AWESOME

WATER-ECOSYSTEM-FOOD

FOOD PRODUCTIVITY PER UNIT WATER

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LIST OF ACRONYMS

Abbreviations

AP: Aquaponic system
DAT: Days after transplantation of seedlings
DO: Dissolved oxygen
DWC: Deep Water Culture
EC: Electrical conductivity
FCR: Feed conversion ratio
HP: hydroponic system
IVA: Integrated Vegetable Aquaculture
MB: Media- bed system
MCDA: Multicriteria Decision Analysis
NFT: Nutrient Film Technique
NOB: Nitrite-oxidizing bacteria
RAS: Recirculating Aquaculture system
SC: Soil Based Cultivation
SP: Sandponic
WP: Work Package

EXECUTIVE SUMMARY

Deliverable 5.2 provides an overview of the experimental tests and comparative analysis of the lettuce productivity and quality based on available water per unit in the AWESOME test facilities, consisting of the technologies Hydroponics and Aquaponics. The experimental design for testing the different cultivation technologies is described in detail within this report. Special concern is given to the subsystem types commonly used in the field of Hydroponics, which are Deep Water Culture (DWC), Nutrient Film Technique (NFT), Media-bed system (MB) and Sandponics (SP). These hydroponic subsystems were tested as a component in an aquaponic context. In addition to this, soil-based cultivation (SC) and Integrated Vegetable Aquaculture (IVA) were compared with different hydroponic subsystems as a component in lab-scale aquaponic experiments. On the other hand, planting spacings were tested in the first experiment, and then the adaption of the different hydroponic system under different growing seasons was tested in the second hydroponic experiment. In aquaponic experiments, plant density was tested to produce more crops. To find best performing hydroponic subsystems, Multi-Criteria Decision Analysis (MCDA) was done based on results of lab-scale experiments. Subsequently, best performing hydroponic and aquaponic setups for mass production of the lettuce were tested as well in the AWESOME pilot test facilities.

1. RATIONALE

Deliverable D5.2 (crop productivity per unit of water) is the report describing the experimental scenarios for food productivity per unit of water in different plant cultivation techniques including soilless systems and soil-based cultivation. Hydroponics and Aquaponics are soilless cultivation techniques, which are independent of soil properties and consume significantly less water compared to traditional agricultural practices. While Hydroponics is a soilless plant cultivation method, Aquaponics combines Hydroponics and aquaculture in one system. Both soilless systems have the potential to be one of the most promising sustainable alternative methods of food production, where they confer the advantages of producing higher yields with better control over plant growth. Under the projected increase in water shortage and non-arable land such as Mediterranean region, the development of these controlled sustainable farming techniques provides an alternative and sustainable food production, that is, the efficient on water and nutrient use yet guarantees higher crop yield compared to conventional farming techniques[1-4].

Various hydroponic subsystems have emerged also in the aquaponic context, each offering unique advantages and limitations. Commonly used hydroponic subsystems are deep water culture (DWC), nutrient film technique (NFT) and media-bed systems which use substrates such as gravel, sand, and rock wool. The comparison of these subsystems is crucial to determine their suitability for lettuce cultivation in terms of growth rates, yield, and resource consumption[5]. Previous studies have shown that hydroponic subsystems affect plant growth and nutrient uptake[6-7].

Simultaneously presenting both an advantage and a challenge of the selected cultivation systems is the requisite manipulation of a plethora of influencing factors, a necessity for the realization of a plant's full genetic yield potential. This task, however, is concomitant with the indispensable provision of a technically adept system for the regulation of these influencing factors such as growing season, and planting density. Consequently, initiating a commercial hydro- or aquaponic system is encumbered by formidable obstacles, chiefly characterized by substantial upfront investments and the imperative acquisition of profound insights into the optimal ranges of these factors, predominantly governing plant and fish growth kinetics. Moreover, it necessitates contemplation that operational expenditures typically surpass those associated with traditional agriculture. This stems from the markedly escalated energy prerequisites, augmented necessity for measuring and regulating instrumentation, and the obligatory inclusion of maintenance outlays within the reckoning[8-12].

One of the main aims of the Work Package 5 (WP5) is the demonstration of the potential of hydro- and aquaponic systems, especially in terms of productivity maximization per unit of water. In order to achieve this, it is crucial to comprehend and present the results of aqua-and hydroponic tests, including comparative analysis of crop outcome (quality and quantity) based on given water availability. Therefore, Deliverable D5.2 serves as the summary of the adaption of the hydroponic subsystems and the aquaponic setups in lettuce growth tested within the AWESOME lab and pilot scale facility. This work also gives a specific characterization of the experimental designs performed in the AWESOME lab and pilot scale facility. In section 2, lab-scale experiments are reported. This section is evidence for quality and quantity analysis for the lettuce growth in aquaponic and hydroponic experiments at a small scale. It is followed by section 3 which demonstrates the steps of multicriteria decision analysis to decision on best performing subsystems. In section 4, pilot scale experiments are presented by elaborating on the adaption of selected subsystems in aquaponic and hydroponic soilless techniques for mass production. Figure 1 shows our experimental flow.

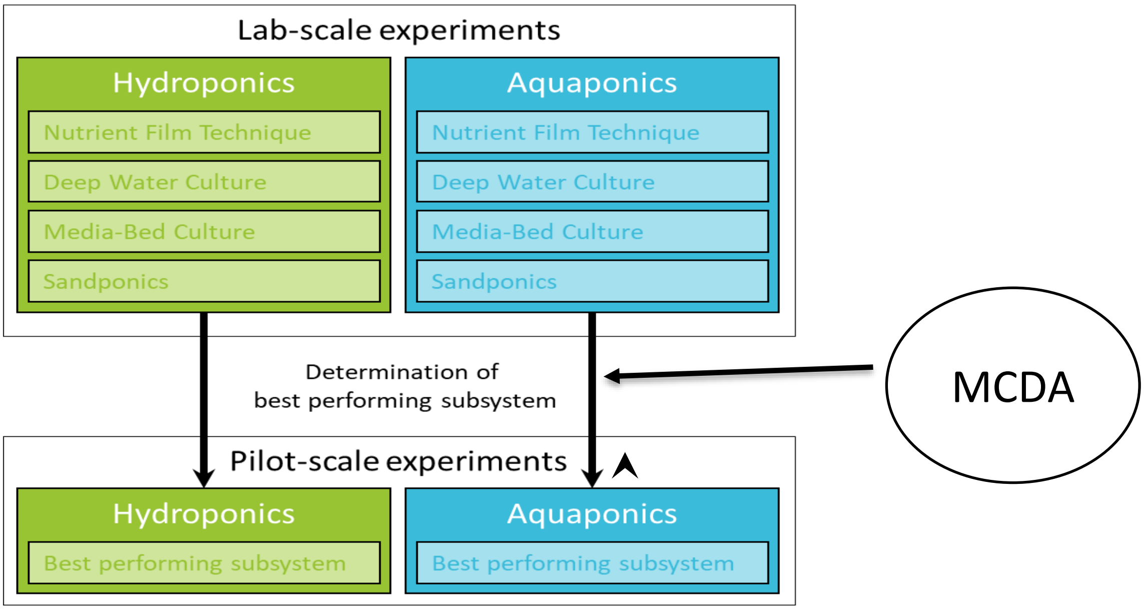

Figure 1 – Hierarchical experimental flow in the AWESOME test facilities

2. LAB-SCALE EXPERIMENTS

Lab-scale experiments consist of hydroponic and aquaponic test cycles. The main aims of the studies are (1) to demonstrate the potential hydroponic subsystem for lettuce growth in hydroponic and aquaponic set-up concepts, especially in terms of efficient nutrient utilization and productivity (2) to test the interaction of the cultivation system and planting system, (3) to investigate the adaption of subsystems with seasonal nuances under different growing seasons, and (4) to compare the crop outcomes from soilless with soil-based cultivation under closed greenhouse conditions.

2.1 HYDROPONIC EXPERIMENTS

Hydroponic experiments comprise 3 separate but related experimental studies, each represented by a distinctive dissemination material. The studies aimed at examining: (i) the effects of the hydroponic subsystem on lettuce growth and development, (ii) the effects of adaption of environmental parameters in hydroponic subsystems, (iii) the water consumption of the lettuce with dependent factors (planting spacing and growing seasons. Table 1 shows all hydroponic experiments on lab-scale.

In these experiments we tested the potential of following subsystems: These are Deep Water Culture (DWC), Nutrient Film Technique (NFT), Media-bed system (MB) and Sandponics (SP) as illustrated in Figure 2.

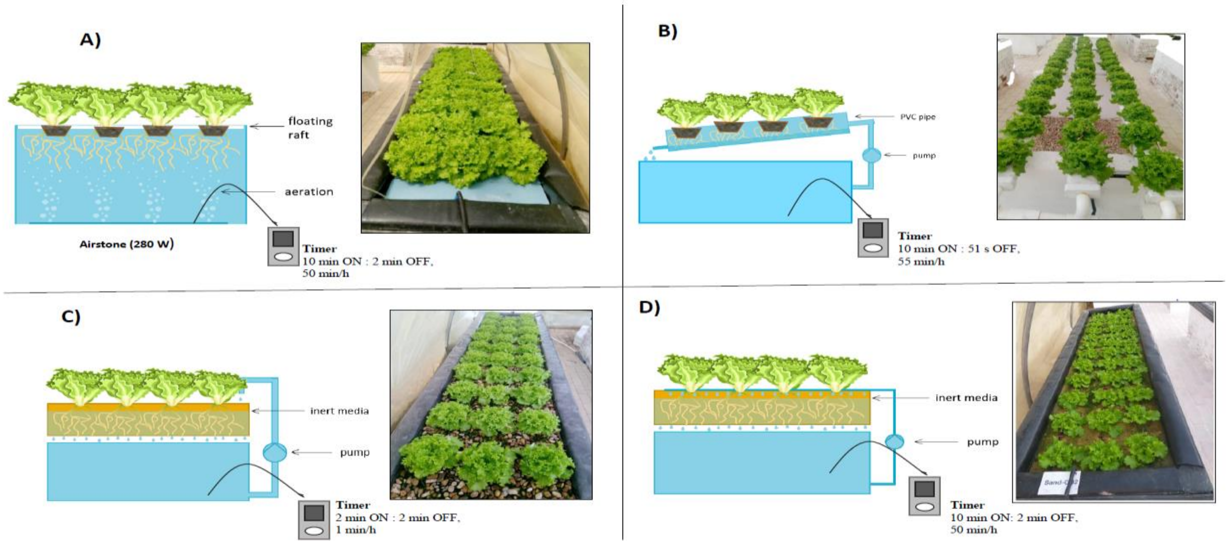

Figure 2. The various closed hydroponic sub-systems tested for lettuce growth under different growing seasons and planting spacing. These systems: (A)- DWC: Deep Water Culture, (B)- NFT: Nutrient Film Technique, (C)- MB: Media- Bed system and (D)- SP: Sandponic.

Table 1 – Hydroponic experiments in lab-scale facility

Experiment number	Experimental time	Planting spacing (cm)
1- HP1-1	08/09-2021	20 X25
2- HP1-2	12/2021 -01/2022	20 X25
3- HP2-1	09/10-2022	24 X25
4- HP2-2	11/12-2021	24 X25
5- HP1-5	06-07/ 2021	20 X25

The reason is why the lettuce is chosen for experiments: Lettuce, a green vegetable, is chosen for soilless farming experiments for several reasons. In soilless farming environments, nutrients are delivered directly to the plant, allowing it to access nutrients more quickly and encouraging faster growth. This controlled environment means that water, light, and nutrients can be better regulated, ensuring that everything the plant needs is provided at optimum levels. Furthermore, soilless farming requires less space compared to traditional soil-based agriculture, making it suitable for urban areas or limited spaces. It also enables more efficient use of irrigation water, as water is delivered directly to the plant, reducing evaporation losses. Additionally, soilless farming eliminates the need to deal with soil diseases or harmful organisms. Moreover, this method uses fertilizers more efficiently, reducing environmental impacts. The system also provides a cleaner and more hygienic environment, which is crucial for food safety. Overall, soilless farming systems are known for high efficiency, resulting in a greater yield.

For these reasons, green vegetables like lettuce are often preferred for soilless farming experiments. Such plants can make the most of the advantages offered by this farming method.

2.1.1 A General Assessment for Hydroponic Experiments

In this section, the productivity and the water consumption per area for a month were evaluated under different planting spacing and cultivation season as described in Table 1. The experiment numbers 1-4 were assessed to determine the water use efficiency of various hydroponic systems and they compared with soil-based cultivation.

Methodology

The water quantity of each individual unit was assessed both before and after each experimental cycle in order to determine the water usage of the systems. The weight of shoots of all the harvested lettuces was measured. The total productivity was calculated fresh shoot mass of lettuce harvested per square meter within a month. Hydroponic-grown lettuces were harvested on the 29th DAT (Days after transplantation of seedlings), whereas lettuces in soil were harvested on the 45th DAT. The productivity and water consumption were evaluated based on the biological cycle of the lettuce produced in soil and hydroponic subsystems within a month. Results for productivity and water consumption of lettuces under different conditions:The fresh mass of lettuce as a vegetative growth parameter was significantly influenced by the cultivation systems. When we compared **all treatments, higher fresh shoot weight was observed in the lettuces grown from the DWC and NFT systems, whereas no significant difference was observed between them** (Figure 3A). Across all tests and trials, there were no significant differences in productivity among the replicated instances within each treatment and experiment. The spacing between plants did not result in any noteworthy differences in productivity within the NFT and DWC systems throughout all testing cycles. However, productivity did exhibit variations depending on the season, with Spring/Summer (HP1-1, HP1-2) demonstrating higher productivity in contrast to Winter (HP1-2, HP2-2). On the other hand, in the MB and SP subsystems, productivity was comparatively lower in the first two treatments. Interestingly, when considering wider spacing, a significant difference in productivity between the MB and SP systems during both Summer and Winter. Lettuces grown in soil exhibited similar results with lettuces from MB. No statistical differences were observed.

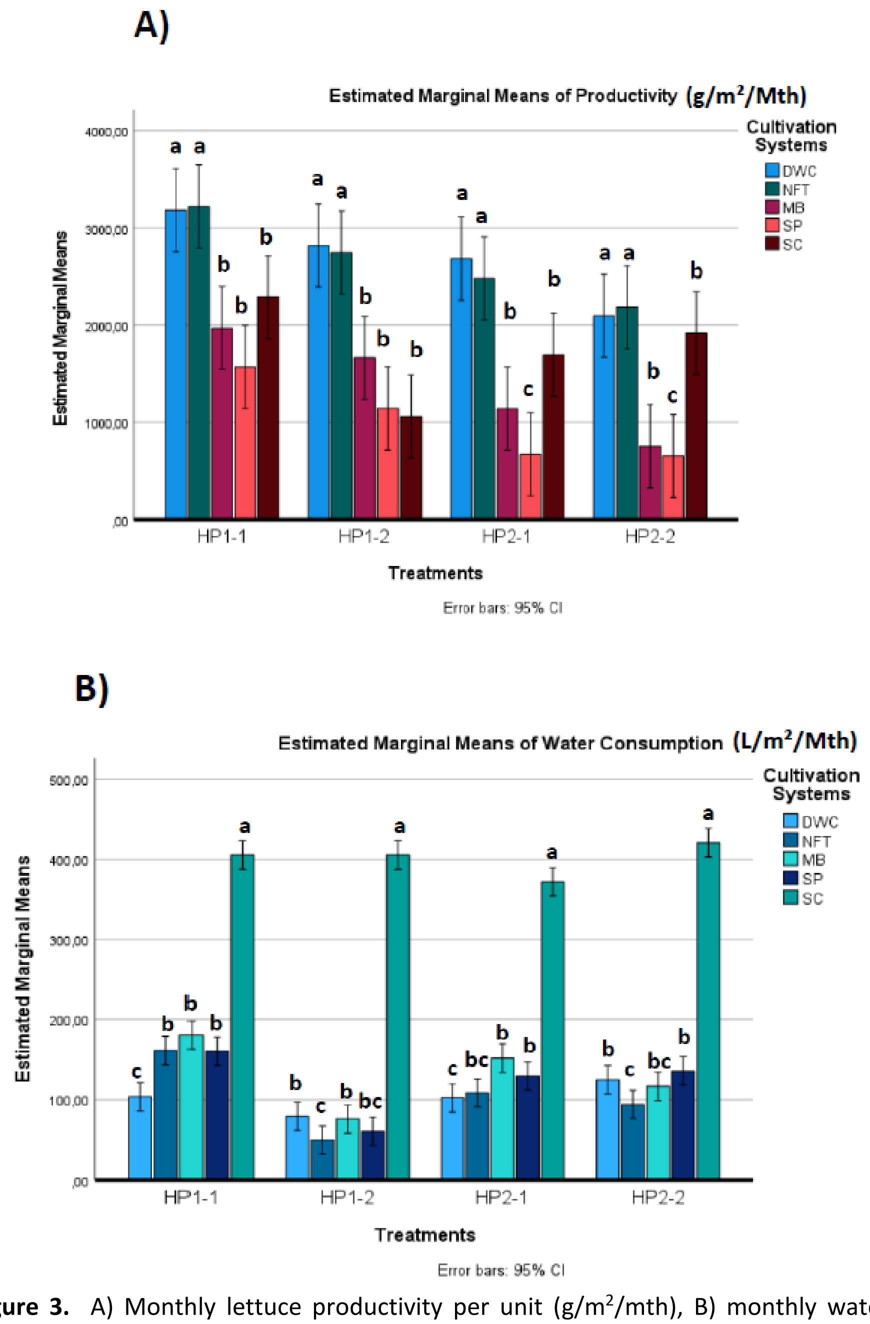

Figure 3. A) Monthly lettuce productivity per unit (g/m^2/mth), B) monthly water consumption by plants per unit (L/m^2/mth). Cultivation systems: DWC: Deep water culture, NFT: Nutrient Film Technique, MB: Media-bed system and SP: Sandponic and SC: Soil- Soil-based cultivation.**The interaction among growing season, planting density and cultivation system affected the water consumption by plants**. The monthly water consumption in the hydroponic subsystems ranged from 49.75 L/m²/mth to 180.45 L/m²/mth and in SC from 371.76 L/m²/mth to 420.76 L/m²/mth (Figure 3B). The water consumption by plants was not influenced by planting spacing. **The interaction between the cultivation system and the growing season. In the DWC sub-system, the monthly water usage of lettuce was observed to be lowest at higher temperatures, whereas, in the NFT sub-system, the monthly water usage of lettuce was**

measured to be minimal during the winter season. The efficient water utilization was obtained in NFT lettuces for the winter growing season with narrower (20 x 25 cm) planting spacing, while the highest water consumption was measured in lettuces grown in soil in the winter term with larger planting spacing (24 x 25 cm). Our findings demonstrate that when a well-chosen soilless subsystem is adapted to environmental conditions, **it can achieve water savings of up to 10-fold compared to soil-based production** and result in higher production quantities in a shorter timeframe.

