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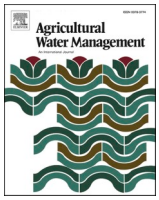

Evaluating hydroponics and aquaponics: Comparative insights into sustainability and strawberry quality

N. Korbee [a,*], B. Bautista [a], M. García-Sánchez [b], P. Cobos [a], J.L. Ferres-García [a], F.L. Figueroa [a], E. Medrano [c]

[a] Universidad de Málaga, Departamento Ecología, Instituto andaluz de Biotecnología y Desarrollo Azul (IBYDA), Centro Experimental Grice Hutchinson, Lomas de San Julián, 2, Málaga 29004, Spain
[b] Grupo de Ecología de Angiospermas Marinas (GEAM), Centro Oceanográfico de Murcia, IEO-CSIC, Murcia, Spain
[c] Instituto de Investigación y Formación Agraria y Pesquera (IFAPA), Junta de Andalucía, Centro IFAPA La Mojonera, Camino San Nicolás, 1, Almería 04745, Spain

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ABSTRACT

Aquaponics provides a more sustainable alternative to hydroponics by integrating fish farming with plant cultivation, thereby reducing the need for chemical fertilizers and promoting the natural recycling of nutrient waste. This study compared the cultivation of 'Primoris' strawberry plants in two systems: a traditional hydroponic system using agricultural fertilizers and an aquaponic system utilizing effluents from thick-lipped grey mullet (*Chelon labrosus*) fishponds. Despite the significantly lower concentrations of key nutrients (primarily nitrate and phosphate) in the aquaponic system, total yield exceeded 600 g per plant, with no significant differences between the two cultivation methods. Strawberry leaves from the aquaponic system exhibited higher levels of chlorophyll (Chl *a*: 1.7 ± 0.15 mg·g^{-1} FW, Chl *b*: 0.98 ± 0.09 mg·g^{-1} FW), carotenoids (1.2 ± 0.09 mg·g^{-1} FW), and calcium (1.3 %). No differences were observed in photosynthesis, organic carbon, total nitrogen, or organic matter content in the leaves between the two systems. Additionally, anthocyanin content in aquaponically grown strawberries was higher (23.5 ± 4.3 mg PE·100 g^{-1} FW). Fruit quality parameters (including °Brix, acidity, vitamin C, and firmness) were comparable between the two cultivation systems, as confirmed by a blind sensory test. These findings suggest that aquaponic strawberry cultivation can reduce fertilizer usage without compromising yield, fruit quality, or plant health. This highlights aquaponics as a viable and more sustainable alternative to conventional agriculture, including hydroponic methods.

1. Introduction

Food and agricultural production systems worldwide are facing unprecedented challenges due to increasing food demand driven by a growing population, the impacts of climate change, overexploitation of natural resources, biodiversity loss, and food waste (Food and Agriculture Organization, 2022). In response to these challenges, aquaponic systems (integrating fish farming with hydroponics) are attracting growing interest from scientists, producers, and consumers (Krastanova et al., 2022).

Notably, hydroponic cultivation enhances yield efficiency for leafy greens and fruit-bearing vegetables by optimizing nutrient delivery and growth conditions compared to traditional farming. Additionally, hydroponics enables year-round production, providing a more controlled and resilient alternative to conventional agricultural methods. However, traditional farming, while more space-intensive and dependent on soil health, remains more accessible and cost-effective for large-scale staple crops. In contrast, hydroponics faces scalability challenges compared to conventional methods, including high investment costs, technical expertise requirements, and increased energy demands (Pomoni et al., 2023).

Aquaponic farms operate by treating fish effluents through mechanical and biological filtration (Zou et al., 2016). This process cleans the water and breaks down compounds into plant-assimilable molecules, allowing the recycled water to be returned to the fish tanks. Therefore, aquaponic systems can significantly reduce water consumption and minimize the use of pesticides and fertilizers while maintaining comparable production levels (Yep and Zheng, 2019). Demonstrating a lower risk profile compared to hydroponic systems due to their efficient nutrient recycling, reduced dependence on synthetic fertilizers, and

* Corresponding author
E-mail address: nkorbee@uma.es (N. Korbee).

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greater resilience. This makes aquaponics one of the most environmentally friendly farming methods without compromising crop production (Boxman et al., 2017). Thus, it represents a sustainable food production solution that aligns with circular economy principles and biomimetic natural processes, minimizing resource input and waste. By promoting local food production, aquaponics can help reduce food transportation costs and environmental impact, contributing to a more resilient and secure food system (Salisu et al., 2024).

There are two main methods of aquaponics, depending on the continuity of the system, coupled and uncoupled (also known as decoupled) (Somerville et al., 2014). In the coupled one, the water returns to the fish tanks after having passed through the hydroponic channels of the plants and having been filtered and recycled, until the components have been reduced to a minimum. In the uncoupled, the water is returned to the channels, discarded once it has nourished the plants or stored again with new water coming from the fish tanks (Colt et al., 2022). These different ways of applying aquaponics allow it to be adapted to a multitude of situations.

The vegetables and fruits that can be grown in an aquaponic system seem to be limited, but interesting species can be found, despite their high nutrient demand, such as tomatoes, cucumbers, strawberries, or peppers. Also, leafy vegetables like lettuce, spinach, basil or chives, among others, do well in this kind of systems making them the preferred choice (Cohen et al., 2018; Yep and Zheng, 2019; Goddek et al., 2020, Wang et al., 2023). However, some studies have reported a lower yield compared to hydroponic systems for some species (Castillo-Castellanos et al., 2016). It is likely related to the fact that fish feed contains low levels of both macro- and micronutrients. Consequently, aquaculture effluent alone may not sufficiently support plant growth in aquaponic systems and may require supplementation with macronutrients (N, P, K, Ca, Mg, and S) and micronutrients (such as Fe, Cu, Zn, and Mn) (Rakocy et al., 2004, Yep and Zheng, 2019, Al Tawaha et al., 2025).

In this study, strawberries (*Fragaria* × *ananassa* v. Primoris) were cultivated in nutrient film technique (NFT) channels using both a hydroponic system and an uncoupled aquaponic system, incorporating waste from thick-lipped grey mullet (*Chelon labrosus*, Risso 1827). This freshwater species is considered easily cultivable and has been identified as a promising low-trophic-level candidate for aquaculture diversification (Khemis et al., 2013; García-Márquez et al., 2021). Grey mullet exhibits omnivorous feeding behaviour in early developmental stages, transitioning to herbivory with age, and possess a high osmoregulatory capacity (Zouiten et al., 2008; Pujante et al., 2018).

