 ± 0.35	0.85 ± 0.03	0.47 ± 0.04	0.24 ± 0.03	18.54 ± 0.3	438.02 ± 5.94
Week 5	6.98 ± 0.04	24.90	5.82 ± 0.15	0.92 ± 0.02	0.72 ± 0.07	0.17 ± 0.05	19.71 ± 0.87	494.11 ± 2.88
Week 6	7.58 ± 0.06	24.81	5.96 ± 0.21	0.97 ± 0.01	0.78 ± 0.02	0.21 ± 0.02	21.99 ± 0.25	473.15 ± 2.38
Week 7	7.01 ± 0.09	24.89	6.05 ± 0.18	0.93 ± 0.05	0.84 ± 0.01	0.16 ± 0.02	28.94 ± 0.46	468.78 ± 2.65
Week 8	7.34 ± 0.02	25.15	6.10 ± 0.25	1.02 ± 0.03	0.81 ± 0.02	0.20 ± 0.02	26.48 ± 0.23	483.61 ± 1.12
Week 9	7.26 ± 0.11	25.07	6.23 ± 0.11	1.07 ± 0.06	0.86 ± 0.05	0.15 ± 0.06	32.05 ± 0.25	501.42 ± 1.32
Week 10	7.15 ± 0.03	24.96	6.44 ± 0.19	1.1 ± 0.01	0.85 ± 0.03	0.13 ± 0.01	36.48 ± 0.39	521.85 ± 1.24

Note: Recorded variables include pH, temperature (°C), dissolved oxygen (DO, mg L^{-1}), electrical conductivity (EC, mS cm^{-1}), ammonia (NH_3–N, mg L^{-1}), nitrite (NO_2^-–N, mg L^{-1}), nitrate (NO_3^-–N, mg L^{-1}) and total dissolved solids (TDS, ppm) across the experimental duration.

the NFT system, pH values ranged from 6.81 to 7.31. A progressive increase was observed from Weeks 1 (6.89 ± 0.03) to 3 (7.31 ± 0.39), after which values stabilized around neutrality for the remainder of the trial. Temperature remained consistent, fluctuating minimally between 24.30°C and 25.01°C, thereby confirming thermal stability. DO concentrations varied between 5.05 ± 0.10 mg L^{-1} (Week 4) and 5.83 ± 0.20 mg L^{-1} (Week 10), indicating adequate oxygenation for both fish and plants. EC values ranged from 0.86 ± 0.02 to 0.97 ± 0.03 mS cm^{-1}, reflecting moderate ionic fluctuations over time. Ammonia (NH_3–N) concentration increased gradually, from 0.19 ± 0.04 mg L^{-1} in Week 1 to 0.87 ± 0.01 mg L^{-1} in Week 10, remaining well below the threshold of 1 mg L^{-1}. Nitrite (NO_2^-–N) levels peaked in Week 1 (0.40 ± 0.01 mg L^{-1}) but stabilized thereafter, while nitrate (NO_3^-–N) accumulated progressively, reaching a maximum of 30.05 ± 0.76 mg L^{-1} by Week 10. TDS also showed a steady increase, from 417.45 ± 6.13 ppm in Week 1 to 469.85 ± 3.35 ppm in Week 10, indicating active nutrient cycling. Collectively, these values remained within permissible ranges for tilapia and hydroponic crops, confirming stable water quality and effective nutrient availability. In the DWC system, all parameters likewise remained within acceptable thresholds (Table 4). The pH fluctuated between 6.86 ± 0.17 (Week 6) and 7.58 ± 0.06 (Week 4), reflecting conditions near neutrality to slightly alkaline. Temperature remained stable, ranging from 24.56°C to 25.64°C. DO concentrations consistently exceeded 5.7 mg L^{-1}, peaking at 6.44 ± 0.19 mg L^{-1} in Week 10, thus ensuring sufficient oxygenation. EC values ranged from 0.82 ± 0.03 to 1.10 ± 0.01 mS cm^{-1}, reflecting a gradual increase in ionic content. Ammonia concentrations rose steadily from 0.22 ± 0.02 mg L^{-1} (Week 1) to 0.85 ± 0.03 mg L^{-1} (Week 10), while nitrite levels peaked modestly in Week 4 (0.24 ± 0.03 mg L^{-1}). Nitrate concentrations increased continuously, reaching 36.48 ± 0.39 mg L^{-1} by Week 10. Similarly, TDS values increased from 463.45 ± 4.08 ppm in Week 1 to 521.85 ± 1.24 ppm in Week 10. These results collectively demonstrate effective nutrient accumulation and cycling in the DWC configuration. Overall, both NFT and DWC systems maintained water quality parameters within the optimal physiological range for tilapia and basil cultivation, with gradual nutrient enrichment over time confirming efficient system performance.

TABLE 5 | Comparative water-use efficiency (WUE) of basil plants cultivated under nutrient film technique (NFT) and deep-water culture (DWC) aquaponic systems at two growth stages (40 and 70 DAS).

System	DAS	WUE (g/L)
NFT	40	$0.131 \pm 0.008^{a,b,c}$
	70	$0.115 \pm 0.003^{a,b,c}$
DWC	40	$0.090 \pm 0.007^{a,b,c}$
	70	$0.077 \pm 0.002^{a,b,c}$

Note: Values represent mean ± standard deviation ($n = 5$) in each group. Superscripts indicate statistically significant effects based on two-way ANOVA ($p < 0.05$).
[a]Significant main effect of system (NFT vs. DWC).
[b]Significant main effect of days after sowing (DAS; 40 vs. 70 days).
[c]Significant interaction effect between system and DAS.

3.2 | NFT System Exhibited Higher Water-Use Efficiency Than DWC

The WUE of basil plants cultivated under NFT and DWC systems is presented in Table 5. Statistical analysis revealed that WUE was significantly influenced by both system design and developmental stage (DAS). Moreover, a notable interaction effect indicated that the impact of growth stage on WUE varied according to system type. In both systems, WUE declined with crop maturity, reflecting a reduction in the efficiency of biomass accumulation relative to water consumption over time. Plants grown in the NFT configuration consistently exhibited higher WUE compared with those in the DWC system. At 40 DAS, WUE in NFT reached 0.131 ± 0.008 g L^{-1}, while at 70 DAS it was 0.115 ± 0.003 g L^{-1}. In the DWC system, WUE decreased from 0.090 ± 0.007 g/L at 40 DAS to 0.077 ± 0.002 g/L at 70 DAS. These findings demonstrate that NFT facilitated a more efficient conversion of water into plant biomass than the DWC system across both growth stages.

3.3 | DWC Supported Greater Fish Biomass Accumulation

Fish growth performance was evaluated at the end of the 6th and 10th week. The recorded parameters included the number of fish stocked per tank, initial biomass (kg, total), final biomass (kg, total), weight gain per fish (g), mean individual weight (g) and total feed intake (g). From these values, performance indices were calculated, including FCR (%), SGR (%) and mortality rate (%). The compiled data are presented in Table 6.