An Overview of experimental design in lab-scale hydroponic experiments

In order to assess the potential and the utilization of efficient resources such as nutrients and water, we performed different experimental designs. Table 2 summarizes the experimental scenarios for hydroponically grown lettuce in the lab-scale experiments. In the first experiment, we assessed the interaction between planting spacings and hydroponic subsystems. The hydroponic systems and their adaption under different growing seasons were tested in the second experiment. In the last experiment, hydroponic and aquaponic systems will be compared by evaluating the subsystem for the lettuce growth. The result of the last experiments has been not presented in the current report.

Table 2 – The detailed list of hydroponic experimental design with treatments in lab-scale facility

Experiments	Treatments	Experiment number	Experimental time
1- Planting spacing and hydroponic subsystems	**Cultivation systems:** DWC, NFT, MB, SP **Planting spacings:** 20 X 25 and 24X25 cm	HP1-1	08/09-2021
		HP2-1	09/10-2022
2- Growing seasons and hydroponic subsystems	**Cultivation systems:** DWC, NFT, MB, SP **Growing seasons:** Winter and summer	HP1-5	06-07/ 2021
		HP1-2	12/2021 - 01/2022
3- Comparison of hydroponic with aquaponic system	**Cultivation methods:** Hydro- and aquaponic **Cultivation systems:** DWC, NFT, MB, SP	HP2-2	11/12-2021

2.1.2 Assessing different hydroponic subsystems for Batavia lettuce growth under different planting density

In this experiment, we tested the lettuce growth and yield interaction between different subsystems of hydroponics and different planting densities. We hypothesized that the leaf yield of lettuces per unit area increases with increased plant density, while leaf yield per plant decreases with increasing plant density. In detail, we aimed to determine the effects of different subsystems and planting densities on vegetative growth, sensory attributes and nutrient uptake by lettuce grown in a closed soilless system.

Two identical treatments were performed in August and September 2021 under greenhouse conditions in Cairo. As Figure 2 shows, Deep Water Culture (DWC), Nutrient Film Technique (NFT), Media-bed system (MB) and Sandponic (SP) are hydroponic sub-systems, in which experimental lettuce plants were grown, and their performance was tested for optimal lettuce growth. Planting spacings were 20x25 cm (90 lettuces), and 24x25 cm (at least 72 plants) for hydroponic subsystems.

2.1.2.1 Summary

The main purpose of this study is to determine differences in growth rates, sensory attributes and nutrient uptake upon growing lettuce (*Lactuca sativa* L.) in various hydroponic subsystems at two different plant spacings. **We investigated the interaction of different effects on lettuce growth in four hydroponic subsystems, Deep Water Culture ((DWC), Nutrient Film Technique (NFT), Media-Bed system (MB) and Sandponic (SP), at two different plant densities, at narrow planting spacings (20 x25 cm), and larger planting spacings (24 x 25 cm).** Our findings show that cultivation methods and planting spacing greatly influence lettuce growth. Overall, the present study provides direct evidence **that DWC and NFT** subsystems at both planting spacings performed the **best in terms of giving higher yield production, higher plant growth parameters,** and better sensory attributes compared to other cultivation systems. Lettuces grown in the DWC system had higher chlorophyll B (29.13±0.82 mg/100 g), and carotene content (32.40±1.27 mg/100 g) in narrow planting spacing and were the most preferred lettuces according to taste tests (52.4%).

2.1.2.2 Methodology

Pre- experimental procedure

Lettuce seeds (*Lactuca sativa* L., cv. *Batavia* F1) produced by Rijk Zwaan were purchased from the local distributor in Egypt. Seeds of Batavia lettuces sown at 1-2 cm depth into trays (70 x 40 cm), 209 cells. A mixture of 70% peat moss, 15% vermiculite, and 15% perlite as the growing media was used for the seedlings. At the time of media preparation, 8.5 g of (N-P-K, 19.19.19 + T.E) fertilizer was added to the growing media for each seedling tray. Once the cotyledons were fully expanded and the first true leaves began to emerge, the seedlings were sprayed with a dose of 0.5 g of NPK (19/19/19+ TE (Trace Elements)) fertilizer per 1 L of water with 3-day intervals. The pH and EC of the growing media were measured daily and maintained within a range of 5.4 to 6.0 and 1.5 to 2.0 dS/m, respectively. In the summer season, seedlings were irrigated 2 times a day, once with water only and once with the nutrient spray. After seedlings reached a growth stage of true 5-7 leaves, along with root development, 23±2-day-old seedlings were transplanted into the grow beds.

Experimental system setup

The experiments were performed under greenhouse conditions in Cairo, Egypt (30°2′41″ N, 31°14′44″ E, altitude 26 masl). The research greenhouse´s dimensions were 30 m L x 6 m W x 2.85m H.

The nutrient solution for the hydroponic lettuce growth was formulated according to Hoagland's nutrient solution[13]. Each hydroponic sub-system was filled with a 500 L total volume of nutritious water. The grow beds of DWC units had 324 L of water, and the water depth was 17 cm. The water flow rate in each grow bed in all subsystems is pumped with the water pump (85 W) for a cycle of 7 L/min of pumping for 10 minutes and then 51 seconds off. In the DWC system, plants were mechanically supported by a styrofoam board which floated on a bath of nutrient solution. The floating rafts (5 cm thick) have holes for supporting the plants, which also allows the roots to be submerged in the water and have constant contact with the nutrient solution. The reservoir in the DWC grow beds contained a submersible pump and air stone. Aeration in DWC was supplied via diffuser air stone to the root zone of plants, which was placed under a raft and connected to an air pump (280 W, ran 12 h/d). In the NFT system, only an air pump is used to constantly disturb high oxygen concentrations. DWC and NFT systems are performed with a continuous flow technique. In DWC, water was pumped with a submersible pump at a rate of 50 min per hour, whereas water in the NFT system was pumped at a rate of 55 min per hour. The NFT system was designed using pipes. In this subsystem, the highly nutrient solution was recirculated continuously to the roots of lettuce plants through a set of channels, the solution ran off into the nutrient tank and was pumped back to the plants. Lettuces in the DWC and NFT grow beds were placed in plastic cups hung in pipes to support the plants, so they do not fall over during continuous streams of water.

Table 3 – Technical details of hydroponic subsystems

	DWC	NFT	Sand	MB
Number of grow system	3	3	3	3
Cultivation area/system	1.92 m^2	1.92 m^2	1.92 m^2	1.92 m^2
Substrate	N/A	N/A	Fayoum sand	River gravel
Test cycle	28-29 days	28-29 days	28-29 days	28-29 days
Amount of water /system	824.48 L	500 L	500 L	500 L
Irrigation system	continuous flow	continuous flow	drip irrigation	continuous flow
Drainage system	Overflow	continuous drain	Underground drainage network	bell siphon
Pump wattage /system	85 W	85 W	85 W	85 W
Pump operation rate/system	10 min ON: 2 min OFF	10 min ON:51 s OFF	2 min ON: 2 h OFF	10 min ON: 2 min OFF
	50 min/h	55 min/h	1 min/h	50 min/h
Pump flow rate/system	7 L/min	7 L/min	7 L/min	7 L/min
Extra accessories	air pump (280 W), 12 h/day	N/A	N/A	N/A

Vegetative Growth Parameter Measurements

The height of leaves, fresh shoot mass, fresh root mass, stem diameter, and head diameter were measured on-site at the harvesting time of the lettuces. A representative sample of 10 plants per replicate was taken to assess the vegetative growth parameters. Before starting measurements, substrates in the roots of the plants in the MB and SP systems were removed, whereas plastic cups were removed in the DWC and NFT systems. The plants were gently washed off. Then, the surface moisture on the lettuce was removed using a soft paper towel. Plant heights were measured from the base of the shoot to the terminal growing point. The root length of the lettuces was measured from the base of the shoot to the tip of the main root on the lettuces. The lettuces were weighed to determine the root and shoot weights. Lettuces were measured from the top of the plant and recorded in two orthogonal directions for head diameter. The lettuce was divided into two parts from the base of the shoot so that the stems' diameters on the lettuce were measured. For the dry mass, randomly taken 6 lettuce samples for each grow unit were sent to an external laboratory at the Agricultural Research Center, Giza, Egypt. Dry mass of lettuces was determined according to AOAC[14]. The leaf samples were dried in an oven at 100-110◦C until dryness, repeated weighing to a constant weight, and then a moisture content percentage was calculated.

Leaf Content Analysis

12 lettuce leaves in each treatment were randomly taken from each unit for nutrient content analysis on 26± 2 DAT. Nutrient content analysis was performed at the Agricultural Research Center, Giza, Egypt. Nitrogen (N) content was determined using the Micro-Kjeldahl method in the digestive solution as described by Plummer[15]. The digestive solution (5ml) was distilled with (10ml) of sodium hydroxide (NaOH) for 10 minutes to obtain ammonia. Phosphorus (P) was determined colourimetrically as described by Jackson[16]. Potassium (K), calcium (Ca), and sodium (Na) contents were determined against a standard using a flame-photometer (JEN way flame photometer) according to the procedures described by Piper[17]. Magnesium (Mg), copper (Cu), manganese (Mn), zinc (Zn) and Iron (Fe) contents were determined by using atomic absorption spectrophotometer (Pyeunican SP1900) according to methods of Brandifeld and Spincer[18]. The contents of chlorophyll and carotenoids were determined using spectrophotometrically according to the acetone method as described by Ritchie[19].

The sand was washed out to remove salt composition for use in SP systems. As growth media, gravel was used in MB for supporting plants. In SP, irrigation was performed with drip irrigation and drainage (surface drainage). MB worked with continuous flow technique and drainage (a bell siphon system). Water was pumped with a capacity submersed water pump (flow rate 7 L/min for 2 min) and was then turned off for 2 h in SP and with the same flow rate capacity of water was performed for 10 min and then turned off for 2 min in MB system (irrigation rate per hour was 1 min in SP and 50 min in MB).

The environmental parameters such as air temperature, relative humidity, and CO_2 were daily measured and data were collected using an online data logger (Tomatiki Smart Data Logger, Model: SDL320). The greenhouse was covered with polyethene plastic and cooled using a pad and fan evaporative cooling system and desired climate set points were maintained by an automatic climate control system. The shading net (73% shading rate) is used in summer treatments to reduce solar radiation. The pH of the solution was maintained at a range of 5.5-6.5 with the addition of a base, potassium hydroxide (KOH) and nitric acid when it increased (Jones Jr., 2016). The electrical conductivity (EC) is a measure of the dissolved salts in a solution, which is another important factor for nutrient uptake in hydroponic systems. The EC value is maintained between 1.5 and 2.0 dS m^{-1} in hydroponic subsystems[20].

Benoit and Ceustermans (1987, 1988)[21,22] recommended maintaining the EC range between (2.0-2.5 dS m^{-1}) in their studies for hydroponics. Therefore, the EC range could be kept in between a large range (1.5- 2.5 dS m^{-1}) in experimental setups based on these two recommendations. When the EC value increased, it was diluted by adding water. Matured hydroponically grown lettuces were harvested on the 28^{th} and 29^{th} DAT (days after transplanting) over 2 days.

Taste tests

Immediately after harvest, lettuces were rinsed in water cut into small-sized pieces stored at 5°C in plastic boxes, and placed in the fridge overnight. Consumer perception tests were conducted on the following day on-site. Lettuce taste was examined by a minimum of 20 tasters. Lettuces were served to tasters with blinding codes in random order. Taste scores for each cultivation method were obtained by taking weighted averages of taste and smell tests. Testers answered demographic questions such as gender and age to determine whether age and gender affect the taste perception of lettuces A 10-point hedonic scale (1 = extremely dislike; 10 = extremely like, 5 = none detected) was used to evaluate the overall appearance, overall flavour, aftertaste and crunchiness of lettuces (1-10), a 5-point hedonic scale 1 = not at all bitter or sweet; 5 = extremely bitter or sweet) was used to evaluate the sweetness and bitterness of lettuces grown in different cultivation methods. In addition, the colour of the lettuces was evaluated with this 5-point hedonic scale (1= extremely dislike, 5= extremely like). Moreover, lettuce smells and preference for best lettuces were evaluated by testers.

Statistical analysis

Data are presented as means ± SE. ANOVA (two-way ANOVA) was performed to detect significant differences in all the measured parameters after verifying homoscedasticity by Levene's test. All statistical analyses were conducted using SPSS Statistics 29 (IBM Software, Chicago, USA). Probabilities of significance among treatments and LSD ($P \leq 0.05$) were used to compare means among treatments.

Environmental Parameters

Table 4 summarizes the environmental conditions for lettuces in growing beds and in the closed greenhouse for experiments.

Table 4 – The environmental conditions for lettuces in growing beds and closed greenhouse

Treatments	CS	pH	EC (µS/cm)	DO (mg/L)	Water T (°C)	Air T (°C)	CO_2 (ppm)	Air RH
Narrow spacing 20x25 cm	DWC	5.65 ±0.56	1.55 ± 0.03	5.16±0.43	27.39±0.67	28±1.4	1759±802	67±4
	NFT	5.74±0.26	1.57±0.05	5.17±0.37	27.59±1.34	28±1.4	1759±802	67±4
	MB	6.36±0.32	1.74±0.14	5.4 ±0.37	27.1 ±0.5	28±1.4	1759±802	67±4
	SP	6.51 ±0.32	2.18 ±0.24	4.25 ±0.63	27.07 ±1.1	28±1.4	1759±802	67±4
	DWC	5.69 ±0.47	1.52 ±0.07	5.21 ±0.3	26.46 ±0.74	26.5 ±1	1906 ±694	70 ±3

Larger spacing 24x25 cm	NFT	5.7 ±0.46	1.55 ±0.05	5.11 ±0.62	26.81 ±0.87	26.5 ±1	1906 ±694	70 ±3
	MB	6.13 ±0.35	1.82 ±0.11	5.48 ±0.31	26.14 ±0.76	26.5 ±1	1906 ±694	70 ±3
	SP	6.5 ±0.19	1.98 ±0.15	3.6 ±0.56	26.25 ±1.3	26.5 ±1	1906 ±694	70 ±3

Parameters: EC: electrical conductivity, DO: Dissolved oxygen, CO_2: Carbon dioxide. CS: cultivation systems: DWC: Deep water culture, NFT: Nutrient Film Technique, MB: Media- bed system and SP: Sandponic.

The outcomes of the vegetative growth parameter analysis highlight the significant impact of hydroponic subsystems and planting spacing on various lettuce growth characteristics. Shoot height exhibited significant variations due to the main effects of hydroponic subsystems and planting spacing. Notably, lettuce plants cultivated in the DWC growth bed demonstrated substantially taller shoot heights compared to other cultivation methods. This finding aligns with studies that attribute superior growth performance to the availability of nutrients and reduced water stress associated with DWC systems[23]. Conversely, the shortest shoot heights were observed in lettuce plants grown using the MB and SP systems.