Strawberries were chosen for this study due to their economic importance in Spain, the leading producer in Europe and the sixth largest worldwide (Morillo et al., 2015; Romero-Gámez and Suárez-Rey, 2020). Strawberry cultivation in Spain is concentrated primarily in Huelva (southwestern Iberian Peninsula), near Doñana National Park, an environmentally sensitive area (Regional Government of Andalusia, 2016). To protect this valuable ecological region, reducing nitrogen effluents is essential to mitigate the eutrophication associated with agricultural activities. Despite the growing interest in sustainable farming, research on strawberry cultivation in aquaponic systems remains limited (Roosta and Afsharipoor, 2012; Abbey et al., 2019; Richardson et al., 2022; Romano et al., 2023).

In this context, the primary objective of this study is to assess whether aquaponics can be as efficient as hydroponics while offering greater sustainability for strawberry production. To achieve this, two cultivation systems were compared: a traditional hydroponic system using agricultural fertilizers and an aquaponic system utilizing fish effluents. The study evaluates fruit yield, quality, bioactive compounds, and antioxidant capacity, as well as photosynthesis, and leaf chemical analysis and pigment content, in strawberry grown in both systems.

2. Materials and Methods

2.1. Biological material (fishes and strawberries) and experimental design

Strawberries (*Fragaria x ananassa v Primoris*) were cultivated in NFT (Nutrient Film Technique) channels using both a hydroponic system and an uncoupled aquaponic system along with waste to thick-lipped grey mullet specimens (*Chelon labrosus*, Risso 1827). The trial was carried out according to the Spanish law (R. D. 53/2013) establishing the basic rules applicable to the protection of animals used in experimentation. Installed at the "Experimental Center of Ecology and Microbiology of controlled aquatic systems (CEMSAC) located in the experimental Center Grice Hutchinson of Malaga University (Malaga, Spain; Spanish Operational Code REGA ES290670002043).

Fishes were collected from the coastal waters of Malaga Bay with a permission provided by the Fish Agency from Andalusian Government. They were maintained in a 5.5 m^3 tank at a density of about 12 fishes per cubic meter with a recirculation aquaculture system (RAS), equipped with physical and biological filters. The filtration system consisted of a 100 L compartment for the physical separation of particulate matter. After this compartment, the water was passed to a 100 L capacity biofilter compartment maintained in aerobiosis. The structures used as biofilter beads, namely biofilm carriers (Acuitec, Spain), consisted of polyethylene cylinders of 1 cm diameter size with inner protruding parts that increase the overall bacterial adherence surface to 1180 $m^2 \cdot m^{-3}$. The fishes were maintained under natural photoperiod in the range of 18 – 24°C and salinity 1.0 – 1.2 ‰. Supplemental aeration was provided to maintain dissolved oxygen at 6.8 ± 0.4 mg $\cdot L^{-1}$. Fish were fed by hand twice per day (9:00 and 17:00 hours) with a commercial diet (32 % protein, 6 % fat, TI-3 Tilapia, Skretting, Spain). Every day, we use an aquarium NH_4-NH_3 test to ensure that the ammonium concentration in the fishpond effluent remained below 0.5 mg$\cdot L^{-1}$. Since the biological filter was mature, the concentration stays within the acceptable limit throughout the experimental period.

The hydroponic system, based on Nutrient Film Technique (NFT) consisted of two identical units for both treatments. Each unit was composed by 9 polyethylene channels (Auxprotec, Murcia, Spain) where 22 'Primoris' strawberry plants transplanted per channel on October 15, 2020 (Fig. 1). A standard nutrient solution for strawberries (Sánchez-González et al., 2017) was applied in the control unit, referred to as the hydroponic system. The initial electrical conductivity (EC) of the nutrient solution in the control unit was 1.5 mS$\cdot cm^{-1}$ and was removed when it exceeded 2.0 mS$\cdot cm^{-1}$ to prevent NaCl accumulation. The average composition of the standard solution and the effluent from the fishpond is presented in Table 1. The application of the fishpond effluent began on March 10, 2021 (147 days after transplanting) and continued until the end of the cultivation period on May 19, 2021. The standard nutrient solution and the fishpond effluent were continuously moved through the strawberry root mass at the rate of 2.3 L $\cdot min^{-1}$ by means of a 400 W pump. Iron chelate (Sequestrene), and a foliar application of calcium (Wuxal-Calcium) were incorporated every two weeks in both systems to supplement the deficiency of these elements in the strawberries.

2.2. Characterization of environmental conditions

Air temperature and irradiance were recorded during the experiment using two HOBO 4-Channel External Data Logger (U12–006). Both were placed on two different spots on the top of NFT channels.

An aquarium NH_4-NH_3 test was used to ensure that the ammonium concentration in the fish effluent remained below 1 mg$\cdot L^{-1}$ throughout the experiment. Water temperature, pH, dissolved oxygen and conductivity were also measured along the experiment every two days, to control the stability of the effluents. The equipment used was LAQUA pH120-K for pH, Hanna HI98198 for dissolved oxygen and LAQUA 9382–10D conductivity cell for temperature and conductivity. These

Fig. 1. Pictures of the Nutrient Film Technique (NFT)-type system, as well as strawberries before and after harvest.

Table 1
Average concentrations (expressed in $mg{\cdot}L^{-1}$) of various anions and cations in the input water used for hydroponic and aquaponic strawberry cultivation throughout the experimental period.

System	Cl^-	NO_3^-	PO_4^{3-}	SO_4^{2-}	Na^+	NH_4^+	K^+	Mg^{2+}	Ca^{2+}
Hydroponic	203 ± 34	475 ± 67	248 ± 29	238 ± 30	95 ± 19	0.24 ± 0.15	250 ± 17	33 ± 4.5	99.5 ± 7.8
Aquaponic	496 ± 78	92 ± 21	12.1 ± 7.9	77 ± 6	303 ± 53	0.74 ± 0.66	16 ± 3.5	BDL**	37.3 ± 5.4

* Mean±standard deviation (n=34).
** BDL: below detection limit

parameters were measured in the decoupling tank. Data not shown.

The main anions and cations present in the water were determined, i.e., Cl^-, NO_2^-, NO_3^-, NH_4^+, Na^+, K^+, Mg^{2+}, Ca^{2+}, SO_4^{2-}, PO_4^{3-}. They were measured using an ionic chromatography 883 Basic IC Plus (Metrohm, Switzerland). For anions a Metrosep A Supp 5–250/4.0 (polyvinyl alcohol) column was used to separate them, using ammonium (NH_4^+) as the ion exchanger, depending of the negative charge and the atomic radius. For cations, the column used was a Metrosep C-3 (also polyvinyl alcohol), but in this case, their separation depends on the positive charge and the atomic radius, therefore a carboxylic group was used as ion exchanger.