Tilapia (*O. niloticus*) fingerlings ($n = 50$/treatment), with an average initial weight of 25 g, were stocked in each system configuration. Final biomass was determined at harvest for both growth stages. In the NFT system, cumulative fish weights reached 1.60 kg at 40 DAS and 2.70 kg at 70 DAS, whereas in the DWC system, values were slightly higher, with final weights of 2.00 kg and 3.45 kg at 40 and 70 DAS, respectively. Both mean weight gain per fish and total weight gain followed a similar trend, with fish in the DWC configuration consistently outperforming those in NFT. FCR, a key indicator of feed utilization efficiency, was marginally higher in the DWC system (1.83–1.90) compared with NFT, suggesting slightly reduced feed efficiency despite higher biomass accumulation. SGR exhibited marked variation across treatments, with the highest value recorded in DWC at 40 DAS (5.20%) and the lowest in NFT at 70 DAS (3.40%). TGC (standardized at 24.5°C) displayed a comparable pattern, with DWC outperforming NFT at both developmental stages. Mortality rates remained low overall, ranging from 2% in DWC at 40 DAS to 6% in NFT at 70 DAS.

3.4 | DWC Enhanced Basil Growth Compared With NFT

The growth performance of basil under NFT and DWC systems at 40 DAS and 70 DAS is summarized in Table 7. Overall, plants cultivated in the DWC configuration consistently exhibited superior growth compared with those grown in NFT, as reflected across all morphological and biomass-related parameters. Total plant length increased substantially over time, with DWC plants extending from 75.68 ± 1.05 cm at 40 DAS to 110.02 ± 1.08 cm at 70 DAS, while NFT plants grew from 68.32 ± 1.34 cm to 95.48 ± 1.38 cm during the same period. Shoot length followed a similar trend, reaching 65.28 ± 0.58 cm in DWC and 58.12 ± 1.35 cm in NFT at 70 DAS, compared with 44.16 ± 0.64 cm and 40.20 ± 1.24 cm at 40 DAS, respectively. Root development was likewise enhanced in DWC, where root length increased from 31.60 ± 0.63 cm to 44.24 ± 0.65 cm between 40 and 70 DAS, compared with 27.06 ± 1.20 cm to 38.36 ± 0.86 cm in NFT. Fresh and dry biomass accumulation also demonstrated a marked advantage for DWC: fresh weight rose from 52.24 ± 0.91 g to 91.06 ± 0.80 g, and dry weight from 5.56 ± 0.40 g to 7.88 ± 0.20 g. In contrast, NFT plants increased from 47.12 ± 1.10 g to 83.88 ± 1.15 g in fresh weight, and from 5.18 ± 0.31 g to 7.14 ± 0.21 g in dry weight. Root dry biomass was consistently higher in DWC (0.94 ± 0.05 g to 1.28 ± 0.03 g) compared with NFT (0.76 ± 0.05 g to 1.19 ± 0.04 g).

Statistical analysis revealed significant interaction effects between system design and developmental stage (DAS) for plant length, shoot length, plant fresh weight and root dry weight ($p < 0.05$), indicating that the influence of system type on these parameters was contingent upon the growth stage. For instance, basil cultivated in the DWC configuration exhibited a disproportionately greater increase in overall length and biomass between 40 and 70 DAS compared with NFT, suggesting that the relative advantage of DWC became more pronounced during later developmental stages. In contrast, parameters such as root length and total plant dry weight exhibited only significant main effects of both system design and growth stage, without evidence of interaction. This finding implies that these factors contributed independently and additively to the observed outcomes. Consistently, basil plants grown in DWC outperformed those in NFT across all growth phases, while plants harvested at 70 DAS displayed superior performance compared with those at 40 DAS, regardless of system configuration.

TABLE 6 | Growth performance parameters of Nile tilapia (*Oreochromis niloticus*) cultured in nutrient film technique (NFT) and deep-water culture (DWC) aquaponic systems at two growth stages (40 and 70 DAS).

Parameter	NFT 40 DAS	NFT 70 DAS	DWC 40 DAS	DWC 70 DAS
Number of fish	50	50	50	50
Initial biomass (kg, total)	0.25	0.25	0.25	0.25
Final biomass (kg, total)	1.60	2.70	2.00	3.45
Weight gain per fish (g)	27.0	49.0	35.0	64.0
Total weight gain (kg)	1.35	2.45	1.75	3.20
Average weight per fish (g)	32.1	54.0	40.2	69.0
Consumed feed (kg)	2.20	4.29	3.20	6.08
FCR (%)	1.63	1.75	1.83	1.90
SGR (%)	4.64	3.40	5.20	3.75
TGC (24.5°C)	5.54	4.47	6.45	5.00
Mortality (%)	4.00	6.00	2.00	4.00

Note: Recorded metrics include the number of fish stocked, initial biomass (kg, total), final biomass (kg, total) and mean weight gain per fish (g).

TABLE 7 | Growth parameters of basil (*Ocimum basilicum*) cultivated under nutrient film technique (NFT) and deep-water culture (DWC) aquaponic systems at two developmental stages (40 and 70 DAS).

Parameter	System	DAS	Mean ± SD
Plant length (cm)	NFT	40	$68.32 \pm 1.34^{a,b,c}$
		70	$95.48 \pm 1.38^{a,b,c}$
	DWC	40	$75.68 \pm 1.05^{a,b,c}$
		70	$110.02 \pm 1.08^{a,b,c}$
Shoot length (cm)	NFT	40	$40.2 \pm 1.24^{a,b,c}$
		70	$58.12 \pm 1.35^{a,b,c}$
	DWC	40	$44.16 \pm 0.64^{a,b,c}$
		70	$65.28 \pm 0.58^{a,b,c}$
Root length (cm)	NFT	40	$27.06 \pm 1.2^{a,b}$
		70	$38.36 \pm 0.86^{a,b}$
	DWC	40	$31.6 \pm 0.63^{a,b}$
		70	$44.24 \pm 0.65^{a,b}$
Plant fresh weight (g)	NFT	40	$47.12 \pm 1.10^{a,b,c}$
		70	$83.88 \pm 1.15^{a,b,c}$
	DWC	40	$52.24 \pm 0.91^{a,b,c}$
		70	$91.06 \pm 0.80^{a,b,c}$
Plant dry weight (g)	NFT	40	$5.18 \pm 0.31^{a,b}$
		70	$7.14 \pm 0.21^{a,b}$
	DWC	40	$5.56 \pm 0.4^{a,b}$
		70	$7.88 \pm 0.2^{a,b}$
Root dry weight (g)	NFT	40	$0.76 \pm 0.05^{a,b,c}$
		70	$1.19 \pm 0.04^{a,b,c}$
	DWC	40	$0.94 \pm 0.05^{a,b,c}$
		70	$1.28 \pm 0.03^{a,b,c}$

Note: Values represent mean ± standard deviation ($n = 5$) in each group. Superscripts indicate statistically significant effects based on two-way ANOVA ($p < 0.05$).
[a]Significant main effect of system (NFT vs. DWC),
[b]Significant main effect of days after sowing (DAS; 40 vs. 70 days),
[c]Significant interaction effect between system and DAS.