Table 5 –Vegetative growth parameters

Treatments	CS	Shoot height (cm)	Shoot fresh mass (g)	stem diameter (cm)	Head diameter (cm)	Number of leaves (n)	root length (cm)	Root weight (g)
NS	DWC	17.3 ±0.7^{a}	160.6 ± 37.0^{a}	1.16 ± 0.12^{b}	25.35 ± 1.48^{a}	34.14 ± 6.61^{a}	33.93 ± 6.55^{b}	27.89 ± 2.55^{b}
	NFT	16.2 ±0.4^{b}	165.2 ± 25.1^{a}	1.37 ± 0.14^{a}	25.71 ± 1.23^{a}	34.39 ± 3.81^{a}	39.19 ± 5.72^{a}	52.34 ± 11.72^{a}
	MB	15.1± 1.3^{c}	100.9 ± 9.5^{b}	1.09 ± 0.14^{b}	21.78 ± 0.9^{b}	27.25 ± 4.33^{b}	21.79 ± 3.86^{c}	20.91 ± 2.42^{c}
	SP	14.3 ±0.8^{c}	78.6 ± 14.7^{b}	0.93 ± 0.12^{c}	19.33 ± 1.33^{c}	22.86 ± 5.53^{b}	10.68 ± 1.19^{d}	11.14 ± 4.18^{d}
LS	DWC	16.5 ±1.2^{a}	204.6 ± 24.7^{a}	1.31 ± 0.19^{a}	23.82 ± 1.74^{a}	35.61 ± 2.72^{a}	28.92 ± 6.02^{a}	32.36 ± 4.57^{a}
	NFT	15.5 ±1.1^{a}	189.2 ± 19.9^{a}	1.19 ± 0.13^{a}	22.36 ± 1.64^{a}	35.82 ± 3.58^{a}	26.13 ± 4.50^{ab}	32.11 ± 6.10^{a}
	MB	13.3 ±0.6^{b}	87.1 ± 23.2^{b}	1.04 ± 0.08^{b}	19.09 ± 1.07^{b}	32.05 ± 5.60^{a}	22.35 ± 2.64^{b}	22.18 ± 6.45^{b}
	SP	12.4 ±0.5^{b}	51.2 ± 14.4^{c}	0.92 ± 0.11^{b}	15.27 ± 1.17^{c}	25.27 ± 4.50^{b}	10.73 ± 1.11^{c}	10.70 ± 1.88^{c}

Data are expressed as means ± standard error (SE). Lower case letters within each main treatment indicate significant differences after the least significant difference (LSD) post hoc test (significance level $p< 0.05$ and $p< 0.01$, not significantly at $p\geq0.05$) for each parameter. NS: Narrow spacing, 20x25 cm, LS: larger spacing, 24x25 cm. CS: Cultivation systems: DWC: Deep water culture, NFT: Nutrient Film Technique, MB: Media-bed system, and SP: Sandponic.

The interaction between planting spacings and cultivation methods significantly influenced the average fresh weight of harvested shoots. Notably, the highest fresh shoot masses were observed in lettuces cultivated in the DWC and NFT systems, particularly for narrow planting spacings. However, planting spacing itself did not exert a significant effect on lettuce shoot weight. These

results underscore the role of hydroponic subsystems in fostering superior shoot growth and biomass accumulation, with DWC and NFT systems showing advantageous performance.
Stem diameter also exhibited considerable variability influenced by interactions between cultivation methods and plant density treatments. Lettuce plants grown in the SP system exhibited the smallest stem diameter among the soilless systems, while NFT and DWC cultivation yielded larger stem diameters. The differences observed suggest that different hydroponic subsystems contribute to varying stem development, possibly due to variations in nutrient availability. Similarly, Head diameter, another critical growth parameter, displayed significant differences influenced by interactions between hydroponic subsystems and planting spacing. Lettuces grown in the DWC and NFT systems demonstrated larger head diameters compared to other hydroponic systems. This could be attributed to the optimized nutrient delivery and root development associated with these systems, resulting in more robust plant growth and head formation[24].
The number of leaves in lettuce plants was significantly affected by the hydroponic subsystem's main effect. DWC and NFT systems consistently yielded more leaves compared to MB and SP, particularly in treatments with narrow planting spacing. However, the number of leaves in lettuce from the MB grow beds did not differ significantly from DWC and NFT with wider planting spacing. The lowest number of leaves was observed in the SP system, highlighting the importance of hydroponic subsystem choice in influencing plant leaf development. Contrary to our results, a recent study demonstrated that the number of leaves and yield were significantly higher in lettuces grown in DWC than in NFT and soil-based cultivation in two different crop cycles cultivated under different growing seasons[6]. Differences in terms of the number of leaves per plant may be associated with the nutrient solution composition, especially N and its uptake by plants[25-27]. However, there was no significant difference in N uptake among hydroponic cultivation systems.
Root length exhibited intricate interactions between treatments and cultivation methods, ultimately impacting the root weight of lettuce plants. The interaction between hydroponic subsystems and planting spacing significantly affected the root length, with NFT and DWC systems showing longer roots. The root length provides a larger surface area for nutrient uptake, which promotes plant growth[28]. Our results show that the lettuce root length in DWC was nearly three-fold longer than the root length in the SP. The poor root development in the media system with sand may have occurred due to lower dissolved oxygen compared to other cultivation methods. These findings emphasize the crucial role of nutrient availability and root environment in determining root length and subsequent plant growth[29,30].
The root weight of lettuces from the NFT system with narrow planting spacing was notably higher compared to other cultivation systems. In our study, the higher root weight in lettuces from NFT systems with narrow planting spacing did not increase at the same rate as shoot fresh mass. This observation aligns with the concept that nutrient availability and root environment significantly impact root development and consequently influence plant biomass accumulation. The greater root growth may not lead to greater shoot growth all the time due to the limited availability of nutrients and water [31]. If it is ensured that each nutrient that the plant needs in the growing systems is in direct contact with the root surfaces in a constant concentration at constant frequent fertigation, this will not be a limiting factor. On the other hand, lettuces grown in the SP system exhibited lower root weights, suggesting potential challenges associated with nutrient uptake and root growth in sand-based hydroponic systems[32].

Leaf Nutrient Composition, Chlorophyll and Carotene Contents

Leaf nutrient composition analysis revealed significant differences among cultivation systems for various nutrients as shown Table 6. While certain nutrients such as phosphorus (P) and potassium (K) exhibited variations based on hydroponic subsystem and planting spacing, others like sodium (Na), calcium (Ca), and magnesium (Mg) demonstrated differential responses. Notably, the presence of certain nutrients was associated with specific cultivation methods, reflecting the intricate relationship between nutrient uptake and hydroponic conditions. The quantitative relationship between the individual elements, as well as the ionic form, may be as significant as the concentration of each element in optimizing the nutritional status of the plant[33]. Moreover, the concentration of certain ions can support or inhibit the uptake of other ions. The connected ions have a synergistic or antagonistic relationship. The increase of Mg and N levels can enter into competition with the uptake of potassium[34]. Our results revealed that higher Mg content in lettuces from the MB with larger spacing decreased the potassium (K) level.

Chlorophyll and carotene contents were examined as essential indicators of plant health and nutritional quality. The chlorophyll A content demonstrated consistency across subsystems and planting spacing treatments (Figure 4). However, chlorophyll B and carotene contents were notably higher in lettuces cultivated in the DWC subsystem with narrow planting spacing. These findings suggest that DWC cultivation, particularly with optimized planting spacing, promotes enhanced chlorophyll and carotene accumulation, potentially indicative of improved photosynthetic efficiency and nutritional quality. While planting spacing predominantly influenced the content of lettuce chlorophylls and carotene content, all production variables in the present study affected the nutrient uptake and concentration of leaf nutrient content. Higher planting density can reduce photosynthetic capacity, as the necessary light cannot be provided enough to the plant for photosynthesis[35]. Our data support these interpretations.

Taste Tests

The sensory evaluation of hydroponically grown Batavia lettuces revealed significant differences in consumer acceptability and preferences among different cultivation systems as shown in Table 7. Lettuces from DWC and NFT subsystems garnered higher overall consumer acceptability ratings, with Sandponic lettuces receiving notably negative ratings. Appearance and aftertaste ratings followed similar trends, with DWC and NFT lettuces receiving the highest scores, Sandponic lettuces receiving the lowest scores, and Media-bed system lettuces receiving moderate scores. Contrary to this, a study from Baba and Ikeguchi (2015)[36] indicated that the sand used in the Sandponic system as substrate can increase the taste of crops such as tomatoes, as moisture in the sand is less absorbed by the plants compared to other substrates and plants have better taste due to the condensed flavours through less water in the crop. These findings suggest that DWC and NFT systems foster lettuce growth that aligns more closely with consumer preferences for appearance and taste attributes.

Table 6 -The leaf nutrient compositions are indicated as percentages from dry mass, and for macro-elements and Na content, and microelements as and mg/100g

T	CS	N %	P %	K %	Na %	Ca %	Mg mg/100g	Mn mg/100g	Zn mg/100g	Fe mg/100g	Cu mg/100g	B mg/100g	Mo mg/100g
T1	DWC	1.9 ± 0.2^{a}	0.93 ± 0.19^{ab}	2.71 ± 0.3^{a}	1.21 ± 0.09^{b}	1.59 ± 0.15^{a}	101.49 ± 16.77^{a}	15.01 ± 2.72^{a}	16.80 ± 3.45^{ab}	70.51 ± 18.16^{a}	1.14 ± 0.14^{a}	13.06 ± 0.52^{a}	4.35 ± 055^{a}
	NFT	2.3 ± 0.6^{a}	1.05 ± 0.17^{a}	2.92 ± 0.2^{a}	1.10 ± 0.17^{b}	1.63 ± 0.02^{a}	102.57 ± 9.56^{a}	14.96 ± 1.54^{a}	15.29 ± 0.94^{b}	66.22 ± 2.98^{a}	1.52 ± 0.22^{a}	13.15 ± 0.12^{a}	3.64 ± 0.61^{a}
	MB	1.6 ± 0.2^{a}	0.78 ± 0.13^{b}	2.91 ± 0.1^{a}	1.28 ± 0.13^{b}	1.66 ± 0.07^{a}	118.90 ± 7.30^{a}	14.48 ± 3.41^{a}	17.45 ± 1.99^{ab}	59.95 ± 8.07^{a}	1.27 ± 0.34^{a}	11.40 ± 3.53^{a}	3.48 ± 0.74^{a}
	SP	2.0 ± 0.7^{a}	0.83 ± 0.05^{ab}	2.94 ± 0.1^{a}	1.75 ± 0.05^{a}	1.60 ± 0.25^{a}	121.12 ± 2.43^{a}	11.48 ± 2.69^{a}	19.68 ± 0.59^{a}	63.27 ± 5.30^{a}	1.49 ± 0.17^{a}	13.09 ± 1.67^{a}	3.75 ± 0.24^{a}
T2	DWC	2.3 ± 0.4^{a}	0.73 ± 0.05^{a}	1.95 ± 0.2^{b}	1.11 ± 0.05^{a}	1.02 ± 0.06^{b}	254.90 ± 79.62^{c}	6.24 ± 1.17^{a}	14.17 ± 2.61^{a}	77.83 ± 22.81^{a}	1.41 ± 0.35^{a}	12.68 ± 0.50^{a}	3.45 ± 0.49^{a}
	NFT	2.3 ± 0.3^{a}	0.71 ± 0.20^{a}	1.34 ± 0.2^{c}	0.96 ± 0.20^{a}	0.98 ± 0.03^{b}	189.41 ± 43.31^{d}	8.17 ± 3.11^{a}	16.02 ± 0.29^{a}	65.67 ± 18.44^{a}	1.51 ± 0.10^{a}	13.33 ± 0.97^{a}	3.77 ± 0.71^{a}
	MB	2.4 ± 0.3^{a}	0.63 ± 0.02^{a}	1.95 ± 0.5^{b}	0.87 ± 0.02^{a}	1.36 ± 0.22^{a}	414.60 ± 41.15^{a}	7.68 ± 1.53^{a}	14.99 ± 1.83^{a}	67.32 ± 19.72^{a}	1.57 ± 0.16^{a}	13.30 ± 1.58^{a}	3.68 ± 0.44^{a}
	SP	2.1 ± 0.2^{a}	0.66 ± 0.15^{a}	2.45 ± 0.1^{a}	0.93 ± 0.15^{a}	1.47 ± 0.09^{a}	337.42 ± 24.31^{b}	8.21 ± 3.01^{a}	15.08 ± 2.99^{a}	64.14 ± 78.10^{a}	1.49 ± 0.13^{a}	13.43 ± 1.42^{a}	3.12 ± 0.31^{a}

Data are expressed as means ± standard error (SE). Lower case letters indicate significant differences after least significant difference (LSD) post hoc test (significance level $p< 0.05$ and $p< 0.01$, not significantly at $p\geq0.05$) for each parameter. Different upper superscript letters within cultivation systems indicate a significant difference at $p< 0.05$ and $p< 0.01$, not significantly at $p\geq0.05$ (LSD test). Treatments: T, T1: Narrow spacing (20 X25), T2: larger spacing (24x25 cm). CS: cultivation systems: DWC: Deep water culture, NFT: Nutrient Film Technique, MB: Media- bed system, SP: Sandponic.

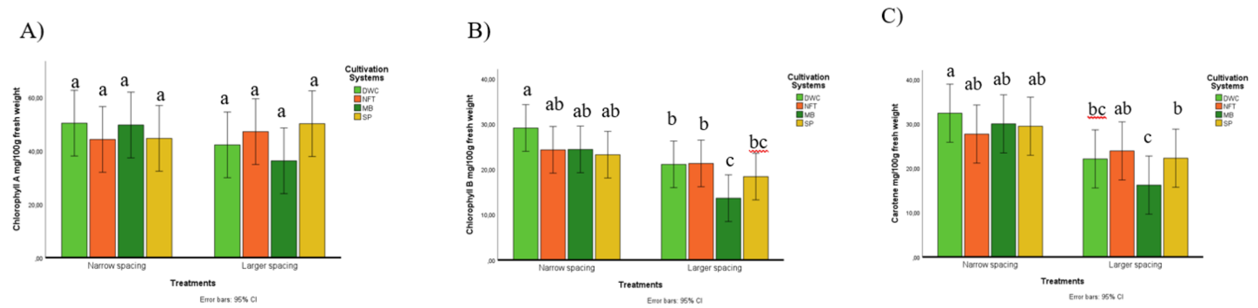

Figure 4, Chlorophyll and carotene contents, and dry mass of lettuces grown under different planting spacing and cultivation methods, (A) chlorophyll a, (B) chlorophyll b, and (C) carotene content, Means with a different letter within each treatment and cultivation methods are significantly different by the LSD test at p< 0,05, DWC: Deep water culture, NFT: Nutrient Film Technique, MB: Media- bed system, SP: Sandponic, Narrow planting spacing (20*25 cm), larger planting spacings (24*25cm).

DWC and NFT lettuces were consistently rated as less bitter and more flavorful compared to lettuces from MB and SP systems. These results indicate that the choice of the hydroponic subsystem has a substantial impact on the taste and sensory attributes of the lettuce crop. The crunchiness, colour, and aftertaste of DWC and NFT lettuces were also perceived more favourably, reinforcing the superior sensory attributes of these cultivation methods. Consumers tend to prefer the crunchy texture of the lettuce and associate this crunchiness with freshness and wholesomeness[37]. Additionally, lettuces from DWC and NFT were the preferred choices among consumers when asked to identify the "best lettuce".

2.1.2.4 Conclusion

The integrated analysis of the results emphasizes the interconnected nature of lettuce growth parameters, nutrient composition, and sensory attributes influenced by hydroponic subsystems and planting spacing. The study affirms the importance of these factors in influencing lettuce growth, biomass accumulation, and consumer preferences. Notably, DWC and NFT systems consistently outperformed other cultivation methods in terms of growth, nutrient accumulation, and sensory attributes. The availability of nutrients, root oxygenation, and nutrient solution pH emerged as key factors influencing lettuce growth and development.

The study's findings underscore the potential of DWC and NFT systems in optimizing lettuce yield and quality. The results also shed light on the complex relationships between nutrient availability, pH, and other environmental factors in determining plant growth and taste attributes. The integration of these findings provides valuable insights for optimizing hydroponic lettuce cultivation practices and enhancing the overall consumer experience. The study opens avenues for further research to explore the underlying physiological and biochemical mechanisms driving the observed effects and to refine hydroponic systems for improved lettuce production and sensory quality.

Overall, this study offers comprehensive insights into the interplay between hydroponic subsystems, planting spacing, and their combined effects on lettuce growth, nutrient composition, and sensory attributes. The outcomes provide valuable guidance for hydroponic practitioners aiming to optimize lettuce cultivation and meet consumer preferences for appearance, taste, and overall quality. The results emphasize the potential benefits of DWC and NFT systems in achieving superior growth performance and enhanced consumer acceptability. Further research in this direction could lead to the development of targeted strategies to fine-tune hydroponic systems and meet the evolving demands of the market for fresh and nutritious produce.