2.3. Photosynthesis as in vivo Chlorophyll a fluorescence

In situ photosynthetic activity was estimated in the leaves of the strawberry plants by using *in vivo* chlorophyll *a* fluorescence associated to Photosystem II through the pulse-amplitude modulated chlorophyll fluorometer Junior PAM (Walz GmbH, Germany). Rapid light curves (RLC) were performed on plants leaves from both systems once a week during the experiment. Maximal quantum yield (Fv/Fm) as indicator of physiological state, was determined by incubating previously the leaves for 15 min in darkness and basal fluorescence was determined by switching on measured light, (F_o) and then saturation light pulse was applied to measure maximal Florescence (F_m). Maximal quantum yield (Fv/Fm) was determined as:

$$Fv/Fm = F_m\text{-}F_o/F_m \quad (1)$$

Then algal samples were exposed for 30 s to twelve increasing irradiances (25, 45, 66, 90, 125, 190, 285, 420, 625, 845,1150, and 1500 $\mu mol\ photons{\cdot}m^{-2}{\cdot}s^{-1}$) of actinic blue light followed by a saturating light pulse determining effective quantum yield (YII) and electron transport rate (ETR) as indicator of photosynthetic capacity.

Y(II) was determined as follows, firstly fluorescence at steady state (F_t) was calculated by measuring red light and then saturating light pulse was applied (800 ms, 5000 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$) to the leaves of strawberries to determine maximal fluorescence at light-acclimated samples (F_m) according to (Figueroa et al., 2021). Effective quantum yield was calculated as:

$$Y(II) = (F_m\text{-}F_t)/F_m\text{´} \quad (2)$$

ETR was calculated as:

$$ETR = Y(II){\cdot}E_{PAR}{\cdot}A{\cdot}F_{II} \quad (3)$$

where E_{PAR} is the irradiance of photosynthetic active radiation (PAR=400–700 nm) of the incident light at the surface of the leaves. A is the absorptance, which was measured every day according to Figueroa et al. (2014). F_{II} is the fraction chlorophyll *a* associated to PSII being 0.5 in higher plants (Schreiber and Bilger, 1993). ETR versus irradiance obtained from light curves were fitted according to (Eilers and Peeters, 1988) models to estimate the variables of maximal electron transport rate (ETR_m), photosynthetic efficiency (α_{ETR}) and saturated irradiance (E_k).

Using R-studio script effective quantum yield was also determined, *in situ* under growth conditions in the green house by using the same Junior PAM in order to control the photosynthetic activity and the physiological state of plants.

2.4. Pigment analysis in leaves

Chlorophyll *a* and *b* and total carotenoids were extracted from the strawberries´ leaves (n = 8) at the end of the experiment (May 2021). 100 mg were homogenized with a mortar in 3.5 mL 90 % acetone. Chlorophylls were calculated using the equations of Ritchie (2006) and carotenoids following Strickland and Parsons (1972) equation. The results were expressed as $mg{\cdot}g^{-1}$ FW.

2.5. Bioproductivity: fruits and biomass of strawberries

Total fruit yield was quantified in four replicates per unit, being each replicate one NFT channel with 22 plants of strawberry. Ripe fruits were harvested twice a week from 21 December 2020 to 19 May 2021 and weighed.

Three other NFT channels per unit were reserved for successive determinations of fresh- and dry-biomass and leaf area. Each determination was performed on 6 plants per crop unit, being each plant divided into four fractions: leaf, stem+crown, fruit, and root. The dry weight of each fraction was obtained by drying in an oven at 80ºC for 48 hours, leaf area was determined with an Mk2 area meter (DeltaT Device, Cambridge, United Kingdom). Four determinations were made at November 2020 (before starting with the fish effluent), March, April and May 2021. In the last biomass determination, the dry matter of leaves from four plants per treatment was ground and organic carbon, organic matter, total nitrogen, calcium, and sodium expressed as % dry matter were determined.

2.6. Quality of fruits

Fruit quality was evaluated at three points during the experiment: at the beginning, after three weeks (March), and at the end, after nine weeks (May), following cultivation under hydroponic and aquaponic systems. For the initial measurements, six replicates, each consisting of five fruits each were used. For the mid-point and final evaluations, four replicates of five fruits each were analysed. Fruit selection was based on similar coloration at harvest, measured at two points in the equatorial region using a Minolta spectrophotometer (Konica Minolta CM-2600d/2500d Ramsey, NJ, USA). A 'b' parameter value between 20 and 30 was set to ensure all fruits were at the same ripening stage. Strawberry firmness was assessed at two orthogonal spots on the equatorial plane of each fruit using a 3.5 mm diameter penetrometer, which results expressed in $kg{\cdot}cm^{-2}$. Each replicate was then homogenized using a mixer to obtain a puree, which was used for various biochemical analyses.

The pH, titrable acidity (TA) and soluble solids content (SSC) were also measured in the purees. TA was expressed as (% citric acid) after a titration with 0.1 NaOH (AOAC, 1984). The SSC was measured with a digital refractometer (PR-32α, Atago, Japan) and expressed as °Brix.

Quantification of vitamin C was performed using test strips on a reflectometer (Rqflex 10, Merck KGaA, Darmstadt, Germany), measuring into 1 g of puree diluted in 10 mL of distilled water. The results obtained were expressed in mg of ascorbic acid per 100 g FW. After these determinations, the purees were stored at −20°C until analysis.

2.7. Fruit Bioactive compounds and antioxidant capacity

The analysis of bioactive compounds and antioxidant activity in the prepared fruit purees (as described in the previous section) was conducted at the beginning, middle (March 25), and end of the experiment (May 19).

Total phenolic compounds (TPC) were measured using 100 mg of puree diluted in 2.5 mL of 80 % methanol. This hydromethanolic extract was also used for the DPPH assay. After storing the samples overnight at 4°C, the mixture was centrifuged at 4000 rpm for 10 min at 4°C, and the supernatant was then collected. TPC was determined colorimetrically using Folin-Ciocalteu reagent and galic acid (SIGMA) as standard. Finally, the absorbance was determined at 760 nm (Celis-Plá et al., 2016). Total phenolic content was expressed as in mg of gallic acid equivalent (GAE) per 100 g.

The total flavonoid content (TFC) was measured as in Dewanto et al. (2002). For it 250 mg of puree were mixed with 2.5 mL methanol 80 %. After storing the samples overnight at 4°C, the mixture was centrifuged at 4000 rpm for 10 min at 4°C, and the supernatant then collected. Briefly, 125 μL of the hydrometanolic extract were taken and mixed with 650 μL of MiliQ water and 37.5 μL of 5 % $NaNO_2$. After 6 min 75 μL of 10 % $AlCl_3$ 6 H_2O were added and incubated for 5 min. Finally, 250 μL of NaOH (1 M) and 137 μL of MiliQ water were added and the absorbance was measured at 510 nm. Catechin was used as standard, and the results were expressed in mg of catechin equivalent (CAE) per 100 g.