TABLE 8 | Photosynthetic pigment concentrations in basil (*Ocimum basilicum*) cultivated under nutrient film technique (NFT) and deep-water culture (DWC) aquaponic systems at two developmental stages (40 and 70 DAS).

Pigment	System	DAS	Mean ± SD
Chlorophyll a (mg/g FW)	NFT	40	$1.39 \pm 0.03^{a,b,c}$
		70	$1.59 \pm 0.04^{a,b,c}$
	DWC	40	$1.77 \pm 0.03^{a,b,c}$
		70	$2.11 \pm 0.04^{a,b,c}$
Chlorophyll b (mg/g FW)	NFT	40	$0.55 \pm 0.03^{a,b}$
		70	$0.65 \pm 0.04^{a,b}$
	DWC	40	$0.81 \pm 0.03^{a,b}$
		70	$0.90 \pm 0.02^{a,b}$
Total chlorophyll (mg/g FW)	NFT	40	$1.92 \pm 0.04^{a,b,c}$
		70	$2.25 \pm 0.04^{a,b,c}$
	DWC	40	$2.54 \pm 0.03^{a,b,c}$
		70	$3.01 \pm 0.05^{a,b,c}$
Carotenoids (mg/g FW)	NFT	40	$0.50 \pm 0.04^{a,b}$
		70	$0.55 \pm 0.03^{a,b}$
	DWC	40	$0.54 \pm 0.04^{a,b}$
		70	$0.65 \pm 0.02^{a,b}$
Xanthophyll (mg/g FW)	NFT	40	$0.32 \pm 0.03^{a,b}$
		70	$0.37 \pm 0.02^{a,b}$
	DWC	40	$0.40 \pm 0.03^{a,b}$
		70	$0.45 \pm 0.02^{a,b}$

Note: Pigments measured included chlorophyll a, chlorophyll b, total chlorophyll, carotenoids and xanthophylls. Values represent mean ± standard deviation ($n = 5$) in each group. Superscripts indicate statistically significant effects based on two-way ANOVA ($p < 0.05$).
[a]Significant main effect of system (NFT vs. DWC),
[b]Significant main effect of days after sowing (DAS; 40 vs. 70 days),
[c]Significant interaction effect between system and DAS.

3.5 | DWC Increased Chlorophyll and Carotenoid Accumulation

Leaf pigment analysis revealed significant differences attributable to both system design and crop developmental stage (Table 8). At 40 DAS, chlorophyll a content was notably higher in the DWC system (1.77 ± 0.03 mg g^{-1} FW) compared with NFT (1.39 ± 0.03 mg g^{-1} FW). By 70 DAS, the disparity widened, with DWC plants accumulating 2.11 ± 0.04 mg g^{-1} FW relative to 1.59 ± 0.04 mg g^{-1} FW in NFT. Chlorophyll b followed a similar trajectory, with DWC values of 0.81 ± 0.03 mg g^{-1} FW at 40 DAS and 0.90 ± 0.02 mg g^{-1} FW at 70 DAS, consistently exceeding NFT values (0.55 ± 0.03 mg g^{-1} FW and 0.65 ± 0.04 mg g^{-1} FW, respectively).

Total chlorophyll concentration increased markedly with crop maturity and was significantly greater in DWC (3.01 ± 0.05 mg g^{-1} FW at 70 DAS) compared with NFT (2.25 ± 0.04 mg g^{-1} FW). A parallel trend was observed for carotenoids and xanthophylls. Carotenoid levels rose from 0.54 ± 0.04 mg g^{-1} FW at 40 DAS to 0.65 ± 0.02 mg g^{-1} FW at 70 DAS in DWC, whereas NFT plants increased more modestly, from 0.50 ± 0.04 mg g^{-1} FW to 0.55 ± 0.03 mg g^{-1} FW. Similarly, xanthophyll concentrations were consistently higher in DWC (0.40 ± 0.03 to 0.45 ± 0.02 mg g^{-1} FW) than in NFT (0.32 ± 0.03 to 0.37 ± 0.02 mg g^{-1} FW) across both growth stages.

Statistical analysis confirmed a significant interaction effect between system design and developmental stage for chlorophyll a and total chlorophyll content ($p < 0.05$). This outcome indicated that the influence of the cultivation system on pigment accumulation was stage-dependent. Specifically, plants grown in DWC exhibited a disproportionately greater increase in chlorophyll content from 40 to 70 DAS than those in NFT, suggesting that prolonged cultivation in DWC favoured enhanced chlorophyll biosynthesis.

For chlorophyll b, carotenoids, and xanthophylls, significant main effects of both system design and developmental stage

were observed, although no interaction effects were detected. This finding demonstrates that while pigment concentrations were consistently higher in DWC than NFT and increased with plant maturity, these effects were additive rather than synergistic.

3.6 | DWC Promoted Higher Protein, Phenolics and Antioxidants

Biochemical profiling revealed pronounced differences in metabolite accumulation and antioxidant activity between system designs and developmental stages (Table 9). Protein content was consistently higher in DWC-grown plants, reaching 6.30 ± 0.23 mg g^{-1} FW at 40 DAS and 6.79 ± 0.14 mg g^{-1} FW at 70 DAS, compared with 5.80 ± 0.18 mg g^{-1} FW and 6.18 ± 0.32 mg g^{-1} FW, respectively, in NFT. Secondary metabolites followed the same trend. TPC increased significantly with plant maturity, from 9.22 ± 0.39 to 11.32 ± 0.62 mg GAE g^{-1} DW in DWC, while NFT plants ranged from 7.64 ± 0.36 to 9.10 ± 0.47 mg GAE g^{-1} DW. TFC also rose with age, attaining 16.76 ± 0.23 to 18.33 ± 0.15 mg QE g^{-1} DW in DWC, compared with 15.43 ± 0.18 to 17.32 ± 0.22 mg QE g^{-1} DW in NFT. Essential oil content exhibited a similar pattern, with DWC plants achieving $1.36 \pm 0.07\%$ w/w at 70 DAS, exceeding the $1.14\% \pm 0.09\%$ w/w observed in NFT. Enzymatic antioxidants also responded positively to system design and growth stage. POD activity reached 2.47 ± 0.07 U mg^{-1} protein in DWC at 70 DAS, compared with 2.27 ± 0.12 U mg^{-1} protein in NFT. CAT activity in DWC rose from 7.25 ± 0.06 to 7.77 ± 0.05 U mg^{-1} protein between 40 and 70 DAS, whereas NFT plants ranged from 6.73 ± 0.06 to 7.29 ± 0.05 U mg^{-1} protein. Non-enzymatic antioxidant activity, quantified by DPPH and ABTS radical scavenging assays, also demonstrated higher values in DWC plants and increased with maturity. DPPH inhibition improved from $69.48\% \pm 0.19\%$ at 40 DAS to $75.36\% \pm 0.12\%$ at 70 DAS in DWC, compared with $67.14\% \pm 0.22\%$ to $72.12\% \pm 0.16\%$ in NFT. ABTS inhibition reached $73.64\% \pm 0.15\%$ in DWC at 70 DAS, compared with $69.84\% \pm 0.20\%$ in NFT.