Table 7- Sensory attributes and mean scores of lettuces grown under different cultivation systems

	CS	OA[1]	AP[1]	OF[1]	AT[1]	SW[2]	BT[2]	C[2]	CR[1]	Smell	BL
T1 (n=21) F:8. M:13	DWC	8.76[a]	8.76[a]	9.0[a]	7.38[a]	4.57[a]	1.00[c]	4.57[a]	8.62[a]	29.60% fresh	52.4%
	NFT	8.95[a]	8.90[a]	9.19[a]	7.71[a]	4.67[a]	1.00[c]	4.62[a]	8.48[a]	29.60% fresh	47%
	MP	6.00[b]	6.00[b]	6.04[b]	5.10[b]	4.29[a]	1.57[b]	3.90[b]	6.29[b]	28.20% fresh, 7.1% neutral	-
	SP	4.81[c]	4.95[c]	4.38[b]	3.19[c]	1.71[b]	3.86[a]	3.43[b]	5.71[b]	10.60 fresh, 92.9 % neutral	-

Sensory attributes of lettuces from hydroponic and soil-based cultivation are assessed independently. Lower case letters within each main treatment indicate significant differences after the least significant difference (LSD) post hoc test (significance level $p < 0.05$ and $p < 0.01$, not significantly at $p \geq 0.05$) for each parameter. Smell and best lettuce preference are expressed as a percentage. Cultivation systems: HP: hydroponic subsystems. Lettuce origins: DWC: Deep water culture, NFT: Nutrient Film Technique, MB: Media- bed system, SP: Sandponic. T1: Narrow spacing. N: number of testers, gender of testers: F: female, M: male. Sensory attributes: Overall acceptability (OA), appearance (AP), Overall flavour (OF), Aftertaste (AT), Sweetness (SW), Bitterness (BT), Color (C), Crunnchiness (CR), Smell, best lettuce (BL).
[1]Evaluated with a 10-point scale: 1 = dislike extremely; 10 = like extremely.
[2]Evaluated with a 5-point scale: 1 = not at all bitter or sweet; 5 = extremely bitter or sweet

2.1.3 Comparative Analysis of Closed Hydroponic Subsystems and Planting Seasons for Lettuce Growth

In this experiment, we investigated the potential and adaptions of the hydroponic subsystems under different growing seasons. Our study aimed to assess the performance of different hydroponic

subsystems for lettuce cultivation in terms of vegetative growth parameters, leaf nutrient content analysis, and water consumption across both winter and summer growing seasons.
Two separate experiments were conducted in the summer and winter of 2021 to 2022 to examine the effects of the four hydroponic growing sub-systems and different growing seasons on Batavia lettuce growth, mineral nutrients and water consumption by plants under Mediterranean climate conditions. The experimental design was a randomized complete block with a 2 × 4 factorial arrangement of the growing season and cultivation system treatments that consisted of three replications (units). Treatments consist of two growing seasons (1) summer, (2) winter, and four cultivation system treatments comprised of (1) Deep Water Culture (DWC), (2) Nutrient Film Technique (NFT), (3) Media-bed system (MB) and (4) Sandponic (SP) as Figure 3 shows. The area of the hydroponic experimental unit was 1.92 m^2 for each replicate. Plants were grown with 20x25 cm planting densities. The NFT units consisted of 45 plants, a total of 135 lettuces, whereas other units consisted of 36 lettuces, a total of 108 plants for each cultivation system. The results provide valuable insights into the effects of subsystem choice and seasonal variations on lettuce growth and nutrient uptake.

2.1.3.1 Summary

Hydroponic cultivation techniques offer innovative solutions to address challenges in conventional agriculture, such as soil infertility, disease outbreaks, and poor drainage. This study focuses on comparing the performance of different closed hydroponic subsystems for lettuce cultivation across distinct winter and summer planting seasons in closed greenhouse environments. **Four closed hydroponic subsystems—Deep Water Culture (DWC), Nutrient Film Technique (NFT), Media-bed system (MB), and Sandponic (SP)—were evaluated** for their impact on vegetative growth parameters, leaf nutrient content, chlorophyll and carotene levels, and water consumption. Our findings reveal that **the DWC system consistently exhibited superior vegetative growth parameters in the winter season due to lower EC values, while the NFT subsystem excelled during the summer season.** Leaf nutrient analysis demonstrated significant variations among subsystems, indicating different nutrient uptake patterns. Notably, DWC lettuces consistently exhibited higher chlorophyll A, B, and carotene content, highlighting their potential for enhanced photosynthetic efficiency and nutritional value. The findings show that **DWC is well-suited for achieving robust and vigorous lettuce growth and almost invariable water consumption** in different seasons. **NFT subsystem also showed promising results, particularly effective utilization of the water per plant in both seasons, Moreover, this subsystem provides higher productivity per unit.** On the other hand, the use of substrate in hydroponics can enhance the storing of nutrients and water by adapting environmental parameters based on the demand of the crop. Overall, this study provides nuanced insights into the adept selection of hydroponic subsystems and astute synchronization with seasonal nuances within controlled greenhouse environments. Besides, the findings substantially enrich the comprehension and operational acumen pertaining to precision-driven lettuce cultivation, thereby propelling year-round sustainable and efficacious leafy vegetable production.

2.1.3.2 Methodology

In these experiments, the pre-experimental procedure, leaf content analysis, vegetative plant growth parameter measurements and statistical analysis were performed as described in the previous study (section 2.1.2). In addition to these measurements, the environmental parameters and water consumption were recorded.

Environmental Parameters

Environmental parameters were regularly measured to maintain within the optimal range for nutrient uptake by plants. Table 8 summarizes these recorded measurements.

Water consumption

At the beginning of the experiments, water tanks connected to hydroponic systems were filled with 500 L of water with nutrient solution for each unit in all subsystems, whereas 324 L of water was also added to the grow beds in the DWC subsystem, which contains total 824 L nutritious water. Water discharge might have happened only through the following cases during experiments: (1) Evapotranspiration and (2) leakage. After maturated lettuces were harvested in each grow bed for each treatment, the remained water in the water tank was measured and thereby the water consumption per square meter and per plant was calculated. The detailed water losses were not calculated but the results show the effective water use for each subsystem.

Table 8 - The environmental conditions for lettuces in closed growing beds and closed greenhouse

Growing seasons	CS	EC (µS/cm)	pH	DO (ppm)	Water T (°C)	Air T (°C)	Air RH (%)	CO_2 (ppm)
Winter	DWC	1.52 ±0.05	6.04 ±0.91	2.94 ±0.74	19.93 ±1.95	23.8±1.5	55±11	1900±710
	NFT	1.73±0.14	5.89±1.06	3.05±0.77	20.22±1.33			
	MB	1.88±0.16	6.34±0.44	3.11±0.71	20.7±1.33			
	SP	1.48±0.14	6.52±0.42	2.73±0.75	20.66±1.69			
Summer	DWC	1.81 ±0.06	5.84±0.62	5.32±0.25	27.12±1.08	27.4±1.9	65±4.6	1036 ±481
	NFT	1.86±0.09	5.85±0.62	5.10±0.31	27.46±1.06			
	MB	2.10 ±0.2	6.48±0.40	5.49±0.29	26.82±0.93			
	SP	2.44±0.22	6.71±0.25	4.06±0.45	26.89±1.16			

Data are expressed as means ± standard error (SE). Parameters: EC: electrical conductivity, DO: Dissolved oxygen, T: temperature, RH: Relative Humidity. CS: cultivation systems, DWC: Deep water culture NFT: Nutrient Film Technique. MB: Media- bed system and SP: Sandponic.

2.1.3.3 Results and Discussion

Vegetative Grow Parameters

The vegetative growth parameters of lettuce were significantly influenced by the hydroponic subsystems and the growing seasons. Our study provides proof that the NFT system consistently outperformed in terms of fresh mass, stem and head diameter, and root growth parameters in the summer season (Table 9). Conversely, the DWC subsystem performed better than other hydroponic systems in terms of vegetative growth parameters except for root weight during the winter season. Similarly, a study found that spinach grown in the NFT system had a higher yield than DWC in the summer growing season[38]. It can be argued that seasonal variations may affect the performance of selected hydroponic subsystems and thereby, it may result in different plant growth responses. For instance, the observed EC value during days with higher solar radiation and air temperature leads to higher water uptake by plants and it directly increases the EC level but not directly the pH value of the nutrient solution. The EC values of the nutrient solution below or above the optimal range may decrease plant growth parameters. Furthermore, DWC and NFT subsystems exhibited higher fresh weights in the winter season, while NFT lettuces showed greater fresh mass in the summer as well. This growth pattern could be attributed to varying temperature conditions and nutrient availability[39]. Interestingly, head diameters were larger for DWC and NFT lettuces in both seasons, whereas MB and SP systems had significantly smaller head diameters. This discrepancy in head diameter might be related to the nutrient composition and root development in different subsystems. The stem diameter of DWC and NFT lettuces was significantly thicker during the winter, but DWC stem diameter was lower than NFT's in the summer. These variations in stem diameter could be linked to differences in light exposure and temperature during the growing seasons[40]. Root length and root weight varied among subsystems and growing seasons, with DWC and NFT lettuces generally exhibiting higher root development. However, root development was negatively impacted by the summer season, leading to 36% reduction in root length. The NFT system showed the highest root weight in both seasons, suggesting its suitability for root growth even in challenging conditions. The suboptimal development of roots in the sand-based media system might be attributed to relatively lower dissolved oxygen levels in comparison to other cultivation methods[29,30]. These findings highlight the dynamic interplay between subsystem choice, growing season, and root development.

Lettuce leaf content analysis

Lettuce leaf nutrient analysis revealed significant differences in nutrient content across different subsystems and growing seasons (Table 10). The interaction between subsystems and growing seasons had a significant effect on leaf nutrient levels, except for nitrogen (N) and potassium (K) content. Notably, the phosphorus (P) content of MB and SP lettuces was higher in winter and summer, respectively. The higher pH of grow beds with medium might increase the Ca and P uptake in these subsystems. The substrates used in the experiments did not influence the solubility and uptake of phosphorus and some microelements, as the pH value of the nutrient solution is kept under 7. The microelement levels in the MB lettuces were higher in the winter season than the lettuce grown in other systems. However, the higher Ca content led to less uptake of microelement Zn. This discrepancy could be attributed to variations in nutrient availability and uptake strategies in different subsystems[35]. Similarly, other nutrient content, such as sodium (Na), calcium (Ca), and magnesium (Mg), varied among subsystems and seasons. Iron (Fe), copper (Cu), and boron (B) content also displayed differences between subsystems and seasons. These differences may result from nutrient solution composition, pH, and interaction with the growth medium. Our results indicate that the growth mediums hold and store oxygen and nutrients for periods where there is no water flowing and a steady supply until the recirculating water reaches the plants again[41].

Chlorophyll A, B, and carotene content was notably higher in DWC lettuces in both seasons, suggesting superior photosynthetic efficiency and potential nutritional value (Figure 5). The higher chlorophyll and carotene readings in DWC lettuces could be attributed to precise control of nutrient availability management by effectively maintaining the optimum growth conditions for nutrient uptake compared to lettuces from the NFT system[6].

Table 9 -Vegetative growth parameters

Cultivation seasons	Hydroponic systems	Shoot height (cm)	Shoot weight (g)	Stem diameter (cm)	Head diameter (cm)	Root length (cm)	Root weight (g)	Dry Mass (g)
Winter	DWC	17.71 ± 1.14[a]	159.81 ± 23.73[a]	1.50 ± 0.13[a]	23.85 ± 0.97[a]	50.72 ± 8.15[a]	31.46 ± 4.86[b]	1.15±0.15[a]
	NFT	16.15 ± 1.12[b]	165.89 ± 34.90[a]	1.51 ± 0.14[a]	23.61 ± 1.80[a]	46.35 ± 4. 18[b]	40.27 ± 8.23[a]	0.93±0.04[b]
	MB	11.60 ± 1.09[c]	57.60 ± 12.39[b]	1.00 ± 0.08[b]	14.07 ± 1.52[b]	21.68 ± 2. 31[c]	15.10 ± 2.35[c]	1.13±0.02[a]
	SP	11.24 ± 1.37[c]	49.71 ± 19.06[b]	0.98 ± 0.13[b]	13.70 ± 2.25[b]	11.52 ± 1. 91[d]	16.77 ± 7.13[c]	1.20±0.14[a]
Summer	DWC	17.93 ± 1.16[a]	155.40 ± 17.38[b]	1.16 ± 0.06[b]	22.57 ± 0.80[a]	32.17 ± 5. 10[b]	26.87 ± 3.52[b]	0.98±0.06[n]
	NFT	16.23 ± 0.92[b]	169.97 ± 18.35[a]	1.25 ± 0.07[a]	23.63 ± 1.27[a]	37.50 ± 4. 17[a]	38.63 ± 5.57[a]	0.92±0.04
	MB	14.80 ± 1.73[c]	97.67 ± 14.74[c]	1.07 ± 0.09[c]	18.47 ± 1.83[b]	19.30 ± 1. 93[c]	20.00 ± 4.74[c]	0.98±0.09
	SP	14.77 ± 0.75[c]	101.07 ± 14.25[c]	1.06 ± 0.12[c]	19.40 ± 1.18[b]	12.40 ± 1. 70[d]	22.10 ± 6.65[c]	0.99±0.10

Data are expressed as means ± standard error (SE). Lower case letters within each main treatment indicate significant differences after the least significant difference (LSD) post hoc test (significance level $p< 0.05$ and $p< 0.01$. not significantly at $p≥0.05$) for each parameter. DWC: Deep water culture. NFT: Nutrient Film Technique. MB: Media- bed system. and SP: Sandponic.

Table 10 -The leaf nutrient compositions are indicated as percentages of dry mass. and for macro-elements and Na content. and microelements as and mg/100g

Treatments	CS	N %	P %	K %	Na %	Ca (mg/100 g)	Mg mg/100g	Mn mg/100g	Zn mg/100g	Fe mg/100g	Cu mg/100g	B mg/100g	Mo mg/100g
Winter	DWC	2.38±0.54	1.03±0.07[ab]	2.17 ±0.21	1.16±0.07[n]	117.16±13.60[b]	270.72±38.56[b]	17.94±1.97[a]	20.23±3.31[a]	110.48±1.29[b]	1.00±0.09[c]	8.54±0.77[b]	1.30±0.12[b]
	NFT	2.24±0.20	1.03±0.07[ab]	2.37±0.08	1.03±0.09	132.34±4.09[b]	216.38±30.47[b]	17.36±0.59[a]	21.42±1.66[a]	114.84±6.74[b]	1.54±0.22[b]	13.23±1.85[ab]	1.69±0.24[ab]
	MB	2.03±0.65	1.08±0.15[a]	2.36±0.13	1.14±0.16	170.01±18.85[a]	340.42±7.17[a]	16.76±0.19[a]	21.06±1.93[a]	138.71±16.63[a]	2.34±0.09[a]	17.68±5.54[a]	2.31±0.67[a]
	SP	1.91±0.24	0.79±0.18[b]	2.13±0.28	0.89±0.12	182.63±12.64[a]	286.77±25.81[a]	13.91±0.75[b]	19.30±2.55[a]	124.47±2.23[ab]	1.47±0.33[b]	12.57±2.85[b]	1.61±0.37[ab]
Summer	DWC	2.37±0.34	1.02±0.09[ab]	2.27±0.18	1.93±0.56[ab]	94.23±23.03[b]	258.29±50.54[a]	15.14±1.82[a]	9.74±2.04[b]	211.50±3.43[a]	0.89±0.08[c]	10.09±1.21[a]	4.23±0.85[a]
	NFT	2.63±0.36	1.08±0.10[ab]	2.51±0.06	2.22±0.61[a]	78.30±23.94[b]	189.91±27.22[b]	16.52±0.97[a]	14.24±0.67[a]	189.11±9.45[b]	1.73±0.23[a]	11.02±0.65[a]	3.78±0.72[a]
	MB	2.26±0.26	0.88±0.14[b]	2.41±0.15	2.10±0.22[ab]	124.81±13.93[a]	293.84±61.41[a]	13.72±0.55[b]	15.75±1.78[a]	177.88±11.17[b]	1.28±0.26[b]	9.15±3.54[a]	3.56±0.75[a]
	SP	2.31±0.38	1.19±0.31[a]	2.33±0.15	1.50±0.09[b]	111.10±13.12[a]	293.33±26.00[a]	15.81±0.26[a]	17.72±2.47[a]	184.78±7.39[b]	1.14±0.19[bc]	10.54±1.86[a]	3.70±0.15[a]

Data are expressed as means ± standard error (SE). Lower case letters indicate significant differences after the least significant difference (LSD) post hoc test (significance level $p< 0.05$ and $p< 0.01$, not significantly at $p≥0.05$) for each parameter. Different upper superscript letters within cultivation systems indicate a significant difference at $p< 0.05$ and $p< 0.01$. not significantly at $p≥0.05$ (LSD test). CS: cultivation systems: DWC: Deep water culture. NFT: Nutrient Film Technique. MB: Media- bed system. SP: Sandponic.