Total anthocyanin content was measured following the differential pH method (Giusti and Wrolstad, 2001) Two different solutions, one at pH 1 (KCl 0.025 M) and another at pH 4.5 (CH_3CO_2Na 0.4 M). An hydromethanolic extract, as the one prepared for TFC, was prepared with 250 mg of puree mixed in 2.5 mL methanol 80 %. It was diluted (1:10 v/v) in both solutions separately. The mixtures were incubated in darkness for 15 min, absorbance was measured at 500 nm and 700 nm. Absorbance (A) was calculated as:

$$A = (A_{\lambda 500} - A_{\lambda 700})_{pH\ 1} - (A_{\lambda 500} - A_{\lambda 700})_{pH\ 4.5} \quad (4)$$

The total anthocyanin content was then calculated as follows:

$$\text{Anthocyanin } (mg{\cdot}mL^{-1}) = (A{\cdot}MW{\cdot}DF{\cdot}1000) / (\varepsilon{\cdot}L) \quad (5)$$

where, MW: molecular weight of the reference anthocyanin (perlangonidine-3-glucoside), DF: Sample dilution factor, ε: molar extinction coefficient of perlangonidine-3-glucoside. The result was expressed in mg of pelargonidin-3-glucoside equivalent (PE) per 100 g.

Antioxidant capacity was measured following two different methods:

(1) ABTS assay (Re et al., 1999) was done by homogenizing 20 mg in 2.5 mL of sodium phosphate buffer (pH=6.5). ABTS reagent was prepared in sodium phosphate buffer (0.1 M, pH 6.5), ABTS (2,2′-azino-bis (3-ethylbenzothiazoline-6-sulphonic acid,7 mM) and potassium persulfate (K_2S_2O8, 2.45 mM). The reagent was incubated in darkness at room temperature for 12–16 h, allowing a complete formation of the radical. After this period, the reaction was performed by adding 940 μL of sodium phosphate buffer (0.1 M, pH 6.5), 10 μL of ABTS and 50 μL of puree extract. The samples were agitated, and absorbance was recorded by a UV–visible spectrophotometer (Shimazdu UV Mini-1240) at 727 nm (A) immediately at the beginning of the reaction (T_0) and after 8 min of incubation (T_8). The blank was phosphate buffer. The antioxidant activity (AA) of free radicals was calculated as:

$$AA\% = [(A_{T0} - A_{T8}) / A_{T0}] \cdot 100 \quad (6)$$

(2) DPPH (2,2-diphenyl-1-picrylhydrazyil) assay (Kim et al., 2002) was performed to the same hydromethanolic extract used for TPC. DPPH was prepared in a 90 % methanol solution (90MeOH:10 H_2O) to a final concentration of 1.27 mM. The reaction was complete after 30 min incubation in the darkness at room temperature (~20°C). Absorbance was determined at 517 nm.

Quantification of antioxidant compounds in both methods were determined using a standard curve with Trolox (6-hydroxy-2,5,7,8-tetramethylchroman-2- carboxylic acid) concentrations. The results were expressed in μmol of TE (trolox equivalent) per g of puree fresh weight (FW).

2.8. Sensory analysis

The biochemical analyses described above were complemented by sensory evaluation. Twenty-two panellists, all familiar with strawberry consumption, were selected based on specific criteria, including regular strawberry consumption, the ability to distinguish sensory attributes, and the absence of allergies or sensitivities to strawberries. The panellists varied in age, sex, and profession. All strawberry samples were free of defects, exhibited uniform ripening (based on external colour), and had similar weights. The samples were presented on two white plates, one for each treatment (hydroponic and aquaponic obtained fruits), and labelled with different codes to prevent treatment identification. The evaluations were conducted under identical environmental conditions with no time constraints.

In total, nine descriptors were selected for the final assessment, along with an overall evaluation. The tasters provided quantitative ratings on a five-point hedonic scale for organoleptic quality attributes (firmness in the mouth, juiciness, sweetness, acidity, aftertaste, and aroma) and visual appearance (size, shape, and colour), as well as an overall assessment. Each attribute was rated on a linear, unstructured scale from 1 to 5, representing levels of acceptance: 5 = excellent, 4 = good, 3 = acceptable (marketability threshold), 2 = poor, and 1 = inedible.

2.9. Statistical analyses

Statistical analyses were carried out with STATISTICA 7.0 analytical software (Stat Sotf Inc., Tulsa, OK, USA). All data sets were tested for normality and homogeneity of variances, by Shapiro wilks and Cochran's test, respectively. Significance was set at $p < 0.05$. Differences in leaf pigment content, leaf area index, dried material produced, leaf number, leaf chemical analysis and sensory evaluation results between hydroponic and aquaponic systems, was determined using a Student's *t*-test. For variables measured twice throughout the experimental period, the effects of the factors "month" and "system" were analysed using a two-way ANOVA. Additionally, when two measurements (pseudoreplicates) were taken from each strawberry puree (e.g., bioactive compounds measured in fruits), a nested ANOVA was conducted, with the

random factor "puree" nested within "system." When a significant interaction was found between "month" and "system," a post hoc comparison was performed using the Newman-Keuls test.

3. Results

3.1. Environmental conditions

Temperature and irradiance remained stable during the first half of the experiment but began to increase in early April, following the typical climatic patterns of Málaga in the southern Iberian Peninsula (Fig. 2).

The input of nutrients in the hydroponics system was much higher than the levels reached in the aquaponic system with the fishpond effluents except for Cl and Na since it was necessary to add sodium chloride for the optimal health status of the fishes (Table 1). Nitrate levels were 4–5 and sulphate and calcium 3 times higher in the hydroponic system compared to the aquaponic one, while phosphate and potassium levels were approximately 15–20 times higher along the experiment. The magnesium level in the aquaponics was lower than that to the detection limit.

3.2. Photosynthetic activity

Photosynthetic parameters in strawberry leaves cultivated under hydroponic and aquaponic systems were measured throughout the experiment. These parameters (including maximal quantum yield, maximal ETR, photosynthetic efficiency and saturation irradiance) were obtained from Rapid Light Curves (RLC) using a PAM fluorometer. The results indicated that the plants remained photosynthetically active, with no signs of photoinhibition. Additionally, the measured trends corresponded with the evolution of irradiance, showing no significant differences between the two systems (Fig. 3).

3.3. Pigments in leaves

Pigment concentrations were measured in the leaves of strawberry plants cultivated under aquaponic and hydroponic systems in May 2021, at the end of the experiment. The concentrations of chlorophylls *a* and *b* (Chl *a* and *b*), as well as total carotenoids, were significantly higher in plants grown in the aquaponic system compared to the hydroponic system ($p < 0.05$). Specifically, Chl *a* and *b* levels were 15 % higher, while carotenoid content increased by 10 % in the aquaponic system (Fig. 4).

3.4. Bioproductivity: fruits and biomass of strawberries

Similar yields were observed for both treatments during the first half of the experiment. By the end of the study, total production was highest in the fish effluent treatment (aquaponic system); however, statistically, no significant differences were found between the two systems (Fig. 5).