Two-way ANOVA indicated significant main effects of both system design (NFT vs. DWC) and growth stage (40 vs. 70 DAS) across most biochemical and antioxidant parameters. Proteins, phenolics, flavonoids and essential oils were consistently higher at 70 DAS, underscoring the role of developmental stage in metabolite accumulation. Furthermore, DWC supported superior biochemical enrichment relative to NFT. Enzymatic antioxidants (CAT and POD) were likewise elevated at 70 DAS, with consistently higher activity under DWC. Importantly, a significant interaction was detected for DPPH and ABTS activities, demonstrating that antioxidant capacity was not only influenced by system design and growth stage independently but also by their synergistic interaction.

TABLE 9 | Biochemical composition of basil (*Ocimum basilicum*) leaves cultivated under nutrient film technique (NFT) and deep-water culture (DWC) aquaponic systems at two developmental stages (40 and 70 DAS).

Parameter	System	DAS	Mean ± SD
Protein (mg/g FW)	NFT	40	$5.80 \pm 0.18^{a,b}$
		70	$6.18 \pm 0.32^{a,b}$
	DWC	40	$6.30 \pm 0.23^{a,b}$
		70	$6.79 \pm 0.14^{a,b}$
Total phenolic content (mg GAE/g DW)	NFT	40	$7.64 \pm 0.36^{a,b}$
		70	$9.1 \pm 0.47^{a,b}$
	DWC	40	$9.22 \pm 0.39^{a,b}$
		70	$11.32 \pm 0.62^{a,b}$
Total flavonoid content (mg QE/g DW)	NFT	40	$15.43 \pm 0.18^{a,b}$
		70	$17.32 \pm 0.22^{a,b}$
	DWC	40	$16.76 \pm 0.23^{a,b}$
		70	$18.33 \pm 0.15^{a,b}$
Essential oil content (% w/w)	NFT	40	$0.98 \pm 0.06^{a,b}$
		70	$1.14 \pm 0.09^{a,b}$
	DWC	40	$1.07 \pm 0.05^{a,b}$
		70	$1.36 \pm 0.07^{a,b}$
Peroxidase activity (U/mg protein)	NFT	40	$1.77 \pm 0.09^{a,b}$
		70	$2.27 \pm 0.12^{a,b}$
	DWC	40	$1.89 \pm 0.05^{a,b}$
		70	$2.47 \pm 0.07^{a,b}$
Catalase activity (U/mg protein)	NFT	40	$6.73 \pm 0.06^{a,b}$
		70	$7.29 \pm 0.05^{a,b}$
	DWC	40	$7.25 \pm 0.06^{a,b}$
		70	$7.77 \pm 0.05^{a,b}$
DPPH antioxidant activity (% inhibition)	NFT	40	$67.14 \pm 0.22^{a,b,c}$
		70	$72.12 \pm 0.16^{a,b,c}$
	DWC	40	$69.48 \pm 0.19^{a,b,c}$
		70	$75.36 \pm 0.12^{a,b,c}$
ABTS antioxidant activity (% inhibition)	NFT	40	$65.94 \pm 0.15^{a,b,c}$
		70	$69.84 \pm 0.20^{a,b,c}$
	DWC	40	$67.88 \pm 0.11^{a,b,c}$
		70	$73.64 \pm 0.15^{a,b,c}$

Note: Parameters measured included protein content (mg g^{-1} FW), total phenolic content (TPC; mg gallic acid equivalents g^{-1} DW), total flavonoid content (TFC; mg quercetin equivalents g^{-1} DW), essential oil content (% w/w), enzymatic antioxidant activities (peroxidase [POD] and catalase [CAT], U mg^{-1} protein) and non-enzymatic antioxidant activities (DPPH and ABTS radical scavenging, % inhibition). Values represent mean ± standard deviation ($n = 5$) in each group. Superscripts indicate statistically significant effects based on two-way ANOVA ($p < 0.05$).
[a]Significant main effect of system (NFT vs. DWC).
[b]Significant main effect of DAS (40 vs. 70 days).
[c]Significant interaction effect between system and DAS.

3.7 | DWC Improved Macro- and Micronutrient Accumulation in Basil

The macronutrient profile of basil leaves varied significantly with both system design and growth stage (Figure 3A–F). Overall, the highest concentrations were consistently recorded in plants grown under the DWC configuration, particularly at 70 DAS. Nitrogen content in DWC plants increased from 6.4% at 40 DAS to 6.9% at 70 DAS, whereas NFT plants accumulated