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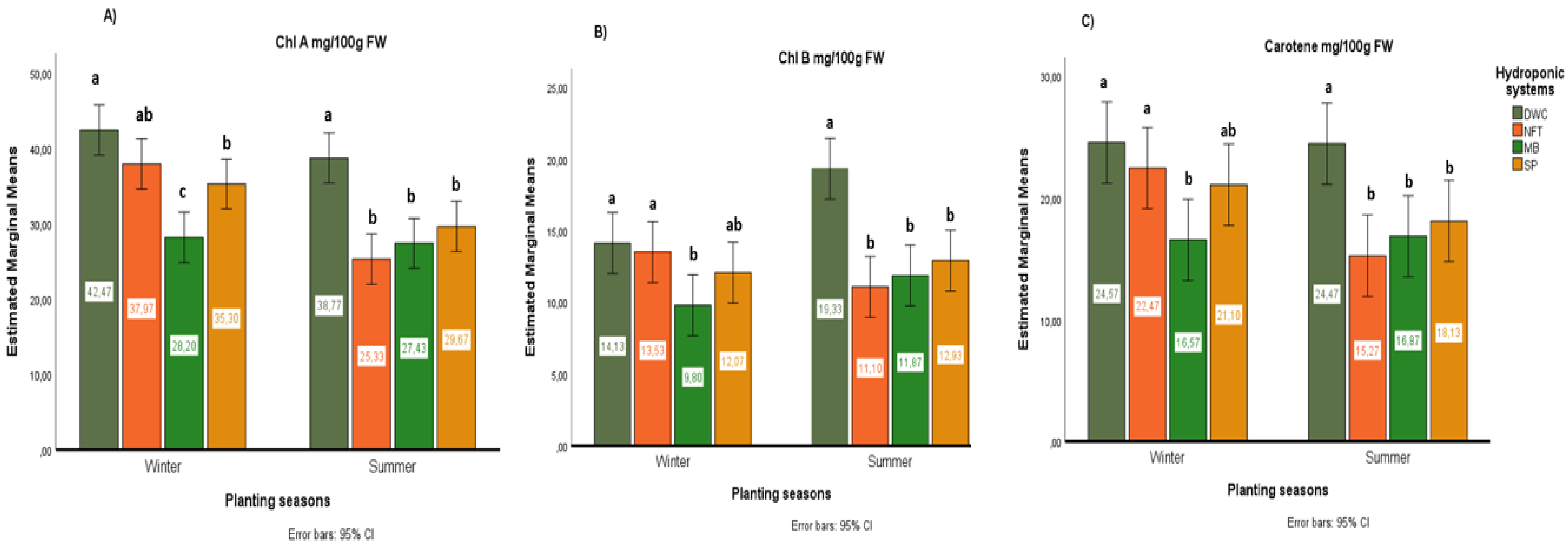

Figure 5. Chlorophyll and carotene contents of lettuces grown in closed hydroponic systems at different planting seasons. (A) chlorophyll a, (B) chlorophyll b, and (C) carotene content. Means with a different letter within each treatment and cultivation method are significantly different by the LSD test at p< 0.05. DWC: Deep water culture, NFT: Nutrient Film Technique, MB: Media-bed system, and SP: Sandponic.

Water consumption

Water consumption was significantly influenced by both growing seasons and hydroponic subsystems (Figure 6). DWC systems exhibited stable water consumption across seasons, while the other subsystems showed increased water consumption in summer., which even increased approximately 2 times. In both seasons, the NFT system needs less water for lettuce growth, while MB growing systems need more water. Additionally, the water consumption per unit in SP subsystems was also significantly lower in winter. These findings underscore the importance of considering water efficiency and management in hydroponic cultivation systems. Similarly, the water consumption per plant was affected by either main effects or interaction between variables. In the winter season, the lettuces grown in the NFT system consumed the least water.

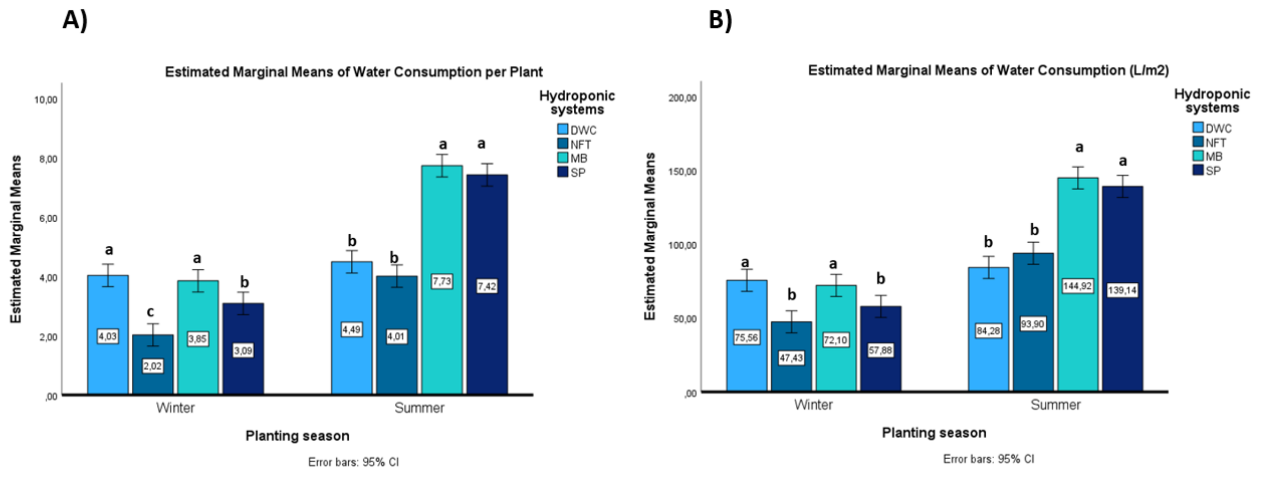

Figure 6. Water consumption per plant and per unit (L/m2) in lettuce growth for different closed hydroponic systems in the winter and summer. Means with a different letter within each treatment and cultivation method are significantly different by the LSD test at $p< 0.05$. Hydroponic subsystems: DWC: Deep water culture, NFT: Nutrient Film Technique, MB: Media-bed system, and SP: Sandponic.

Water use efficiency for each subsystem was expressed as kg/ m^3. The productivity of lettuce per unit of water was obtained by dividing the total weight of lettuce (shoot weight + root weight) by used water by plants during a plant cultivation cycle (28 days) as shown in Figure 7. The water use efficiency was influenced by the growing season and hydroponic subsystem. In the winter term, NFT lettuce had the highest productivity per unit of water, while the least water use efficiency was observed in the MB lettuces during summer time.

According to Figure 6, the estimated water demand for the NFT during the system was significantly higher in winter and more crops were produced per drop in both seasons. The swallow root system of lettuce was unable to utilize most of the water in DWC subsystems, which was also reported by Gonnella et al. (2003)[42] and Majid et al. (2021)[6]. However, the higher air and water temperatures increased water consumption during summer, it has even been observed that the water consumption per square meter is higher than the DWC system. This result can be explained by the higher air and water temperatures leading to water losses in the NFT system due to evaporation during the summer season. On the other hand, the MB subsystem exhibited higher water consumption, particularly in the summer season. This could be attributed to its design and nutrient delivery methods, indicating the need for further investigation to improve water efficiency in this subsystem.

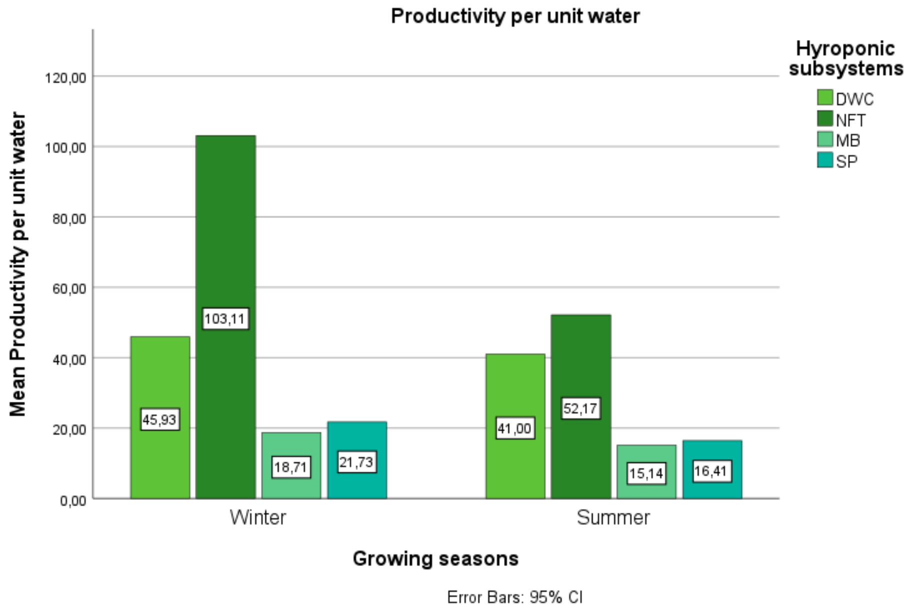

Figure 7. Productivity per unit water (kg/m^3). Hydroponic subsystems: DWC: Deep water culture, NFT: Nutrient Film Technique, MB: Media-bed system, and SP: Sandponic.

2.1.3.4 Conclusion

Overall, this hydroponic study documents the comprehensive analysis of various hydroponic subsystems and their performance during different planting seasons for lettuce cultivation within closed greenhouse environments. **Our results demonstrate that the DWC system consistently displayed enhanced vegetative growth parameters during the winter, attributed to lower EC values, whereas the NFT subsystem excelled in the summer**. Leaf nutrient analysis unveiled noteworthy variations among subsystems, underscoring diverse nutrient uptake patterns. Remarkably, DWC lettuces consistently manifested higher chlorophyll A, B, and carotene content, suggesting heightened photosynthetic efficiency and nutritional value potential. These empirical findings underscore the suitability of the DWC subsystem in fostering robust and vigorous lettuce growth, while concurrently maintaining a consistent water consumption pattern across diverse seasonal contexts. **Likewise, the NFT subsystem exhibits promising efficacy, particularly in terms of efficient per-plant water utilization during both seasonal regimes.** However, it is noteworthy that the hermetically sealed configuration intrinsic to the NFT subsystem engenders elevated rates of water evaporation, with pronounced manifestation during the summer season. Given these empirically substantiated outcomes, we posit that strategic adaptations, encompassing targeted cooling interventions amid the summer months and judicious greenhouse heating during winter, could be judiciously employed to modulate prevailing environmental parameters. This orchestrated approach, orchestrated to attain optimal air and water temperatures, holds the potential to engender a conducive milieu for uninterrupted year-round lettuce cultivation. Notably, this judicious modulation of microclimatic conditions not only augments the growth milieu but also serves as a mitigation strategy against undue water losses stemming from exacerbated evaporation dynamics. These insights emphasize the significance of hydroponic subsystem selection and maximizing lettuce production year-round in closed greenhouse environments, contributing to the advancement of efficient and sustainable controlled-environment agriculture practices.

2.2 AQUAPONIC EXPERIMENTS

Aquaponics is a sustainable agricultural method that integrates the cultivation of aquatic organisms, such as fish or other aquatic animals, with the growth of plants in a symbiotic environment. In an aquaponic system, the waste produced by the aquatic organisms provides essential nutrients for the plants, acting as a natural fertilizer. In return, the plants help to filter and purify the water, creating a closed-loop ecosystem where both plants and aquatic life thrive. This method aims to maximize resource efficiency by minimizing water usage and reducing the need for external fertilizers, making it an environmentally friendly and efficient way to produce both food and plants[43].

Aquaponic experiments aimed at examining: (i) the interaction between planting spacing and grow bed types as hydroponic components under the same fish stocking density and environmental conditions, (ii) the water consumption of the lettuce with dependent factor planting spacing in various cultivation systems, (iii) food productivity (lettuce and fish amount) per unit water.

2.2.1 Methodology

In these experiments, the pre-experimental procedure for lettuce growth, leaf content analysis, vegetative plant growth parameter measurements and statistical analysis were performed as described in the previous study (section 2.1.2). Fish weighed at the beginning and after experiments. In addition to these measurements, the environmental parameters and water consumption were recorded.
2.1.1.2.

Materials

In the aquaponic experiments, lettuce and Nile tilapia were used in experiments. Lettuce seeds (*Lactuca sativa* L., cv. *Batavia* F1) produced by Rijk Zwaan were purchased from the local distributor in Egypt, while Nile Tilapia *(Oreochromis niloticus*), is chosen as aquaculture to be used in experiments.

As solid-waste filters are used to retain solids. The type of disc filter was installed in the NFT and DWC systems and has a maximum 30 m^3/h flow rate and minimum 125-micron particle size. Mechanical filtration is provided through passive disc-based techniques (e.g. as opposed to active drum filters) in order to reduce power requirements (Figure 8).

In the biological filter, bacteria degrade the excretions of the fish so that they are available for the plants. These bacteria belong to the group of Nitrobacter and Nitrosomonas. As there is no reliable supply of these bacteria, the filters are built up naturally. Before starting experiments, bacteria cultures were obtained from a research centre. The natural filter build-up is expected to take about 2 months. During this period, the water in the fish tanks has to be substituted partly, as the degradation capacity of the biological filter is not sufficient and as the aquaculture and hydroponic systems are not connected yet. The nitrate and ammonia concentrations in the fish water are of special concern, as they can quickly reach fish toxic levels.

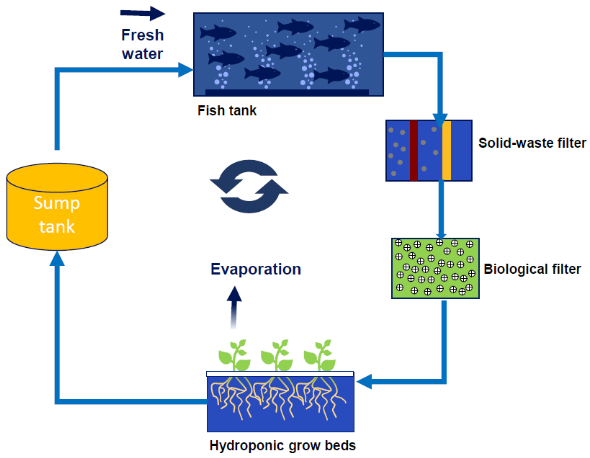

Figure 8. The components of the one-loop closed aquaponic systems, which is the combination of hydroponics and aquaculture.

Pre- experimental procedure

Fish rearing is the main component of the aquaponic system. In the lab scale facility, circular fish tanks are used with a volume of 1200 L each (for DWC, NFT, Media-bed, Sandponics, IVA). The water source is fresh water from the Nile through the Al-Ismailiyah Canal. The fish species, Nile Tilapia (*Oreochromis niloticus*), are chosen as aquaculture to be used in experiments. The circular tank nature ensures a circular path for the fish in the tank, which provides them with a sense of a larger habitat.

For the experiment, Nile tilapia are purchased in the size range of 5–50g. To build up the biological filter, the fish were kept at least **two months before the start of the experiments**. During the entire lab scale trial, the animals are not caught for consumption but kept under constant conditions. However, to provide **biomass consistency**, some fish were removed from the system during the growth phase.

Table 11 provides an overview of parameters and their specifications relevant for Nile tilapia farming, and used in the experiments.

During the experimental procedure, fish are not harvested. Fish weights are determined to keep the stocking density constant at around 15 kg/m^3. Hence, fish are removed during the experiments. All fish are weighed after each trial (after plant harvest) to track weight gain. The number of fish to be weighed is calculated based on the equation Yamane (1967)[44] as follows.

Table 11 - Aquaculture data for the aquaponics experiment of the lab scale system.

Parameter	Specification
Species	*Oreochromis niloticus*
Number of fish per 1200 L tank	250 – 100 (dependent on the fish weight)
Fish size (at test start)	5 – 50 g
Stocking density (at test end)	15 kg/m³
Fish feed	Skretting® 30- 32% Protein
Feeding rate	3 times/ Day, 2 - 3% of overall biomass depending on fish size.
Acclimatization procedure	1. Measure the temperature of the water inside the container/ tank that carries the fish when it reaches the farm. 2. Measure the water temperature inside the fish tank (breeding tank). 3. Do not transfer the fish into the breeding tank if the difference between the temperature in the incoming fry tank and the temperature in the breeding tank on the farm is 5°C or higher. 4. Gradually adjust the temperature by adding water from the farm breeding tank to the incoming fish tank to bring the temperature to a difference of 2-3°C. 5. Now it is ready to transfer the fish to the rearing tanks.

Precision (e) is set to 10% instead of the common 5% since all fish are weighed between the single experiments.

$$n = \frac{N}{1 + N(e)^2}$$

where; n: sample size (people); N: population size; and e: precision rate (10%). Fish sorting done between 2 experimental cycles. 6 days between the two test cycles is prescribed. The biomass of the fish is 4kg /tank, and it is expected to reach up to 5 kg/tank at the end of the one experimental test cycle.

Experimental design

The experiments were performed under greenhouse conditions in Cairo, Egypt (30°2′41″ N, 31°14′44″ E, altitude 26 masl). The research greenhouse´s dimensions were 30 m L x 6 m W x 2.85m H. The experimental design was a randomized complete block with a 2 × 6 factorial arrangement of the planting spacing and cultivation system treatments that consisted of three replications (units). Treatments consist of two planting spacings (1) 20X25 cm, (2) 24 X25 cm, and six cultivation system treatments comprised of (1) Deep Water Culture (DWC), (2) Nutrient Film Technique (NFT), (3) Media-bed system (MB) and (4) Sandponic (SP), which are hydroponic component, and Integrated Vegetable Aquaculture (IVA) and Soil-Based Cultivation (SC).
The aquaponic consists of two parts, which are LS2-1 and LS2-2 as illustrated in Figure 9. In these experiments, we investigated the planting spacing in various cultivation systems by keeping the number of lettuce and fish stocking densities the same. The objective of the aquaculture component is to keep the nutrient flow constant. In experiments LS2-1 and IVA2-1, 24 plants are cultivated with

a spacing of 20x25 cm in each unit, whereas in LS2-2, and IVA2-2, 24 plants are planted at a spacing of 24x25 cm per unit. Total 72 seedlings were transplanted for each cultivation system.