The initial leaf area index (LAI) after transplantation was 0.4 $\pm$ 0.2 m^2, increasing to 2.9 $\pm$ 0.5 m^2 by the end of the experiment. LAI followed a similar trend in both hydroponic and aquaponic systems throughout the study, with no significant differences.

Dry matter production in different plant parts increased consistently over the course of the experiment, without significant differences between hydroponic and aquaponic systems. The values ranged as follows: 2.3 $\pm$ 1.0 – 22.1 $\pm$ 3.5 g DW·plant^{-1} (leaves), 1.1 $\pm$ 0.6 – 15.5 $\pm$ 2.8 g DW·plant^{-1} (stems + crowns), 2.0 $\pm$ 1.0 – 13.4 $\pm$ 1.6 g DW·plant^{-1} (roots), and 24.5 $\pm$ 0.3 – 63.0 $\pm$ 2.2 g DW·plant^{-1} (fruits). Additionally, the leaf number increased from 7 $\pm$ 3 – 40 $\pm$ 6, with no significant differences between plants grown in hydroponic and aquaponic systems.

Chemical analyses of strawberry cv. "Primoris" leaves revealed no significant differences between the hydroponic and aquaponic systems in terms of organic carbon, total nitrogen, organic matter, and sodium. However, internal calcium content was approximately 25 % higher in plants grown in the aquaponic system compared to those in the hydroponic system (Table 2).

3.5. Quality of fruits

In terms of fruit quality, the data indicate similar values for acidity, °Brix, vitamin C, and fruit firmness in both treatments, hydroponic and aquaponic systems. Significant differences in °Brix levels between treatments were observed only in March. In the hydroponic system, °Brix degrees decreased toward the end of the experiment, while acidity increased, resulting in a lower °Brix/acidity ratio (Table 3). Over time, acidity, vitamin C, and fruit firmness increased from the beginning to the end of the experiment.

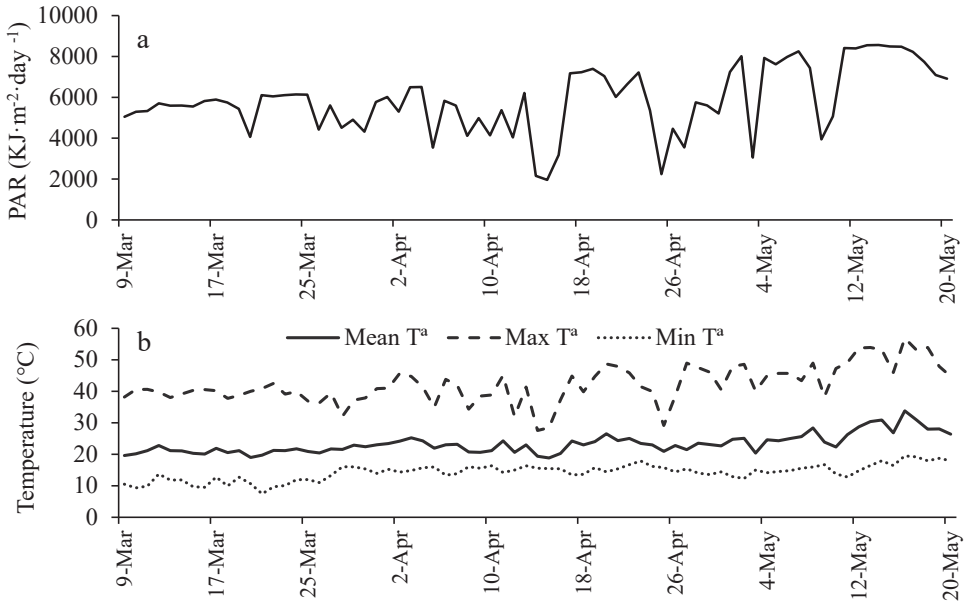

Fig. 2. Photosynthetically active radiation (PAR) (a), and mean, maximum and, minimum air temperature (b) registered inside the greenhouse throughout the experiment.

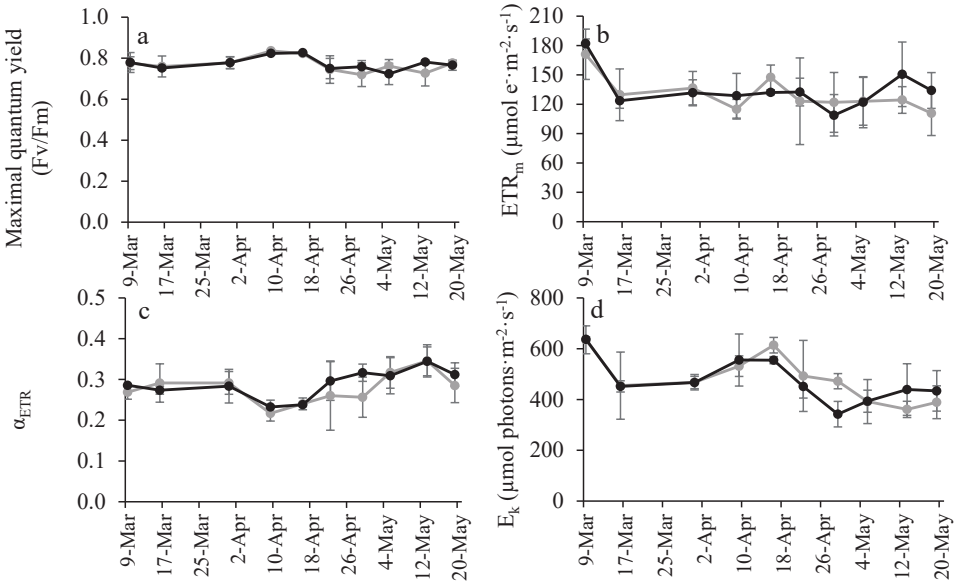

Fig. 3. Photosynthetic parameters measured on strawberry leaves. a) Maximal quantum yield (Fv/Fm) b) maximal electron transport rate (ETR_m), c) photosynthetic efficiency (α_{ETR}), and d) saturation irradiance (E_k) in hydroponic (grey lines) and aquaponic (black lines) cultivation throughout the experiment.