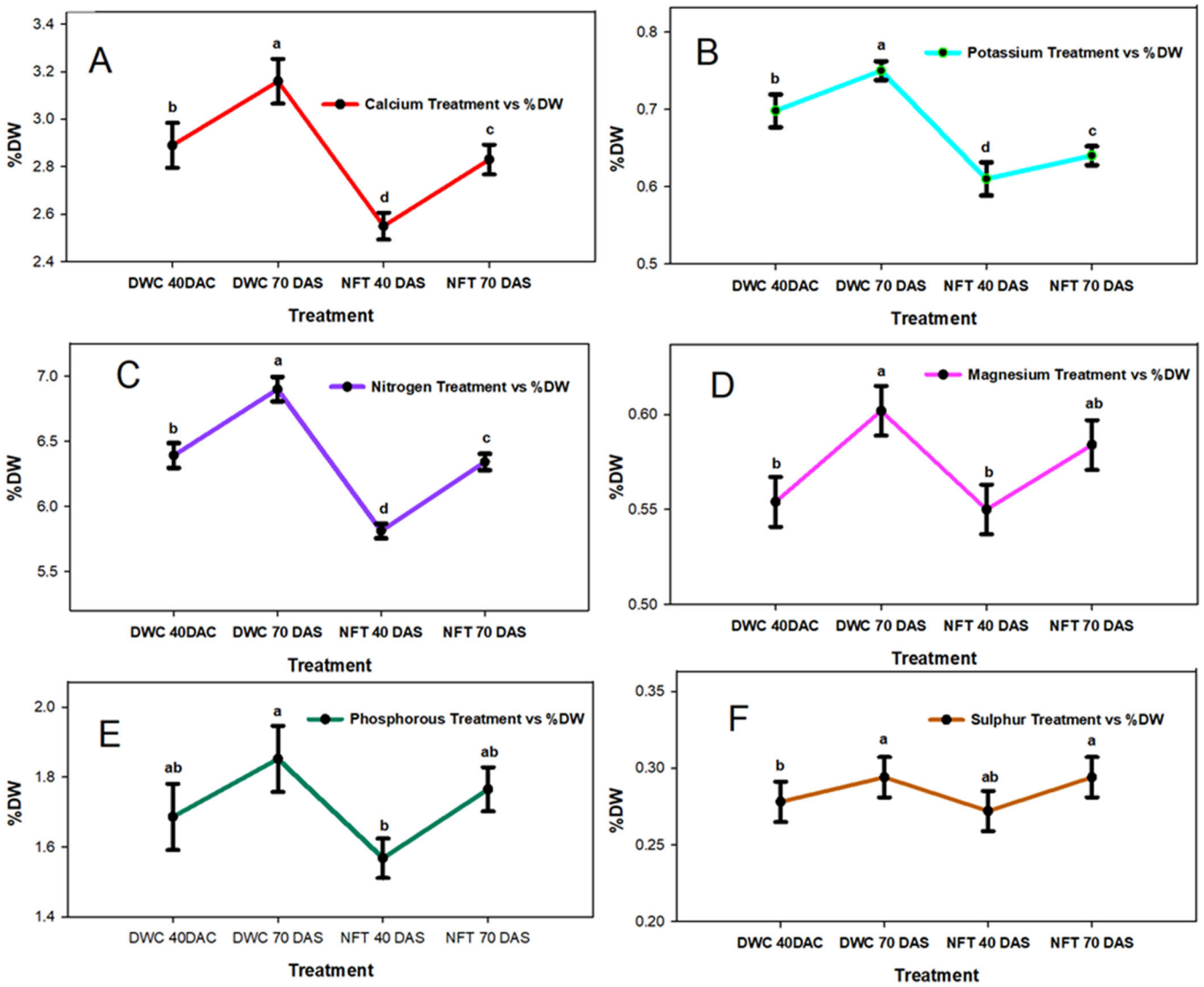


FIGURE 3 | Macronutrient concentrations (% DW) in basil (*Ocimum basilicum*) cultivated under nutrient film technique (NFT) and deep-water culture (DWC) aquaponic systems at two developmental stages (40 and 70 DAS). Panels illustrate individual macronutrients: (A) calcium, (B) potassium, (C) nitrogen, (D) magnesium, (E) phosphorus and (F) sulphur. Values are presented as mean ± standard deviation ($n = 5$). Across all nutrients, concentrations were generally higher in DWC plants compared with NFT, with levels increasing between 40 and 70 DAS. Two-way ANOVA indicated significant main effects of system design and growth stage ($p < 0.05$), while no interaction effects were observed. Means followed by different letters within each panel indicate significant differences among treatments.

lower levels, ranging from 5.81% to 6.34% over the same period. Phosphorus followed a similar pattern: DWC plants contained 1.69% at 40 DAS and 1.85% at 70 DAS, compared with 1.57% and 1.77% in NFT. Potassium exhibited a marked difference at 70 DAS, where DWC plants achieved the highest concentration (0.75%), while NFT plants reached only 0.61% at 40 DAS and 0.64% at 70 DAS. Calcium concentrations were also significantly greater in DWC (2.89–3.16%) than in NFT across both stages, while magnesium levels showed less variability, converging at 0.55% in both systems by 70 DAS. Sulphur exhibited the least variation among macronutrients, remaining relatively stable at 0.27–0.29% across all treatments. Two-way ANOVA indicated significant main effects of system design and growth stage for all macronutrients, but no interaction effects were detected. This outcome suggests that nutrient accumulation increased in parallel across systems as plants matured, with DWC consistently supporting higher concentrations than NFT. Leaf macronutrient levels—particularly nitrogen, phosphorus, potassium, calcium and magnesium—were significantly higher at 70 DAS than at 40 DAS, whereas sulphur content remained comparatively stable. Collectively, these findings highlight the superior nutrient assimilation capacity of basil cultivated in DWC, especially during later growth stages.

Micronutrient concentrations in basil leaves varied significantly with both aquaponic system design and sampling time (Figure 4). Boron (B) ranged from 38.44 to 42.23 mg kg^{-1}. At 40 DAS, DWC-grown plants exhibited slightly higher levels (39.04 ± 0.32 mg kg^{-1}) than NFT (38.44 ± 2.56 mg kg^{-1}). By 70 DAS, boron content increased in both systems, reaching 42.23 ± 0.24 mg kg^{-1} in DWC and 42.06 ± 0.34 mg kg^{-1} in NFT. Copper (Cu) concentrations were nearly identical at 40 DAS (DWC: 12.80 ± 0.52 mg kg^{-1}; NFT: 12.81 ± 0.41 mg kg^{-1}). By 70 DAS, levels rose modestly, with NFT showing a slightly

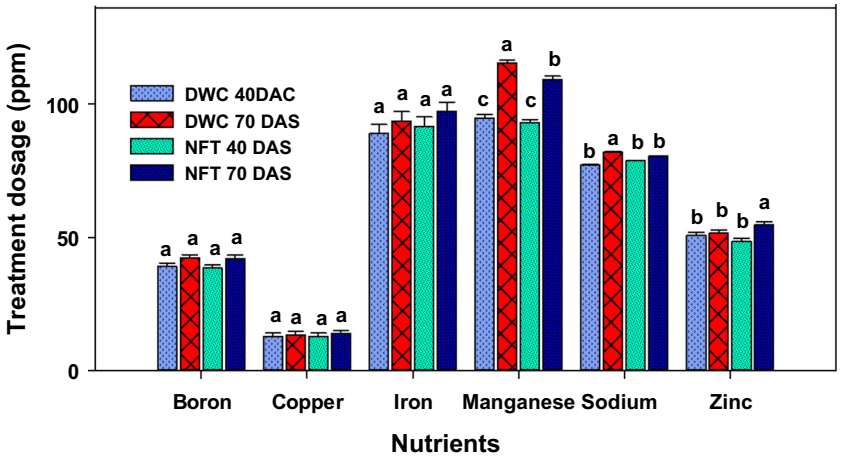


FIGURE 4 | Micronutrient concentrations in basil (*Ocimum basilicum*) cultivated under nutrient film technique (NFT) and deep-water culture (DWC) aquaponic systems at two developmental stages (40 and 70 DAS). Bars represent mean concentrations (ppm) of boron (B), copper (Cu), iron (Fe), manganese (Mn), sodium (Na) and zinc (Zn), with error bars indicating standard deviation ($n = 5$). Means (SEM±) followed by the same letters above bars indicate no significant difference ($p \leq 0.05$) by using Probit analysis.