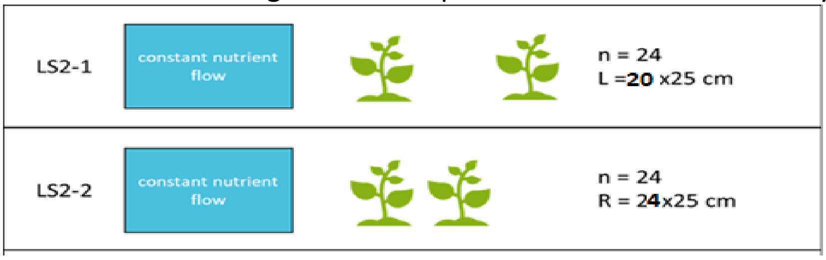

Figure 9- Experiments in the AWESOME lab-scale aquaponics setup. In these experiments, planting spacing is tested. Nutrient flow from the fish tanks is kept constant (adjusted by feeding and fish density)

Table 12 provides an overview of the technical setup of the Hydroponic grow bed area. Details regarding the subsystems are provided in the section of Methodology (2.1.2.2).

Table 12 - Technical properties of the aquaponics setups investigated in the AWESOME lab-scale facility

	DWC	NFT	Sand	MB	IVA
Number of grow system	3	3	3	3	3
Cultivation area/system	1.92 m^2	1.92 m^2	1.92 m^2	1.92 m^2	12m^2
Water volume fish tank/system	1200 L	1200 L	1200 L	1200 L	1200 L
Overall water volume /system	2200 L	2700 L	2700 L	1700 L	1700 L
Biofilter	Yes	Yes	No	No	No
Solid-water filter	Yes	Yes	No	No	No
Sterilization	No	No	No	No	No
Water circulation	Closed-loop	Closed-loop	Closed-loop	Closed-loop	Flow-through
Irrigation system	Continuous flow	Continuous flow	Drip irrigation	Continuous flow	Drip irrigation
Drainage system	Overflow	Continuous drain	Underground drainage network	Bell siphon	Deep infusion
Pump wattage	500 W	500 W	500 W	500 W	500 W
Pump operation rate/system	30 ON: 5 min OFF	30 ON: 5 min OFF	30 ON: 5 min OFF	30 ON: 5 min OFF	7 mins / day
	55 min/h	55 min/h	55 min/h	55 min/h	7 min/day
Pump flow rate/system	10 L/min	10 L/min	10 L/min	10 L/min	10 L/min
Extra accessories	air pump (280 W), 12 h/day				

Media-bed systems with gravel (MB) and sand (SP) can serve as biological and mechanical filters without adding them as shown Figure 10A. As above mentioned, the lettuce growth grown in aquaponic systems was compared with soil-based cultivation (SC) and Integrated Vegetable Aquaculture (IVA). In the IVA system, nutrient-rich wastewater from flow-through aquaculture is used to irrigate and fertilize crops in soil as illustrated in Figure 10B.

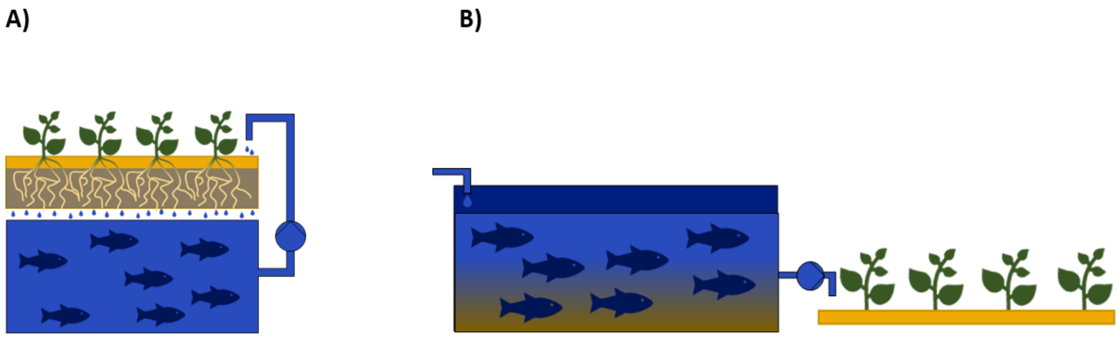

Figure 10. A- Aquaponic system design with media without adding any mechanical and biological filter (MB and SP), B- and Integrated Vegetable Aquaculture (IVA) design.

2.2.2 Results and Discussion

Vegetative Growth Parameters

The analysis of vegetative growth indicated a pronounced impact of the cultivation method as a primary factor. Notably, the interaction between the cultivation method and planting spacing exhibited a significant effect on lettuce growth and development. This finding aligns with previous research demonstrating the pivotal role of cultivation methods in determining plant growth outcomes for Aquaponic subsystems[45]. In the current study, lettuces cultivated using the SP (soilless system with planting spacing) method exhibited superior shoot height and fresh shoot mass, surpassing those cultivated using the SC (conventional soil) and IVA (alternative soilless) methods. This superiority in vegetative growth parameters could be attributed to the favourable conditions provided by the SP grow beds, which offer enhanced nutrient availability, stored in the sand[41]. Moreover, our findings reveal that the sand as a media promotes lettuce growth by cleaning water for healthy fish growth through mechanical filters and providing a surface for beneficial nitrifying bacteria as mechanical and biological filters. Regarding lettuce yield, the SP cultivation method stood out with an impressive 9 to 11-fold increase in yield compared to the SC and IVA methods, respectively. This remarkable difference in yield demonstrates the potential of the SP method for lettuce production in aquaponic systems. This result echoes findings from studies emphasizing the efficacy of hydroponic systems in enhancing crop yields through efficient nutrient delivery and reduced competition for resources.
Planting spacing emerged as a critical factor influencing stem and leaf development. In larger planting spacing (24 x 25 cm), stem lettuces experienced a significant reduction. These findings concur with previous investigations highlighting the balanced N-P-K availability for lettuce growth[46]. Moreover, our findings demonstrate that the narrower plant spacings led to increased stem diameter. This result can be attributed to the lower light intensity. The number of leaves exhibited a reduction in the SP soilless system with narrower planting spacing (20 x 25 cm), while the largest

planting spacing in the SP method yielded the highest leave number. These outcomes underscore the intricate interplay between planting density and nutrient availability, which collectively shape leaf development.
However, the SP method showed compromised root development compared to other soilless cultivation systems. Conversely, the DWC (deep water culture) method displayed the longest root length, while the NFT (nutrient film technique) method exhibited the highest root weight across both planting spacings. These findings reflect the varying degrees of root support provided by different cultivation systems, with each system having distinct implications for nutrient uptake and overall plant health. Intriguingly, the IVA and SC lettuces displayed the least root development, demonstrating similar root characteristics despite their distinct cultivation methods. The decreased root development in these cultivations may have occurred due to decreased dissolved oxygen compared to other cultivation methods[29,30]. Furthermore, increased root temperature and light intensity in summer trials can negatively affect the root development of lettuces[32,46].

Table 13- Vegetative growth parameters

T	CS	Shoot height (cm)	Shoot mass (g)	Number of leaves	Stem diameter (mm)	Root length (cm)	Root weight (g)
T1	DWC	12.1 ± 0.2^{b}	109.03 ± 4.76^{c}	31.11 ± 0.80^{b}	18.44 ± 0.54^{ab}	40.69 ± 0.94^{a}	22.03 ± 1.61^{c}
	NFT	11.5 ± 0.2^{bc}	126.64 ± 4.76^{b}	35.08 ± 0.80^{a}	17.25 ± 0.54^{b}	30.61 ± 0.94^{b}	40.69 ± 1.61^{a}
	MB	11.2 ± 0.2^{c}	77.11 ± 4.76^{d}	27.39 ± 0.80^{c}	17.94 ±0 .54^{b}	16.22 ± 0 .94^{c}	30.28 ± 5.22^{b}
	SP	12.8 ± 0.2^{a}	142.31 ± 4.76^{a}	32.78 ± 0.80^{b}	19.72 ± 0.54^{a}	7.78 ± 0.94^{d}	21.72 ± 6.78^{c}
	IVA	5.8 ± 0.2^{e}	10.17 ± 5.83^{e}	14.96 ± 2.98^{d}	7.88 ± 2.66^{c}	6.29 ± 2.15^{d}	5.71 ± 1.29^{d}
	SC	6.6 ± 0.2^{d}	21.19 ± 4.76^{e}	17.19 ± 0.80^{d}	8.81 ± 0.54^{c}	8.67 ± 0.94^{d}	9.72 ± 2.67^{d}
T2	DWC	10.7 ± 0.2^{b}	136.31 ± 4.76^{a}	39.33 ± 0.80^{a}	15.86 ± 0.54^{a}	51.44 ± 0.94^{a}	30.56 ± 2.44^{b}
	NFT	10.6 ± 0.2^{b}	105.03 ± 4.76^{b}	35.53 ± 0.80^{b}	11.39 ± 0.54^{c}	28.44 ± 0.94^{b}	37.50 ± 0.44^{a}
	MB	10.2 ± 0.2^{b}	68.64 ± 4.76^{c}	27.61 ± 0.80^{c}	11.94 ± 0.54^{c}	15.08 ± 0.94^{c}	17.72 ± 3.08^{c}
	SP	11.9 ± 0.2^{a}	145.50 ± 4.76^{a}	38.69 ± 0.80^{a}	14.17 ± 0.54^{b}	11.86 ± 0.94^{d}	20.39 ± 8.86^{c}
	IVA	6.8 ± 0.2^{c}	12.75 ± 5.83^{d}	14.00 ± 2.98^{d}	6.83 ± 2.66^{e}	7.13 ± 2.15^{e}	5.33 ± 0.13^{d}
	SC	6.6 ± 0.2^{c}	16.17 ± 4.76^{d}	15.81 ± 0.80^{d}	8.53 ± 0.54^{d}	7.81 ± 0.94^{e}	6.28 ± 5.81^{d}

Data are expressed as means ± standard error (SE). Lower case letters within each main treatment indicate significant differences after the Duncan multiple range test (DMT) post hoc test (significance level $p< 0.05$ and $p< 0.01$. not significantly at $p\geq0.05$) for each parameter. Treatments: T1: 20*25 cm, T2: 24*25 cm. Cultivation systems (CS): DWC: Deep water culture, NFT: Nutrient Film Technique, MB: Media-bed system, SP: Sandponic, IVA: Integrated Vegetable Aquaculture and SC: Soil Cultivation

Food productivity and water use efficiency

Water is needed for each lettuce grown in various cultivation systems during one lettuce growth cycle of 28 day illustrated in Figure 11. The water in a closed aquaponic system is used not only for lettuce cultivation but also is used for fish rearing, which reduces the supplementary fertilizer. Moreover, these systems allow the reuse of water in the next cultivation. Even though this, the needed water in closed aquaponic systems was less than IVA and soil-based cultivation (SC). Our findings demonstrate that when a well-chosen soilless subsystem is adapted to optimal planting spacing, it can achieve water savings of up to 110-fold and 4-fold compared to IVA and soil-based production, respectively, thereby resulting in higher production quantities per area within 28 days. One lettuce from the MB system needed the least water amount (including the amount for fish in the system) compared to other cultivation systems in both planting spacing. However, the needed water was higher in larger planting spacings.

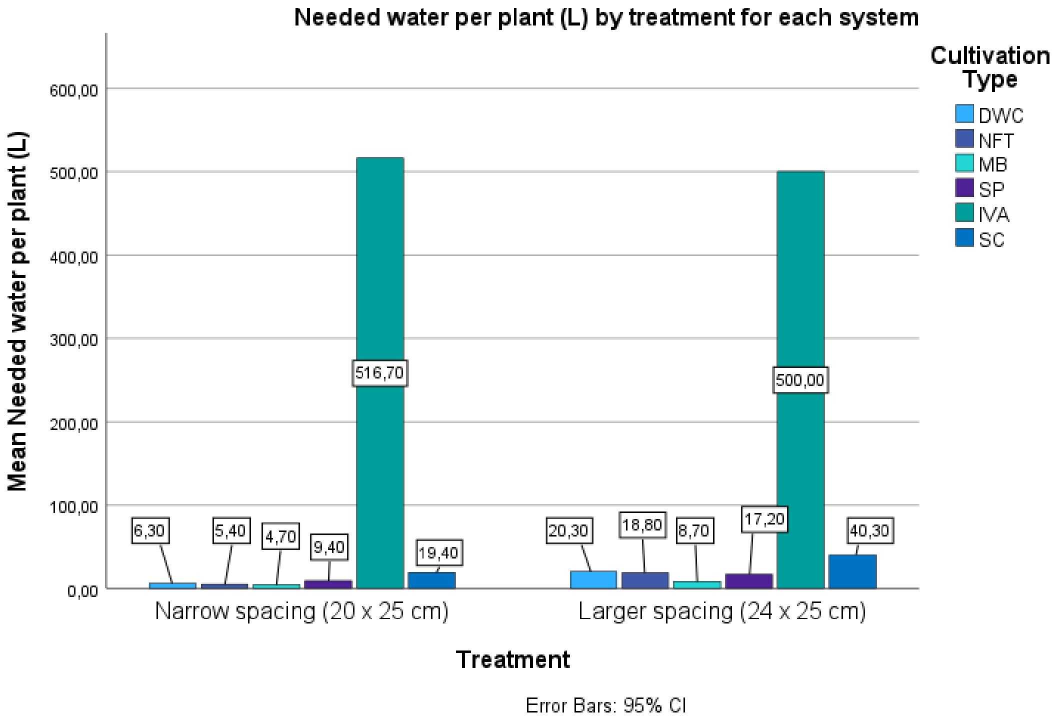

Figure 11. The water per plant in various cultivation systems under two different planting spacing. Cultivation systems: DWC: Deep water culture, NFT: Nutrient Film Technique, MB: Media-bed system, SP: Sandponic, IVA: Integrated Vegetable Aquaculture and SC: Soil Cultivation

The greatest lettuce productivity per unit of water was obtained in the NFT system with the narrower planting spacing (20 x 25 cm) at 30.90 kg/m^3, whereas this water use efficiency was higher in the MB lettuces with larger spacing (24 x25 cm) compared to other cultivation systems as Figure 12 shows. Conversely, the lowest lettuce productivity was measured in IVA and SC soil-based open systems. Our findings reveal that lettuce can efficiently utilise water and produce more crops by allowing nutrient uptake better than IVA and SC lettuces.

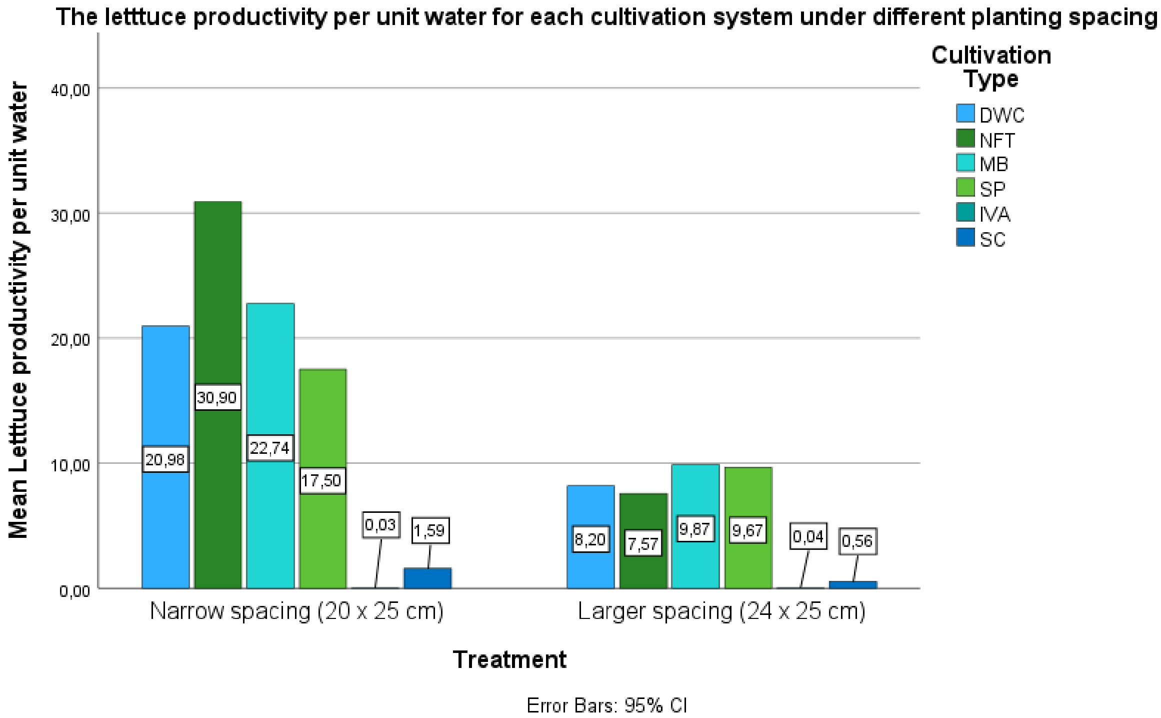

Figure 12. Lettuce productivity per unit of water in several aquaponic systems, IVA and Soil-based (SC) systems with different planting spacings.