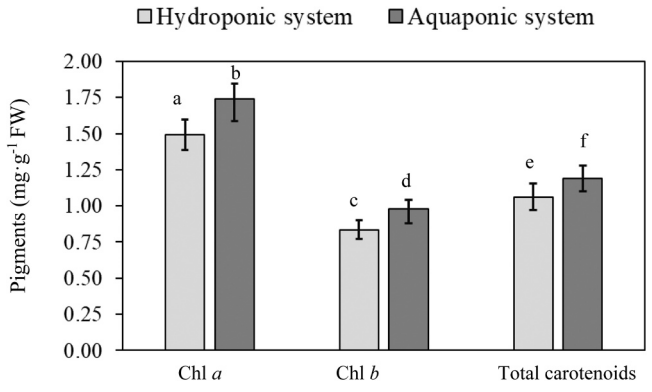

Fig. 4. Chlorophyll *a* (Chl *a*), chlorophyll *b* (Chl *b*), and total carotenoid contents (expressed in $mg \cdot g^{-1}$) in strawberry leaves grown in hydroponic and aquaponic systems at the end of the experiment (May 2021). Values are presented as mean ± SD (n = 8). Significant differences ($p < 0.05$) according to t-student's test for "system" are indicated by different letters for each pigment.

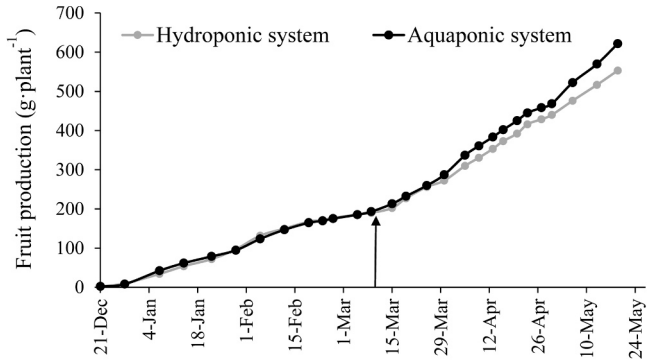

Fig. 5. Strawberry cv. 'Primoris' production ($g \cdot plant^{-1}$) in hydroponic and aquaponic systems throughout the fruit production period. The arrow indicates the point at which effluent input to the aquaponic system began.

3.6. Fruit bioactive compounds and antioxidant capacity

The trend of phenolic compound concentrations in strawberries changed significantly from March to May ($p < 0.001$). In the hydroponic system, phenolic compound levels increased by approximately 24 % over this period, whereas in the aquaponic system, they decreased by around 21 %. The recorded values were around 150–200 mg GAE·100 g^{-1} FW (Fig. 6a).

Another bioactive compound evaluated in the strawberries was flavonoids. These were not affected by the cultivation system but were influenced by time, with lower values observed in May compared to March ($p < 0.001$; Fig. 6b). Anthocyanin content was also measured in the fruit and was higher in strawberries cultivated in the aquaponic system ($p < 0.05$). However, no significant differences were observed over time (Fig. 6c).

Antioxidant activity in the fruits was measured using DPPH and ABTS assays. A slight increase in activity was observed in May for fruit from the hydroponic system when analysed with the ABTS method (Fig. 7a).

However, according to the DPPH assay results, antioxidant capacity increased from March to May in both treatments ($p < 0.001$). The lowest value was recorded in March for the hydroponic system (Fig. 7b).

3.7. Sensory evaluation

The results of the blind test, conducted with 22 volunteers who evaluated various descriptors of strawberries grown under hydroponic and aquaponic systems, including organoleptic quality, visual appearance, and overall rating, are presented in Table 4. The only significant difference observed between treatments was in the aroma of the strawberries, which was slightly lower in fruits from the aquaponic system ($p = 0.047$, marginally significant). However, the mean rating of 4 indicates a very good aroma. No significant differences were found in other olfactory, gustatory, or visual attributes between the two cultivation systems (Table 4).

4. Discussion

In the present study, strawberry plants were cultivated using hydroponic and aquaponic systems, the former utilizing agricultural

Table 2
Leaf chemical analysis of strawberry cv. 'Primoris', including organic carbon, total nitrogen, organic matter, sodium, and calcium (expressed as %), from plants grown in hydroponic and aquaponic systems. Measurements were taken at the end of the cultivation period on May 2021.

System	Organic C	Total N	Organic matter	Na	Ca
Hydroponic	53.1 ± 1.36	2.1 ± 0.13	91.3 ± 2.35	0.04 ± 0.03	1.0 ± 0.11[a]
Aquaponic	53.4 ± 0.52	2.4 ± 0.24	91.8 ± 0.90	0.08 ± 0.04	1.3 ± 0.08[b]

*Mean ± standard deviation (n = 4) with different letters indicates significant differences according to t-Student's test ($p < 0.05$), while no letter indicates non-significant differences.

Table 3
Quality descriptors of strawberry cv. "Primoris", including soluble solid concentration (°Brix), acidity (g citric acid·100 g^{-1} FW), °Brix/acidity ratio, vitamin C (mg ascorbic acid·100 g^{-1} FW), and firmness (kg·cm^{-2}), from plants grown in hydroponic and aquaponic systems. Measurements were taken at the initial time, in the middle (March 2021) and at the end of the cultivation period (May 2021).

	System	°Brix	Acidity	°Brix/Acidity	Vitamin C	Firmness
Initial		8.9 ± 0.81	1.0 ± 0.06	8.9	53.2 ± 4.49	4.3 ± 0.25
March	Hydroponic	10.1 ± 0.65[a]	0.8 ± 0.03[a]	12.6	60.5 ± 4.20[a]	4.2 ± 0.30[a]
	Aquaponic	7.9 ± 0.17[b]	0.8 ± 0.05[a]	9.9	55.3 ± 3.09[a]	4.2 ± 0.36[a]
May	Hydroponic	9.8 ± 1.08[a]	1.0 ± 0.09[b]	9.8	76.8 ± 5.97[b]	6.1 ± 0.42[b]
	Aquaponic	9.8 ± 0.45[a]	0.9 ± 0.01[b]	10.9	76.3 ± 4.11[b]	6.0 ± 0.38[b]

*Mean ± standard deviation (n = 4) with different letters indicates significant differences between treatments and time according to Newman-Keuls's test ($p < 0.05$)