higher value (13.89 ± 0.86 mg kg^{-1}) compared with DWC (13.42 ± 1.18 mg kg^{-1}). Iron (Fe) content increased over time in both systems, though NFT consistently recorded slightly higher values. DWC plants rose from 88.97 ± 3.67 mg kg^{-1} at 40 DAS to 93.68 ± 3.48 mg kg^{-1} at 70 DAS, while NFT plants increased from 91.72 ± 0.32 mg kg^{-1} to 97.27 ± 0.50 mg kg^{-1}. Manganese (Mn) accumulation exhibited a pronounced increase with plant maturity. In DWC, concentrations rose from 94.83 ± 1.26 mg kg^{-1} at 40 DAS to 115.28 ± 2.08 mg kg^{-1} at 70 DAS. NFT plants followed a similar trajectory, with values increasing from 92.96 ± 2.00 mg kg^{-1} to 109.64 ± 1.99 mg kg^{-1}. Sodium (Na) levels also rose moderately with time. DWC plants increased from 77.22 ± 0.19 mg kg^{-1} at 40 DAS to 82.46 ± 0.26 mg kg^{-1} at 70 DAS, while NFT plants ranged from 78.64 ± 0.11 mg kg^{-1} to 80.36 ± 0.21 mg kg^{-1} over the same period. Zinc (Zn) concentrations, although comparatively lower than other micronutrients, also increased with age. DWC plants contained 50.64 ± 0.17 mg kg^{-1} at 40 DAS and 51.68 ± 0.28 mg kg^{-1} at 70 DAS, while NFT plants increased from 48.45 ± 0.70 mg kg^{-1} to 54.62 ± 0.08 mg kg^{-1}. Collectively, these results indicate that while both NFT and DWC systems supported gradual micronutrient enrichment with plant age, DWC tended to enhance B, Mn and Na accumulation, whereas NFT favoured slightly higher Fe, Cu and Zn concentrations.

4 | Discussion

An optimal water pH in the range of 6.5–7.0 is widely endorsed in aquaponic systems, striking a delicate balance that underpins the physiological and biochemical stability of the three principal biotic constituents fish, plants and nitrifying microorganisms (Tyson et al. 2004). At this neutral window, the equilibrium between non-toxic ammonium (NH_4^+) and toxic ammonia (NH_3) is optimized, minimizing fish stress while sustaining nitrifying bacterial activity. Recently, this consensus has been reaffirmed in contemporary studies, which emphasize that ammonia-oxidizing and nitrite-oxidizing bacteria (AOB and NOB) achieve near-maximal nitrification rates within a slightly higher pH band of ~7.2–8.2 though the ideal operational pH remains centred around neutrality for system-wide compatibility (Wang et al. 2023). In the present study, both NFT and DWC configurations maintained pH values within this optimal interval throughout the cultivation period. Stability in pH is particularly critical, as fluctuations may compromise overall system resilience, affecting both microbial activity and plant nutrient acquisition (Mori et al. 2021). For example, the solubility and uptake of essential macronutrients such as phosphorus are strongly pH-dependent, becoming increasingly restricted under alkaline conditions (da Silva Cerozi and Fitzsimmons 2016). Water temperature is another key determinant of aquaponic system stability, with direct effects on pH buffering capacity, DO dynamics and, most critically, fish physiology (Maulini et al. 2022). Tilapia, the model fish in this study, exhibits superior performance within the range of 24°C–27°C (Maulini et al. 2022). The water temperature across all treatments remained between 24°C and 25°C, thereby minimizing thermal stress. Among water quality parameters, DO concentration has consistently been identified as one of the most critical factors influencing both plant performance and nutrient cycling in aquaponics. In DWC systems, the use of aerators and air stones markedly increases oxygen availability to roots, thereby enhancing root respiration, nutrient solubilization and beneficial microbial activity. Empirical studies have confirmed that such aeration-driven enhancements translate into improved crop yields and water quality stability (Homoki et al. 2021). NFT systems demonstrated superior WUE. This divergence can be attributed to fundamental design differences between the two systems: while DWC prioritizes root submersion and oxygenation, NFT minimizes water consumption through thin-film nutrient delivery. Interestingly, previous work by Bodenmiller (2017) cautioned that excessive aeration may have unintended consequences, potentially disrupting system pH dynamics and thereby reducing nutrient availability. EC is a pivotal indicator of ionic strength in aquaponic systems, directly influencing nutrient solubility, root absorption kinetics and overall plant performance (Yuhasari et al. 2021; Maarif 2016). EC values in both NFT and DWC gradually shifted over time, remaining within the operationally acceptable range of 0.8–1.2 mS cm^{-1}, as earlier recommended for

aquaponic production (Maarif 2016). This stability suggests that nutrient bioavailability was sufficient to sustain crop growth while avoiding excessive salinity accumulation. Interestingly, EC values tended to be marginally higher in DWC than NFT, a pattern consistent with earlier observations by Somerville et al. (2014), who attributed such differences to enhanced nutrient retention and microbial mineralization in deep-water reservoirs relative to flowing-film configurations. The temporal decline in EC observed in both systems, however, may be interpreted as a signal of progressive nutrient drawdown, underscoring the need for supplementation (Goddek et al. 2019). Ammonia dynamics further illuminated the distinct system responses. As a critical parameter shaping aquaponic health, ammonia must be tightly regulated to avoid toxic accumulation while supporting the nitrification pathway essential for nutrient cycling. In our experiment, ammonia concentrations increased steadily in both systems, but the trajectory differed. NFT initially exhibited lower concentrations than DWC, a result likely linked to continuous water flow and greater biofilm surface area, which accelerate nitrification efficiency (Rakocy 2012). Yet, by Week 5, a pronounced spike in NFT ammonia was observed, suggesting a lag in microbial colonization or an imbalance between fish waste generation and bacterial oxidation. By contrast, the DWC system, while displaying higher baseline ammonia, showed a slower and buffered increase over time, reflecting the stabilizing effect of its larger water volume. The behaviour of nitrite (NO_2^-) further substantiated the dynamic maturation of the nitrifying consortia. Both NFT and DWC exhibited an initial elevation in nitrite, followed by stabilization as the experiment progressed. This pattern is consistent with earlier reports (Wongkiew et al. 2017), where transient nitrite accumulation was linked to delayed colonization of NOB. The initial surge likely reflected incomplete nitrification, as ammonia was rapidly oxidized to nitrite before further conversion to nitrate (Rakocy 2012). Stabilization of nitrite levels in later weeks indicates improved NOB functionality, essential for sustaining water quality and mitigating nitrite toxicity to both fish and crops (Graber and Junge 2009).