Conclusion

The findings of this study underscore the significance of the **SP cultivation method in promoting superior vegetative growth and substantial yield improvement in lettuce**. Furthermore, planting spacing was demonstrated to have a nuanced influence on stem, leaf, and root development, emphasizing the need for careful consideration of planting densities for optimizing lettuce cultivation. The insights gained from this research could contribute to the refinement of lettuce production strategies, enhancing resource efficiency and crop productivity.

3. MULTICRITERIA DECISION ANALYSIS (MCDA)

Multicriteria Decision Analysis (MCDA) is a systematic approach used for evaluating and selecting options from a set of alternatives based on multiple criteria. For addressing the problem of evaluating different alternatives about expert judgements, scientific results and cost-benefit analysis, Multicriteria decision analysis (MCDA) has become a vital tool for decision-making[47-48]. MCDA offers a well-structured evaluation procedure considering numerous decision-relevant criteria. Not only hard facts but also fuzzy assessments are considered. In our studies, we had several factors come into play for choosing “the best-performing subsystem”. These include technical, economic, environmental, and social considerations. MCDA allows decision-makers to weigh these factors according to their significance and preferences. For instance, technical aspects might involve factors like system efficiency, water usage, and crop yield. Economic considerations could encompass initial investment costs, operating expenses, and potential revenue generation. Environmental factors might touch upon resource consumption, waste management, and ecological impact. Lastly, social perspectives may involve aspects such as community engagement, job creation, and overall societal benefits. Using MCDA, decision-makers assign weights to each criterion based on their importance

3.1 METHODOLOGY

In the context of selecting hydroponic and aquaponic subsystems, MCDA offers a structured framework to make good decisions considering various perspectives. After the definition of the problem, the available solution alternatives were determined and followed by the definition of criteria, which should be involved in the decision process. In a workshop, we clarified the MCDA procedure to different experts from project partners and stakeholders with different perspectives and asked them to give each one of them a rating between 0 and 10, with 0 meaning no influence on the result and 10 being associated with the highest score. After a workshop for all project partners and stakeholders, the participants rated the criteria weighting which influences the impact of each criterion. Thereby, the stakeholders' subjective perspectives as well as experiences are considered. Based on weighting and the estimated or measured values, a single value was calculated for each alternative. The higher the value the better the result. The steps of MCDA approaches are illustrated in Figure 13.

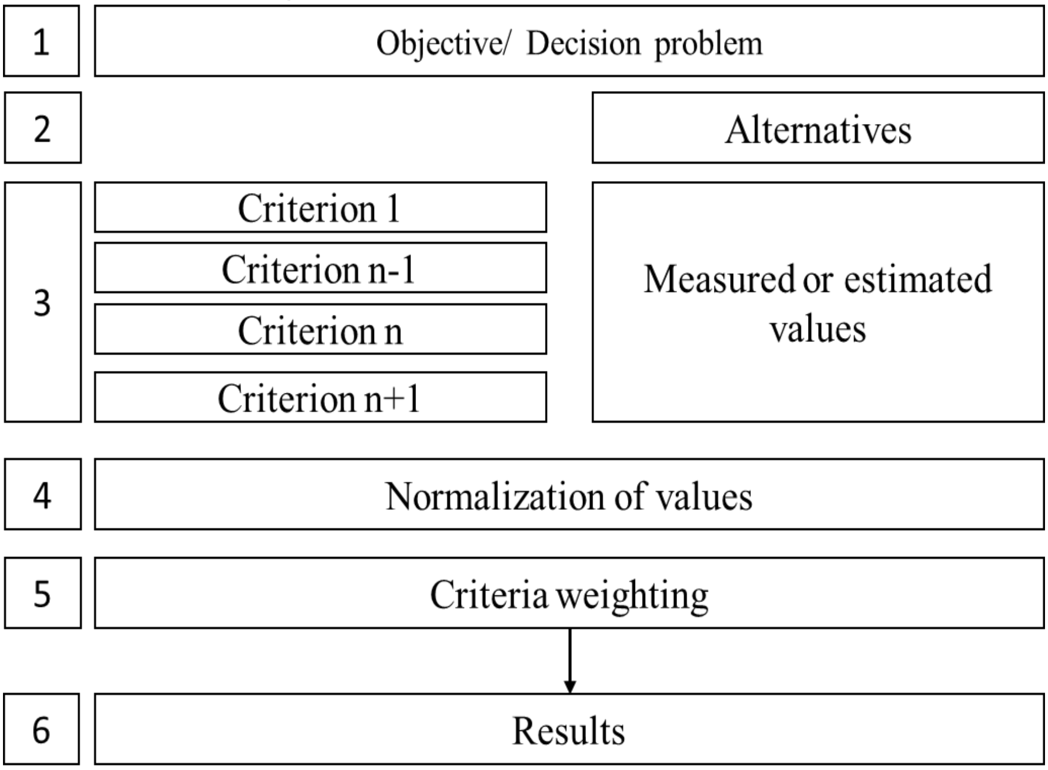

Figure 13. Steps of a Multi-Criteria Decision Analysis

The weightings were calculated as follows. Firstly, the average values of the ratings for each category and criterion were calculated. Afterwards, percentages were calculated. For this purpose, the rating of a criterion is divided by the sum of all criterion ratings assigned to a category. Accordingly, the sum of the criteria weights of a category is always 100%. The same procedure is again applied to the categories. An overview of the procedure and equations is shown in Figure 14.

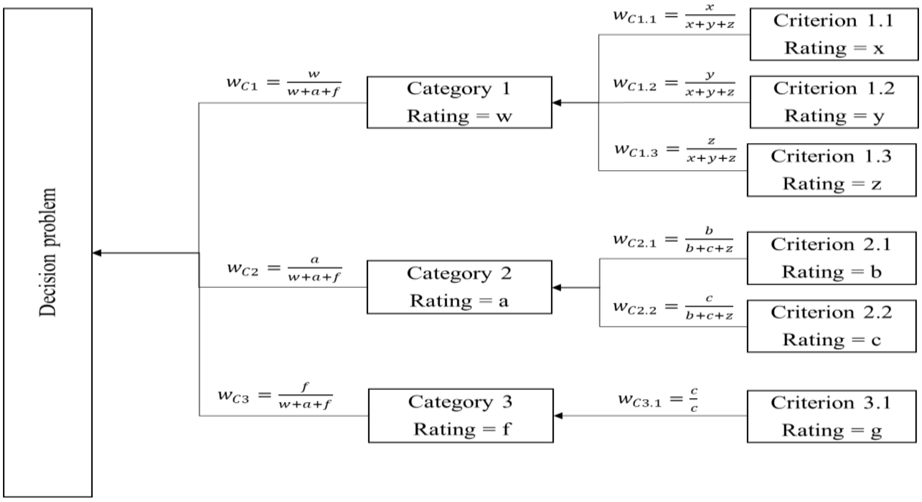

Figure 14. MCDA weighting procedure used in the study

3.1 RESULTS AND DISCUSSION

To make the decision on the best-performing system for hydroponic and aquaponic to be upscaled in the AWESOME pilot facility, main criteria were consumer perspective, producer perspective, ecological goals and system resilience. Then, sub-criteria were hierarchically defined.

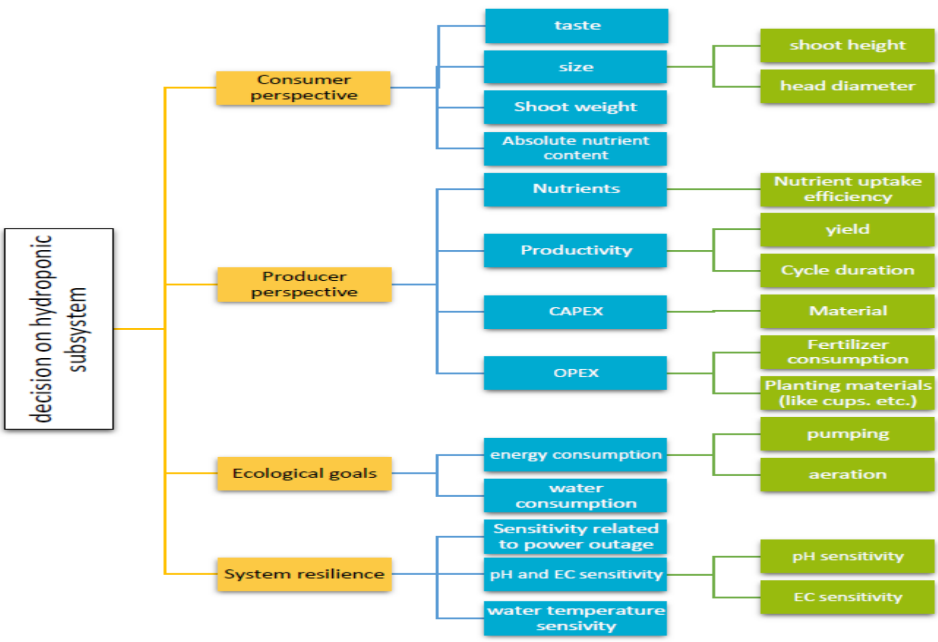

Figure 15. Decision parameters in choice of subsystems

In the survey conducted to determine criterion weights with the participation of 24 individuals, participants prioritized criteria as follows: the highest producer perspective was selected at 26.3%, followed by consumer perspective at 25%, ecological objectives at 24.8%, and system resilience at 23.9%. At the lower hierarchy, water consumption received the highest votes at a rate of 13.06%, followed by energy consumption at 11.72%. From the consumer perspective, the nutritional value of the lettuce had the least influence on decision-making as illustrated Figure 16.

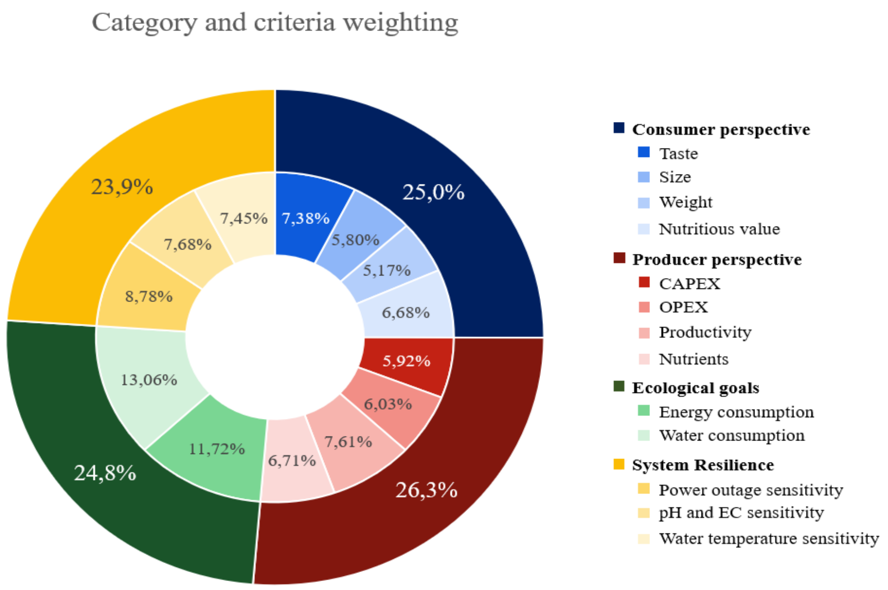

Figure 16. Category and criteria weighting in MCDA

Based on the chosen criterion weights as discussed earlier, it was determined that within the hydroponic concept, the Deep-water culture (DWC) subsystem gained the highest preference score for a narrower plant spacing of 20 x 25 cm. **Concurrently, in the aquaponic concept, the sandponic subsystem (SP) received the highest number of votes for a narrower planting arrangement.** The preference for the DWC subsystem with a narrower plant spacing within the hydroponic setup underlines its alignment with the prioritized criteria, particularly the emphasis on higher production perspectives and ecological objectives. The choice reflects an understanding of the potential benefits of efficient space utilization, increased yields, and optimal resource management. In the context of the aquaponic concept, the preference for the NFT subsystem with a more concentrated planting arrangement indicates the significance of adapting system configurations to stakeholder preferences. This alignment underscores the importance of not only balancing production efficiency and resource conservation but also acknowledging the distinct characteristics of aquaponic systems, where the integration of aquaculture and hydroponics necessitates unique considerations.

These findings collectively demonstrate the intricacies of decision-making in both hydroponic and aquaponic systems. The preferences for specific subsystems and planting spacing emphasize the necessity of considering multiple criteria and perspectives. Furthermore, these outcomes highlight the adaptability of different subsystems to meet the outlined priorities, demonstrating the versatility and potential of these cultivation approaches in addressing varying agricultural demands.

In conclusion, the study's results underscore the significance of tailoring subsystem choices to specific contexts, based on criterion weights derived from a multifaceted evaluation. By understanding and aligning with stakeholder preferences, practitioners can make better decisions that optimize resource usage, enhance production outcomes, and promote sustainability in both hydroponic and aquaponic systems.

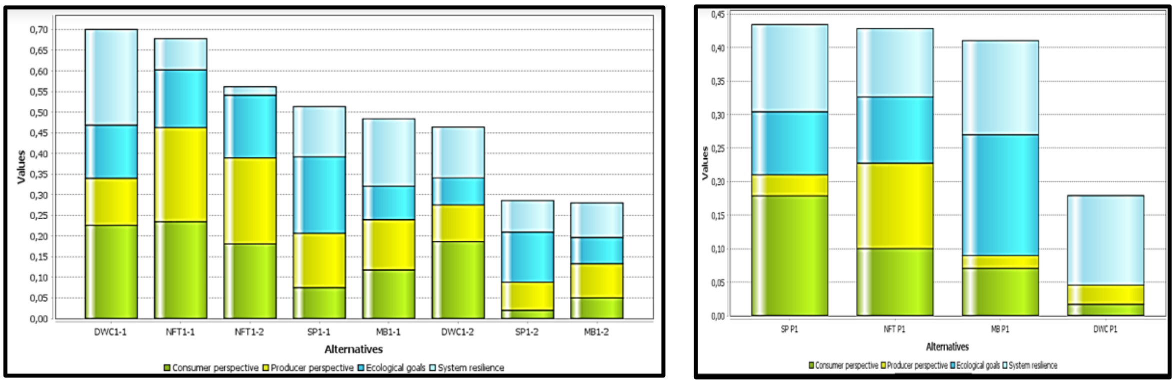

Figure 17. The results of MCDA for hydroponic and aquaponic soilless systems

4. PILOT-SCALE EXPERIMENTS

A pilot-scale system in AWESOME has been developed to assess the feasibility and efficiency of upscaling two distinct subsystems, namely DWC (Deep Water Culture) in a hydroponic context and sandponics within an aquaponic framework. The primary objective of this endeavour is to evaluate the adaptability of these subsystems for mass production and to identify any potential challenges that may arise during the scaling process.

The DWC hydroponic subsystem involves cultivating plants in a nutrient-rich water solution while allowing their roots to be suspended directly in the water. This method maximizes nutrient uptake and encourages rapid plant growth. In the pilot-scale system, multiple DWC units have been established, each equipped with precise nutrient delivery systems, oxygenation mechanisms, and environmental monitoring devices. The subsystem's performance is closely monitored in terms of plant growth rate, nutrient consumption, and water quality parameters. The DWC subsystem's scalability is evaluated based on its ability to maintain consistent and robust plant growth across a larger cultivation area without compromising efficiency.

The sandponic subsystem (SP) integrates the principles of aquaculture and sand-based plant cultivation. This approach involves using sand as the growth medium for plants while utilizing nutrient-rich water from an aquaculture system to irrigate the plants. The pilot-scale SP subsystem includes designated beds filled with high-quality sand, where crops are cultivated. The subsystem incorporates mechanisms for controlled water flow, filtration, and nutrient cycling to optimize plant growth and maintain water quality. The SP subsystem's scalability was assessed by analyzing its capacity to effectively handle increased water flow and nutrient distribution while supporting healthy plant growth at the pilot-scale facility. The SP subsystem is connected to a shared aquaculture unit, completing the aquaponic loop. The aquaculture unit provides nutrient-rich water that is utilized by the SP subsystem, creating a symbiotic relationship where waste products from fish are converted into nutrients for plants, and the plants help filter and purify the water before it returns to the fish tanks.

Throughout the pilot-scale testing, various parameters such as plant growth metrics, water quality parameters (pH, dissolved oxygen, nutrient concentrations), energy consumption, and maintenance requirements were meticulously recorded and analyzed. This data-driven approach allows for a comprehensive assessment of the subsystems' viability for mass production.

By subjecting the DWC subsystem in hydroponic and SP subsystem in aquaponic concept to pilot-scale testing, these initiatives aim to uncover insights into their scalability potential, operational challenges, and performance optimization requirements. The outcomes of this pilot-scale system serve as a proper basis for the existing gap-filling regarding the adaptation of these subsystems for large-scale production within hydroponic and aquaponic contexts. The primary objective of this endeavour is to ascertain the adaptability of these selected subsystems for mass production while identifying any challenges that may arise during the scaling process.
By subjecting the DWC hydroponic and sandponic subsystems to rigorous pilot-scale assessment, this initiative aims to establish a comprehensive foundation for determining their feasibility in large-scale aquaponic production. The knowledge gained can play a pivotal role in informed decision-making for the potential adaptation of these subsystems to meet the demands of mass production within the hydroponic and aquaponics framework.