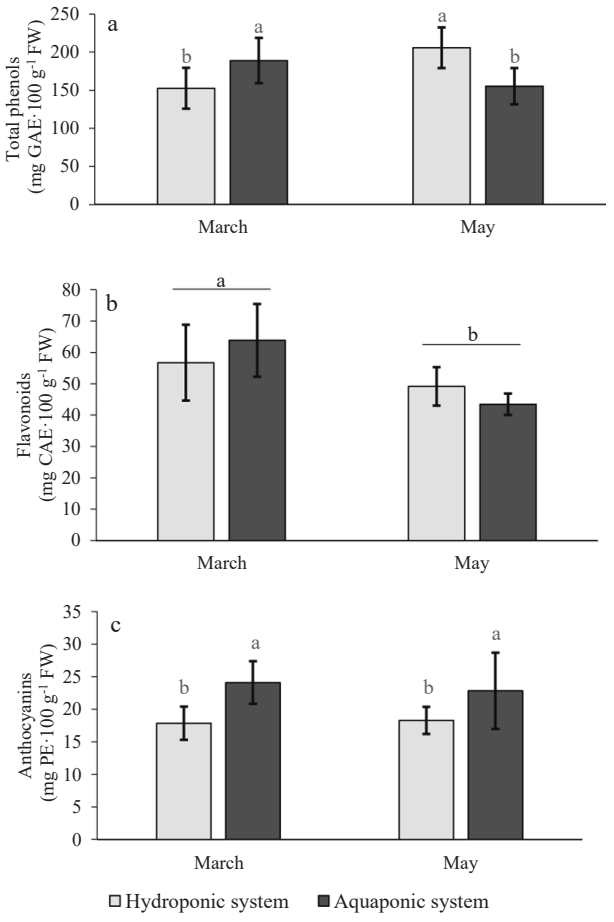

Fig. 6. Total phenolic compounds (mg gallic acid equivalent (GAE)·100 g^{-1} FW) (a), total flavonoid compounds (mg catechin equivalent (CAE)·100 g^{-1} FW) (b) and, total anthocyanin compounds (mg pelargonidin-3-glucoside equivalent (PE)·100 g^{-1} FW) (c) in strawberries grown under hydroponic and aquaponic cultivation, measured at mid-period (March 2021) and at the end of the cultivation period (May 19, 2021). Values are presented as mean ± SD (n = 8). Significant differences ($p < 0.05$), determined by the Newman-Keuls test following a nested two-way ANOVA, are indicated by different letters. The initial measured values were 136 ± 56 mg GAE·100 g^{-1} FW, 47.3 ± 11.9 mg CAE·100 g^{-1} FW, and 19.4 ± 2.34 mg PE·100 g^{-1} FW (n = 8).

fertilizers and the latter relying on fish effluents. Among the various soilless cultivation techniques for sustainable agriculture, aquaponics appears to be the most promising. Our results support this notion, as total yield exceeded 600 g per plant regardless of the cultivation system. Additionally, fruit quality remained unaffected by the treatment. This finding aligns with our initial hypothesis, suggesting that an excess of nutrients in hydroponics does not necessarily lead to increased or improved production. Similar results have been reported for other species, including strawberries (Yang and Kim, 2020; Aslanidou et al., 2023).

The total strawberry yield per plant in our study surpassed the 420 g previously reported for the same variety cultivated in soil (Miranda-Enamorado et al., 2020). Furthermore, the aquaponic system demonstrated additional benefits, such as higher leaf pigment and calcium content. Plants grown in aquaponics exhibited healthier, longer-lasting leaves with increased pigment levels, which play a protective role in the xanthophyll cycle, preventing photoinhibition (Milivojević and Stojanović, 2003). Other studies have similarly reported higher calcium content in aquaponic-grown crops compared to hydroponics, including basil and other strawberry cultivars (Modarelli et al., 2023; Richardson et al., 2022). These findings suggest that aquaponic-grown plants may exhibit enhanced physiological well-being, a reduced risk of leaf senescence, and potentially high fruit production. Notably, despite the lower nutrient levels in fish effluents compared to hydroponic solutions, strawberry plants in both systems demonstrated high photosynthetic capacity. These results were consistent with those reported in previous studies (Roosta and Afsharipoor, 2012; Choi et al., 2016), supporting the hypothesis that both cultivation methods promote healthy plant growth.

Integrating aquaponic techniques into existing recirculating aquaculture systems (RAS) enhances the profitability of intensive aquaculture operations (Petrea et al., 2016; Oniga et al., 2020). Fish effluents have been successfully utilized to cultivate a variety of crops, effectively closing the nutrient cycle in fish farming and yielding promising production results (Elia et al., 2014; Espinosa Moya et al., 2016; Delaide et al., 2016; Wilson et al., 2017; Ayipio et al., 2019; Modarelli et al., 2023; Fruscella et al., 2023). From a sustainability perspective, aquaponics presents an advantage over hydroponics, as it requires lower nutrient inputs and reduces the risk of effluent eutrophication (Kloas et al., 2015). However, a life cycle assessment (LCA) conducted by Boxman et al. (2017) on a commercial scale aquaponic system identified two major environmental impact hotspots: electricity consumption and feed production. The cost of feed is particularly high for carnivorous fish species, whereas herbivorous and omnivorous species offer more

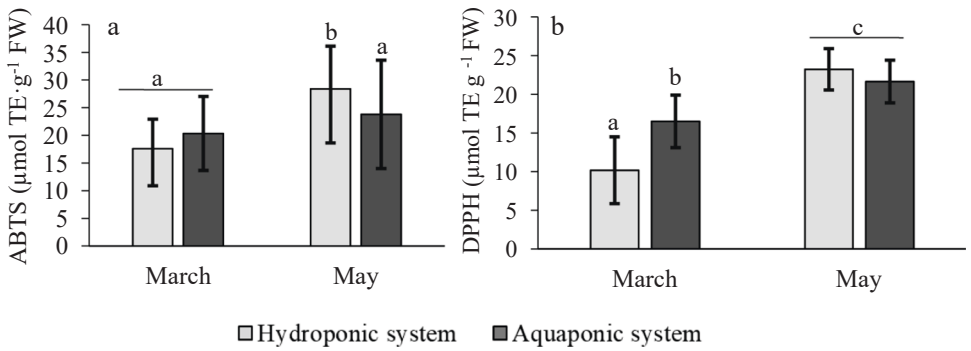

Fig. 7. ABTS (a) and DPPH (b) assay results expressed in µmol trolox equivalent (TE)·g^{-1} FW in strawberries grown under hydroponic and aquaponic cultivation, measured at mid-period (March 2021) and at the end of the cultivation period (May 2021). Values are presented as mean ± SD (n = 8). Significant differences ($p < 0.05$), determined by the Newman-Keuls's test following a nested two-way ANOVA, are indicated by different letters. The initial values were 38.78 ± 7.37 for ABTS and 10.7 ± 1.79 µmol TE·g^{-1} FW for DPPH (n = 8).

Table 4
Descriptor for organoleptic quality (firmness, juiciness, sweetness, acidity, aftertaste, and aroma), visual appearance (size, shape and colour) and overall rating of strawberry cv. 'Primoris' after 70 days of cultivation under hydroponic and aquaponic systems. Each attribute was evaluated using a linear, unstructured scale from 1 to 5, representing different levels of acceptance: 5 = excellent, 4 = good, 3 = acceptable (marketability threshold), 2 = poor, and 1 = inedible.