Correspondingly, nitrate (NO_3^-) concentrations showed a continuous upward trend in both systems, in agreement with Goddek et al. (2019), who highlighted nitrate enrichment as the inevitable endpoint of efficient nitrification. Notably, nitrate levels were consistently higher in DWC than NFT, plausibly due to the larger system volume enhancing retention before assimilation by plants (Yep and Zheng 2019). WUE further distinguished system performance, with NFT consistently outperforming DWC at both developmental stages. Remarkably, WUE in NFT was 45% greater at 40 DAS, although efficiency declined over time in both systems, decreasing by 12% in NFT and 14% in DWC between 40 and 70 DAS. These findings align with broader literature underscoring aquaponics as a highly water-efficient production strategy, capable of reducing water demand by up to 90% compared to conventional agriculture (Nishanth et al. 2024). More specifically, Gillani et al. (2023) demonstrated that NFT systems also deliver superior energy-use efficiency relative to DWC, attributing these gains to reduced water volume requirements, lower pumping demands and improved nutrient delivery efficiency. Similar to their findings, our results highlight the advantages conferred by the thin nutrient film in NFT, which facilitates superior oxygen diffusion into the root zone (Nitu et al. 2024). Enhanced oxygenation improves root metabolic activity and water uptake, thereby translating into higher WUE. Fish reared in the DWC system consistently attained greater final weights at 40 and 70 DAS, a trend attributable to the larger water volume and greater buffering capacity of DWC, which collectively create a more stable and less stressful rearing environment. FCR remains a pivotal index of production efficiency, reflecting the extent to which feed is assimilated into fish biomass. The FCR values observed in this study fell within the ranges previously documented for tilapia under aquaponic conditions, typically 0.9–1.2 (Danner et al. 2019), and were comparable to values reported in conventional systems (Khater 2012). Interestingly, higher ratios, up to 1.28, have been recorded in integrated multi-trophic aquaculture frameworks (Goda et al. 2024). Because FCR is highly sensitive to variables such as stocking density, feeding regimes and system stability, its optimization remains central to balancing production efficiency with resource use. SGR, which measures the relative daily increase in biomass, revealed a nuanced system-dependent trend. At 40 DAS, NFT fish exhibited an SGR of 4.64% compared with 5.20% in DWC, suggesting marginally greater early-stage growth efficiency under NFT's shallower and more dynamic water column. However, by 70 DAS, SGR values had declined in both systems (NFT: 3.40%; DWC: 3.75%), reflecting the expected reduction in relative growth rate as fish approach physiological maturity. Previous reports indicate that SGR for tilapia under aquaponics ranges from 1.03%–1.14% day^{-1} (Tadeo and Malaya 2021) to peaks of 5.56% day^{-1} under optimized culture conditions (Mustikasari et al. 2018). TGC, which adjusts growth performance to thermal conditions, further confirmed system-related differences. At a maintained water temperature of 24.5°C, DWC fish exhibited consistently higher TGC values compared with NFT. As TGC is widely regarded as a robust tool for cross-system growth comparisons under varying thermal regimes (Jobling 2003), these results suggest that the DWC system more effectively exploits the prevailing temperature to sustain growth potential. The larger volume and enhanced circulation capacity of DWC reduce competition, mitigate stress and create a more favourable swimming environment, all of which are known to influence feeding behaviour and growth trajectories. By contrast, NFT, while less conducive to maximal biomass accumulation, may provide system efficiencies during the early rearing phase, potentially making it advantageous for phased or staggered production strategies. Taken together, these findings reinforce the notion that DWC is superior for achieving greater tilapia biomass yield, whereas NFT offers modest early-stage growth advantages. Basil cultivated in the DWC system demonstrated consistently superior growth outcomes, with significantly greater plant height, shoot and root extension, fresh and dry biomass and root fresh weight compared with plants grown under NFT. The continuous submersion of roots in a nutrient-enriched medium within DWC ensures uninterrupted access to water and dissolved minerals, thereby enhancing uptake efficiency. Aeration provided through air stones or pumps further supports root respiration, stimulates microbial processes and facilitates robust biomass accumulation (Rakocy 2012). Moreover, the relatively stable nutrient concentrations and moderated root-zone temperature characteristic of DWC create a physiologically favourable environment that sustains plant vigour throughout the production cycle (Dhumal et al. 2024).

NFT, while more water-efficient, is more vulnerable to transient nutrient imbalances, which may constrain vegetative growth (Fathidarehnijeh et al. 2023). Resh (2022) and Lennard and Ward (2019) similarly reported that, although NFT confers advantages such as system simplicity and lower water demand, it does not consistently match the growth outcomes achieved in DWC—particularly for species reliant on stable root-zone conditions. Dhumal et al. (2024) demonstrated significantly higher biomass accumulation in lettuce cultivated under DWC, attributing the advantage to more consistent nutrient availability and improved root-zone oxygenation. Walters and Currey (2015) also observed that DWC systems tend to deliver higher yields, though they emphasized that system choice must be contextualized by broader production factors such as space constraints, energy consumption and resource availability. It is, however, important to recognize that NFT is not intrinsically inferior. When nutrient delivery and root-zone aeration are optimized, NFT has been shown to achieve performance comparable to or in some cases surpassing DWC. For example, Lennard and Ward (2019) documented aquaponic NFT systems that produced outcomes on par with or exceeding those of hydroponics, underscoring the potential of NFT when system conditions are carefully regulated. Walters and Currey (2015) likewise highlighted the operational efficiency of NFT for crops such as basil, where oxygen availability to roots exerts a strong influence on both growth trajectories and final yield. The findings from the pigment analysis help to reinforce the superior performance of DWC in promoting pigment biosynthesis and align with earlier studies that highlighted similar advantages. Yang et al. (2022), for example, reported that lettuce grown in DWC exhibited a 5.2% increase in chlorophyll content and a striking 41.0% increase in carotenoids relative to NFT. Likewise, Çekin et al. (2025) confirmed that DWC not only enhanced chlorophyll accumulation in lettuce but also improved consumer taste preference, underscoring the practical implications of pigment enrichment for crop quality. The observed increase in pigment levels under DWC conditions can be mechanistically attributed to the continuous immersion of roots in a nutrient-rich and well-aerated solution, which ensures consistent ion availability and fosters stable photosynthetic metabolism. Adequate oxygenation in the root zone reduces hypoxic stress and supports metabolic processes linked to chlorophyll and carotenoid biosynthesis. By contrast, NFT systems are inherently more prone to fluctuations in nutrient concentration and water flow, particularly under variable environmental conditions. Such instability may impose mild physiological stress, thereby constraining pigment formation and limiting the photosynthetic potential of plants cultivated in NFT.

Biochemical accumulation was consistently greater in basil plants cultivated under the DWC system, with the highest concentrations recorded at 70 DAS. A temporal increase was observed in both systems, but the magnitude of enrichment was markedly higher in DWC. Although direct comparative studies across aquaponic system designs remain limited, related work on hydroponic and conventional cultivation systems has demonstrated that aquaponically grown basil tends to exhibit elevated protein levels and enhanced biochemical composition (Yang and Kim 2020a, 2020b). DWC systems appear to underpin this trend through greater nitrogen availability and uptake efficiency, facilitated by their relatively large water volume, which confers improved buffering capacity and nutrient stability (Nozzi et al. 2018; Ayipio et al. 2019). Consequently, basil grown under DWC consistently accumulated higher protein content compared with NFT, where nutrient concentrations are more prone to fluctuation. While phenolic compounds and flavonoids are often associated with stress-induced defence responses (Sharma et al. 2019), their elevated levels in this context are more plausibly explained by improved nutrient availability. Adequate and stable nutrient supply enhances the biosynthetic pathways underlying secondary metabolism, thereby promoting higher accumulation of these metabolites (Naseri et al. 2022). The present findings are consistent with this interpretation, suggesting that DWC enhances both the quantity and quality of basil by reinforcing the biochemical pathways responsible for functional metabolite production. Essential oil concentration followed a similar trajectory, with basil plants grown in DWC recording consistently higher values at both 40 and 70 DAS. Although studies directly comparing aquaponic system designs are scarce, Albadwawi et al. (2022) reported that aquaponically grown basil produced greater essential oil yields compared with soil-based systems. Given that secondary metabolite enrichment is often linked to antioxidant activity, the higher essential oil accumulation observed here is consistent with the improved ABTS and DPPH scavenging activities detected in DWC plants. Supporting this, Braglia et al. (2022) demonstrated that aquaponically cultivated plants generally possess superior antioxidant profiles compared with conventionally cultivated counterparts, although no prior studies have directly contrasted antioxidant production between NFT and DWC aquaponic systems. Antioxidant enzyme activity provided further evidence of system-related effects. POD activity increased progressively with plant age and was consistently higher under DWC, reflecting a more robust oxidative stress response (Albadwawi et al. 2022). CAT activity exhibited a parallel trend, reinforcing the enhanced resilience of DWC-grown plants to oxidative stress. The elevation of both enzymatic and non-enzymatic antioxidant mechanisms suggests that DWC not only supports plant growth and metabolite accumulation but also strengthens intrinsic defence capacity. Statistical analyses confirmed significant main effects of system design and developmental stage for all biochemical parameters, with interaction effects detected in some cases. These outcomes highlight that basil's biochemical composition is shaped synergistically by both system type and plant maturity. Importantly, DWC appears to amplify the natural ontogenic increase in proteins, metabolites and antioxidants observed as plants mature, thereby providing a compounded advantage in terms of both yield and quality.

Aquaponic configurations rely on fish-derived waste as the principal nitrogen source, with microbial transformations converting ammonia to nitrite and then to nitrate, the bioavailable form for plant assimilation (Eck et al. 2019). Differences in nitrogen concentrations between NFT and DWC were evident, reflecting system architecture effects on nutrient retention and distribution. Significant main effects of system type and developmental stage were observed, with no interaction, suggesting additive influences. Elevated nitrogen in DWC basil at 70 DAS is attributable to sustained nutrient availability, supporting protein biosynthesis and biomass accumulation (Braglia

et al. 2022). Planting density also modulates nitrogen removal, with denser configurations facilitating uptake (Petrea et al. 2014). Phosphorus dynamics showed system and growth stage effects without interaction. DWC plants consistently accumulated higher phosphorus at 70 DAS, confirming stable nutrient environments promote uptake. A phosphorus concentration of ~1.1% dry matter from fish-derived inputs sustains aquaponic crop growth (Yang and Kim 2020a). Potassium also exhibited system and stage effects, with higher values under DWC, consistent with superior mineral uptake in stable aqueous conditions (Rakocy 2012). Potassium enrichment enhances osmotic regulation, drought tolerance and water retention (Rascio et al. 2001). Calcium uptake reflected significant system and stage effects but no interaction. DWC plants at 70 DAS achieved the highest calcium, consistent with hydroponic observations where continuous immersion improves transport and mitigates tip burn (Yang et al. 2024). Magnesium accumulation increased with growth stage across both systems, reflecting its central role in chlorophyll and higher photosynthetic demand (Ahmed et al. 2023). Sulphur also increased with plant maturity, essential for sulphur-containing amino acids and protein synthesis (Marschner 2012).

Micronutrients showed more complex patterns. Boron increased with growth stage, peaking at 70 DAS in DWC, supporting cell wall architecture and division (Rasheed 2009; Marschner 2012). Copper also increased with maturity but was not system-dependent, reflecting roles in photosynthesis, respiration and redox enzyme function (Chen et al. 2022; Hunter et al. 2022). Iron showed significant effects of system and stage, with higher uptake in DWC due to prolonged root contact and favourable redox conditions (Yang et al. 2024). NFT plants experienced restricted oxygenation, limiting iron assimilation. Manganese dynamics showed main effects of system and stage, with interaction: DWC at 70 DAS accumulated the highest Mn. Dissolved Mn^{2+} in recirculating systems oxidizes rapidly, but chelation or complexation can maintain bioavailability (Langenfeld et al. 2022; Alejandro et al. 2020). Larger water volume and steadier root contact in DWC likely sustained higher dissolved Mn. Recent studies highlight the roles of pH/ORP control and complexing ligands in Mn bioavailability (Vought et al. 2024; Khoshru et al. 2023), with system advantages amplified as plants mature. Sodium concentrations were influenced by system and stage, with interaction. Sodium functions as a compatible osmolyte, and cumulative uptake increases with age (Subbarao et al. 2003; Yep et al. 2020). Higher sodium in DWC at 70 DAS reflects system volume and nutrient distribution. Zinc exhibited effects of system, stage, and interaction, supporting enzymatic activation and protein synthesis (Das and Green 2016). Enhanced DWC accumulation at later stages reflects stable nutrient exposure.

5 | Conclusion

The present investigation offers a rigorous comparative evaluation of basil cultivation within two distinct aquaponic configurations DWC and NFT—across two developmental stages (40 and 70 DAS). The findings reveal a fundamental trade-off between resource-use efficiency and biological performance. NFT systems demonstrated markedly superior WUE, underscoring their potential as a climate-smart production strategy for arid and water-constrained environments. Conversely, DWC consistently supported enhanced fish productivity, greater vegetative growth, elevated pigment accumulation and enriched biochemical composition, thereby reinforcing its suitability for maximizing biomass yield and nutritional quality. The outcomes of this study establish, for the first time, a comparative framework for basil performance across aquaponic designs, thereby contributing novel insights into how system architecture dictates both plant and fish productivity. This dual emphasis on efficiency and output underscores that system selection should be guided by production priorities whether the objective is to conserve limited water resources or to optimize biomass and metabolite accumulation. Looking forward, future research should extend beyond single-species evaluations to include multi-crop and multi-fish integrations, enabling the design of aquaponic systems that maximize both productivity and resilience. Advanced sensor-based monitoring of nutrient fluxes, coupled with microbial community profiling, could elucidate the mechanistic underpinnings of nutrient dynamics across designs. Moreover, life-cycle analyses incorporating energy use, GHG emissions and economic feasibility will be indispensable for situating aquaponic systems within broader sustainability frameworks. Collectively, these directions will facilitate the development of optimized, design-specific aquaponic models that integrate ecological efficiency with high-value crop production, advancing the paradigm of circular agriculture in resource-limited regions.

Author Contributions

Drishya Nishanth: conceptualization, data curation, visualization, writing – original draft preparation. **Ramya Manoharan:** visualization, data curation, writing – review and editing. **Chythra Somanathan Nair:** visualization, data curation, writing – review and editing. **Radhakrishnan Subramanian:** writing – review and editing. **Abdul Jaleel:** funding acquisition, supervision, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data are contained within the article.

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