	Organoleptic quality						Visual appearance			Overall rating
System	Firmness	Juiciness	Sweetness	Acidity	Aftertaste	Aroma	Size	Shape	Colour	
Hydroponic	3.9 ± 0.8	4.0 ± 0.9	3.3 ± 1.1	3.1 ± 0.8	3.5 ± 0.9	4.5 ± 0.7[a]	3.5 ± 0.9	3.9 ± 0.9	4.4 ± 0.7	3.7 ± 0.1
Aquaponic	4.0 ± 0.7	4.2 ± 0.7	3.9 ± 1.0	2.7 ± 1.0	3.8 ± 0.9	4.0 ± 0.9[b]	3.3 ± 0.8	3.8 ± 0.7	4.1 ± 0.7	3.8 ± 0.2

*Mean ± standard deviation (n = 22) with different letters indicates significant differences according to t-student's test ($p < 0.05$), while no letter indicates non-significant differences.

cost-effective alternatives. Additionally, energy savings related to temperature regulation can be achieved by using eurythermal fish species, such as tilapia. Despite these challenges, Chen et al. (2020) found that aquaponics produced nearly half the environmental impact of hydroponics due to the higher total value of its combined fish and plant products. In our study, we used thick-lipped grey mullet (*Chelon labrosus*), an omnivorous and euryhaline species considered suitable for aquaculture diversification in Spain. This species can be cultured with algal meal-based diets, reducing feed costs while producing high-quality fish with enhanced dietary levels of highly polyunsaturated n-3 fatty acids (García-Márquez et al., 2021, 2022). Thus, its use in aquaponic systems not only minimizes feed expenses but also enhances fish quality.

The economic viability of aquaponic systems is also influenced by market price fluctuations (Xie and Rosentrater, 2015). Petrea et al. (2016) reported a positive economic impact of aquaponics, including cost-benefit analyses of various fish-plant combinations such as rainbow trout with spinach, basil, mint, and tarragon. Engle (2016) recommended basil for its economic feasibility, while Drogeanu et al. (2021) explored its cultivation alongside Siberian sturgeon. While hydroponic farming offers economic advantages over conventional soil-based agriculture, significant barriers remain, including high initial investment costs and the need for specialized labour (Mishra et al., 2024). In this context, Drogeanu et al. (2021) proposed using alternative substrates to enhance the profitability of basil aquaponic systems. These substrates demonstrated comparable production performance to conventional materials while reducing both initial investment and labour costs. Additionally, production slightly increased, and the improved system configurations proved beneficial for aquaponic operations targeting premium-quality crops for niche consumer markets (Drogeanu et al., 2021). In that sense, strawberries are a high-value commercial crop, making the optimization of their cultivation methods crucial for maximizing yield and profitability.

Throughout the experiment, the levels of bioactive compounds remained stable, except for anthocyanins, which increased in strawberries grown in aquaponic systems, while phenolic compounds were slightly lower compared to those in hydroponic systems. This variation may explain the minor difference in antioxidant activity observed with the ABTS method. Our results are consistent with previous findings in other vegetables, as nutrient availability and high irradiance induced the accumulation of phenolic compounds in some algae, which were related to antioxidant capacity (Abdala-Díaz et al., 2006; Celis-Plá et al., 2015; Vega et al., 2020).

The average values for bioactive compounds and antioxidant activities found in this study falling within or even exceeding the expected range when compared to similar strawberry varieties (Tulipani et al., 2011; Cervantes et al., 2020; Salazar-Orbea et al., 2023). The bioactive compounds in strawberries have been reported to play a role in preventing chronic diseases associated with oxidative stress and inflammation (Battino et al., 2021). Therefore, our findings suggest that strawberries cultivated in aquaponic systems may offer potential health benefits due to their high anthocyanin, flavonoid, and phenolic compound content, which contributes to sustained antioxidant capacity. Based on these results, we conclude that the small differences found in the measured variables do not justify the higher economic and environmental costs of hydroponic strawberry cultivation compared to aquaponic systems.

Other results supporting this finding include the strawberry quality descriptors measured, which indicated a general improvement in fruit quality throughout the experiment, regardless of the cultivation method. The °Brix/acidity ratio was higher in the aquaponic system, a factor associated with enhanced sweetness and greater consumer acceptability (Klakotskaya et al., 2023). The sensory evaluation further confirmed this trend. These results highlight the potential of aquaponic systems as an environmentally friendly alternative that produces high-quality strawberries with comparable consumer acceptance and total yield.

Exploring the underlying reasons why strawberries developed satisfactorily in the aquaponic system despite the significantly lower availability of nutrients, we propose that fish effluent may contain molecules acting as biostimulants. While fish effluents are rich in organic matter and some key nutrients, they may not always provide sufficient levels of essential elements such as phosphorus, potassium, or certain micronutrients required for optimal plant growth. Previous

studies have hypothesized that the accumulation of humic-like and protein-like dissolved organic matter components in the water could act as biostimulants (Hambly et al., 2015; Delaide et al., 2016; Nicoletto et al., 2018). These compounds may enhance nutrient absorption and improve plant metabolism, potentially mitigating nutrient deficiencies. Additionally, the interaction between fish-derived nutrients and plant root systems could stimulate the production of beneficial secondary metabolites, such as phenolic compounds and flavonoids, thereby enhancing the antioxidant capacity of the strawberries. Therefore, the potential presence of biostimulants in fish effluents using in aquaponic systems could play a crucial role in improving strawberry growth and quality.

According to Krastanova et al. (2022), future research in aquaponics systems work has include diverse combinations of aquaculture species and crops and such that have a much higher quality and market value. Further research not only on the biological and technological parameters of aquaponic systems is required, but also on the environmental, operational and socio-economic aspects (Forchino et al., 2017; Krastanova et al., 2022). A key factor for the success of aquaponics is the balance between research and business interests, as well as the positive attitude of end users toward it.

5. Conclusions

This study highlights the potential of aquaponics as a viable and more sustainable alternative to conventional hydroponics or traditional agriculture for strawberry cultivation. The results indicates that by utilizing fishpond effluents, aquaponics reduces dependence on synthetic fertilizers while maintaining comparable yield and fruit quality in strawberries. These findings reinforce the role of aquaponics in promoting circular agriculture, minimizing nutrient waste, and enhancing resource efficiency. Our results suggest that by stimulating root growth and increasing the efficiency of nutrient uptake, potential biostimulants present in fish effluents may enable plants, such as strawberries, to thrive even when traditional nutrient levels are suboptimal.

Despite the promising results obtained, future research should explore strategies for optimizing nutrient management, without compromising sustainability. In order to further optimize aquaponic production, long-term studies on system stability, and economic feasibility will be crucial for scaling up aquaponic practices in commercial agriculture. By addressing these aspects, aquaponics can contribute significantly to sustainable food production and environmental conservation.

CRediT authorship contribution statement

N. Korbee: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. B. Bautista: Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. M. García-Sánchez: Methodology, Investigation, Formal analysis. P. Cobos: Methodology, Formal analysis. JL Ferres-García: Methodology, Investigation. FL Figueroa: Writing – review & editing, Visualization, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. E. Medrano: Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Felix L. Figueroa reports financial support was provided by University of Malaga. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Data availability

Data will be made available on request.

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