System specifications

The total dimension of the plant greenhouse is 36.5 x 9 x 4.3 m. The pilot scale system is a plant greenhouse containing two compartments: (i) One hydroponic DWC grow bed, that is divided into three phases, in which plants are grown for 10 days in each phase; plants are transferred from one phase to the next until harvested. Planting spacings for each phase are as follows: Phase 1: 7.5 x 7.5cm, Phase 2: 14.5 x 14.5 cm and Phase 3: 20 x 25 cm. This phasing model enables maximizing the yield per grow area. (ii) Aquaponics systems in the form of three SP grow beds; the lettuce seedlings occupied 33% of grow beds at 10-day intervals. Phases are not possible in this system, as the plants cannot be transferred without damaging the roots before harvesting. Sand media not only acts as supporting media for plants, but it also has filtration properties for fish solid waste. Moreover, it acts as solid media for the attachment of the naturally growing nitrifying bacteria: *Nitrosomonas europaea* and *Nitrobacter sp*. that convert toxic ammonia into nitrites and nitrates that are safer for fish and beneficial for plants. Figure 18 shows the layout of the soilless systems at the pilot facility. The fish greenhouse consists of different fish-rearing tanks that divide fish into three different phases, in which fish are reared for two months in each phase until harvested. The two hydroponics and aquaponics systems are running on continuous water circulation: for the hydroponics system, water flows into the dosing tank that contains sensors connected to a fertigation unit; the unit injects nutrient solution and buffers in the appropriate correct dose according to the system's EC and pH readings.

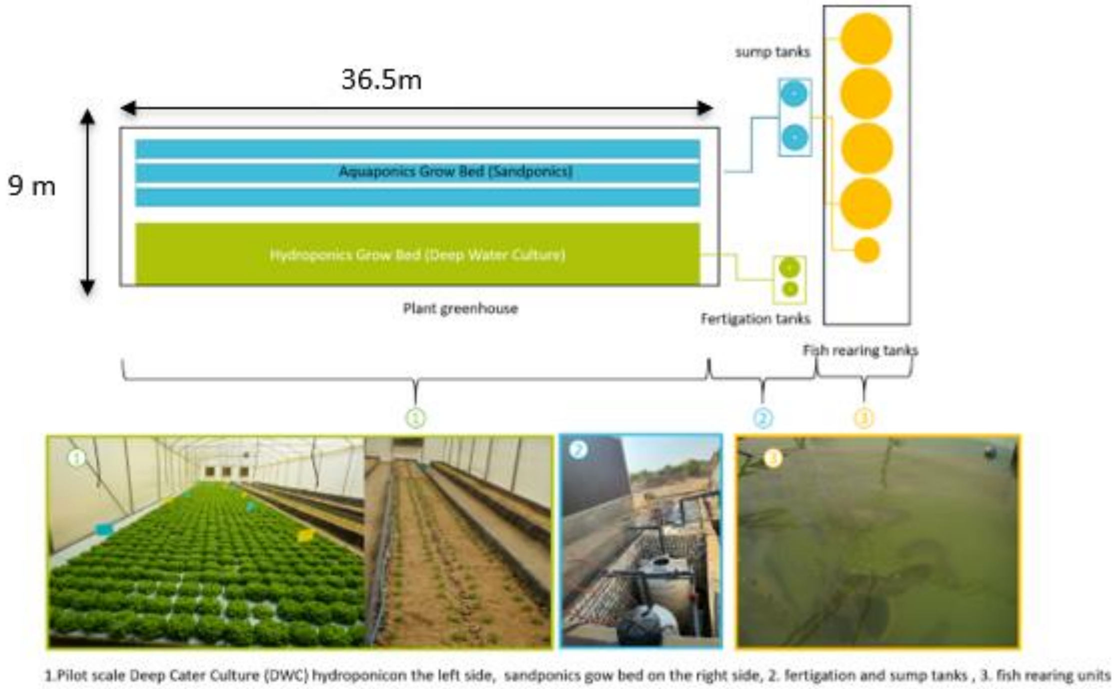

Figure 18. an illustrated schematic view of the pilot-scale greenhouse design, and a layout of the subsystems: (1) Plant Green House, (2) Fertigation and circulation tanks unit, (3) Fish greenhouse and rearing tanks.

Afterwards, the water flows into the -three phases-DWC grow bed and then returns to the dosing tank. As for the aquaponics system, the water filled with nutrients and fish waste exits the fish tanks into the first and then second collection tanks (sumps) where it flows into the three SP tanks, returns to the third collecting tank, then returns to the fish tanks. In aquaponic systems, 3 fish tanks are reared with different sizes of fish separately but connected with each other.

4.1 HIGHLIGHTED RESULTS

Total plant weight

In the pilot-scale facility, 1590 lettuces in hydroponic, and 1630 lettuce in sandponic (aquaponic) systems were cultivated at the same time within one lettuce growth period.

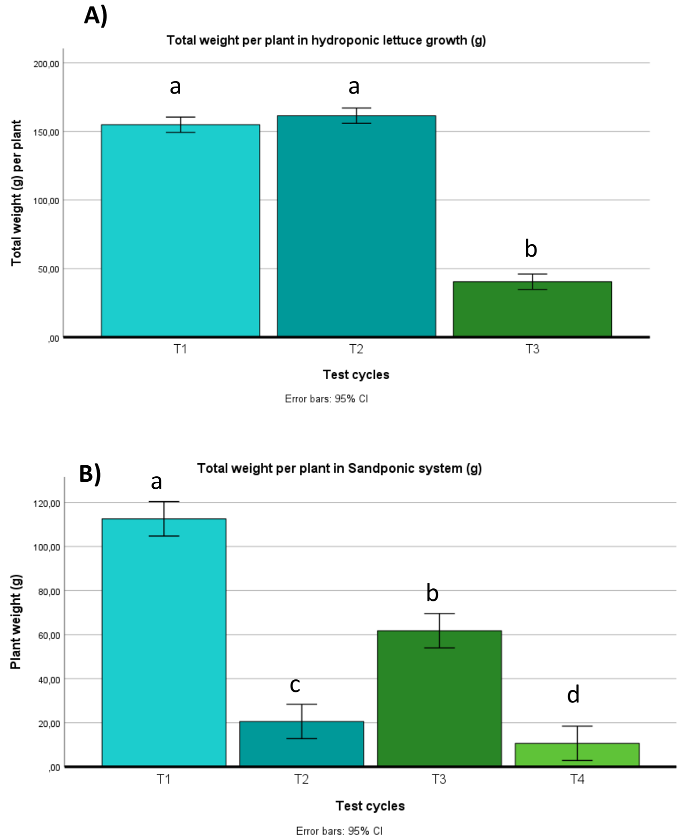

Figure 19. Total plant height per plant (g) in hydroponic (A) and aquaponic (B)

In the hydroponic system, the higher lettuce growth was obtained in T1 and T2 test cycles, 154 g and 161 g, respectively. However, the lettuce growth is reduced in the last test cycle (mean plant weight is 40 g) as shown in Figure 19 A. Similarly, after a successful test cycle of lettuce, the plant pathogens reduced the growth in the aquaponic system (Figure 19b). The highest plant weight was obtained in T1 with 112.5 g, followed by 61.7 in the T3 test cycle, whereas the lowest growth was observed in the T4 test cycle with 10.6 g.

The needed water

During the performance of hydroponic and aquaponic setups, we recorded the needed water for each system for 60 days. As Figure 20 shows, hydroponic systems needed less water (7.01 m^3) than aquaponic systems (29.73 m^3).

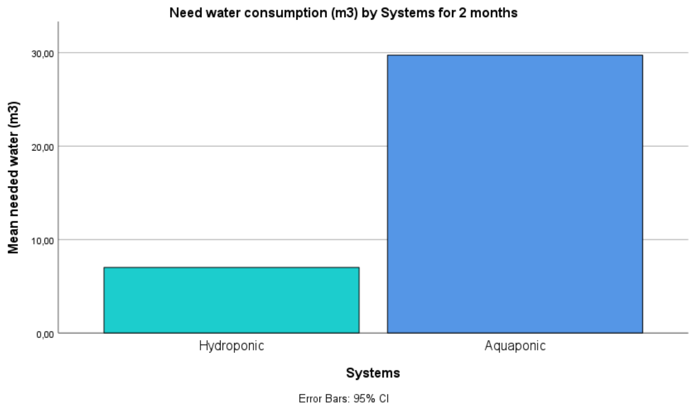

Figure 20. The needed water by systems (m^3) in 60 days.

The food productivity per unit water

In the first month, the experimental running started with 2 fish tanks. Within one month, the gained biomass was measured as 6.81 and 7.47 in tank 1 and 2, respectively. Figure 21 shows the food productivity per unit water (kg/m^3).

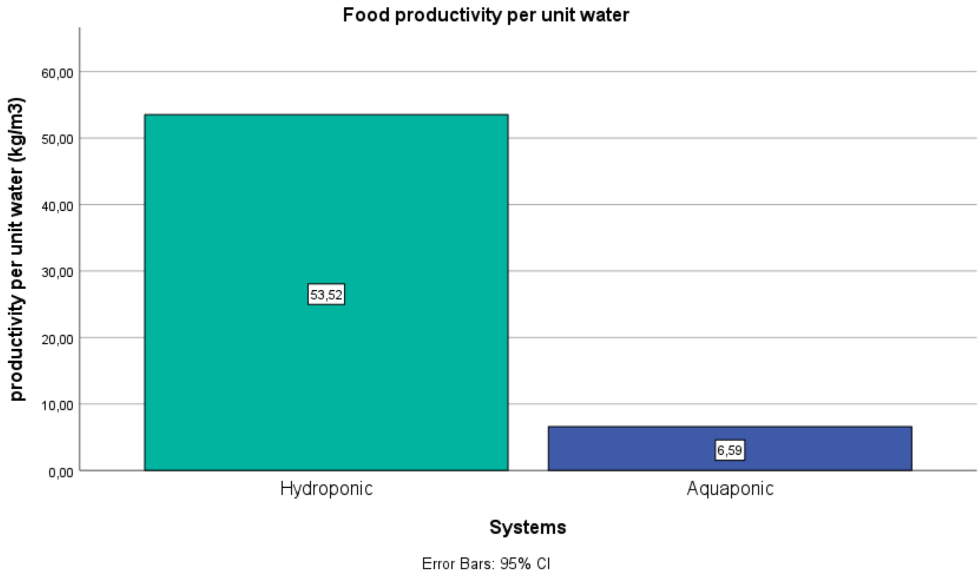

Figure 21. Food productivity per unit water (kg/m^3) in hydroponic and aquaponic.

In hydroponic system, the obtained lettuce growth per unit water was more than 8-fold compared to gained fish biomass and lettuce cultivation in aquaponic systems. The fungal plant pathogens reduced the lettuce growth. However, this reduction was stronger in lettuce from the aquaponic system.

The nutrient value

Table 14 provides a comparison of nutrient values in lettuce grown using hydroponic and aquaponic systems, alongside values obtained from a nutrient database in the literature.
Chlorophyll A and Chlorophyll B content were measured in milligrams per 100 grams (mg/100 g). In the hydroponic system, Chlorophyll A content was recorded at 21.09 mg/100 g, while Chlorophyll B

content was 29.05 mg/100 g. In contrast, the aquaponic system exhibited higher levels with 34.67 mg/100 g of Chlorophyll A and 50.08 mg/100 g of Chlorophyll B. The nutrient database values were 20.53 mg/100 g for Chlorophyll A and 6.44 mg/100 g for Chlorophyll B. Moving to Carotene content, the hydroponic lettuce demonstrated the highest value at 38.6 mg/100 g, while the aquaponic lettuce had a lower value of 21.19 mg/100 g. The nutrient database range for Carotene was 20.4 to 40.6 mg/100 g.

When considering, Vitamin A, the hydroponically grown lettuce contained 0.24 = 799.9 IU (International Units), whereas the grown lettuce in aquaponic contained 0.11 = 366.66 IU. The nutrient database value for Vitamin A was 0.09 = 330 IU. Lastly, for Vitamin C, both hydroponic and aquaponic lettuces had similar values, with 5.59 mg/100 g and 5.8 mg/100 g, respectively. The nutrient database value for Vitamin C was reported as 4.2 ± 0.7 mg/100 g.

In summary, the data suggests that aquaponic cultivation generally yields higher levels of chlorophyll and carotene compared to hydroponic cultivation. On the other hand, hydroponic lettuce tends to contain more Vitamin A than aquaponic lettuce. The values from the nutrient database are largely consistent with the observed nutrient levels in both hydroponic and aquaponic systems.

Table 14- Nutrient value in lettuce grown in hydroponic and aquaponic systems

Nutrient value	Chlorophyll A	Chlorophyll B	Carotene	Vitamin A	Vitamin C
Hydroponic (mg/100 g)	21. 09	29. 05	38.6	0.24 = 799, 9 IU	5.59
Aquaponic (mg/100 g)	34.67	50.08	21.19	0.11=366.66 IU	5.8
Nutrient Data Base from reference (mg/100 g)	20.53	6.44	20.4 -40.6	0.09 =330 IU	4.2 ±0.7
References	Lei & Engeseth (2021)[49]	Lei & Engeseth (2021)[49]	Mou (2005)[50]	Mou & Ryder (2002)[51]	Llorach et al. (2008)[52]

4.2 SUMMARY

In conclusion, the results obtained from the pilot-scale hydroponic and aquaponic lettuce cultivation systems yield several important insights. The highlighted findings emphasize the need for robust plant protection measures and control methods in both systems. The total plant weight measurements revealed fluctuations in growth across different test cycles for both hydroponic and aquaponic setups. While the hydroponic system initially showed promising growth in the first two test cycles, there was a noticeable decline in plant weight during the subsequent cycle. Similarly, the aquaponic system experienced reduced growth following an initially successful test cycle. Notably, this reduction was more pronounced in lettuce from the aquaponic system, indicating heightened vulnerability to plant pathogens. Effective plant protection measures are imperative to counteract the detrimental impact of pathogens on growth and ensure consistent productivity.

Regarding water usage, a significant contrast emerged between hydroponic and aquaponic systems. **Hydroponic systems demonstrated substantially lower water requirements (7.01 m3) over a 60-day period compared to aquaponic systems (29.73 m3).** This underscores the necessity of implementing efficient water management practices, particularly within aquaponics, to optimize water usage and minimize wastage.

The evaluation of food productivity per unit of water involved comparing fish biomass to lettuce growth. **In the aquaponic system,** lettuce growth per unit of water exceeded that of gained fish biomass and lettuce cultivation by **over eight times compared to hydroponic mass production.** However, the presence of fungal plant pathogens hampered this productivity, with a more pronounced adverse effect observed in aquaponic lettuce. Effective disease control strategies are crucial to enhancing and sustaining food productivity in both hydroponic and aquaponic systems.

The nutrient content analysis highlighted variations in chlorophyll, carotene, Vitamin A, and Vitamin C levels between the two cultivation methods, as well as in comparison to values from a nutrient database. Aquaponic cultivation generally led to higher levels of chlorophyll and carotene, while hydroponic lettuce exhibited higher levels of Vitamin A. Vitamin C content remained relatively consistent between the two systems. These disparities underscore the influence of cultivation techniques on nutrient composition and the potential for tailored nutrient enhancement strategies.

To conclude, the outcomes from the hydroponic and aquaponic lettuce cultivation systems underscore the significance of fortified plant protection measures and meticulous control strategies. As both systems display unique challenges and advantages, it is imperative to address pathogen susceptibility and optimize resource usage to achieve sustainable and productive lettuce cultivation. Further investigation and refinement of cultivation practices are essential to ensure the success and viability of both hydroponic and aquaponic systems for lettuce production.

5. CONCLUSIONS

Through our tests of food productivity per unit of water, this report illuminates the efficacy of distinct hydroponic and aquaponic subsystems in addressing the critical challenge of sustainable food production. In the realm of hydroponics, the **DWC subsystem emerged as the champion,** showcasing remarkable efficiency in food productivity per unit of water. Its adept nutrient delivery system and precise environmental control mechanisms translated into consistently higher yields, affirming DWC's potential to be a cornerstone for water-efficient crop cultivation.

Within the aquaponic soilless concept, the Sandponic (SP) subsystem emerged as the superior performer. Though slightly trailing behind the top hydroponic contenders in terms of food productivity per unit of water**, the SP subsystem demonstrated its prowess in integrating fish and plant cultivation symbiotically.** By capitalizing on fish waste as a nutrient source for plants and reciprocating water purification, the **SP subsystem showcased a holistic and resource-efficient approach to sustainable food production**.

The process of Multicriteria Decision Analysis (MCDA) proved tool in steering the selection and evaluation of these subsystems, expertly weighing consumer and producer perspectives, and ecological and system resilience. The findings of MCDA reinforced the importance of context-sensitive decision-making, aligning each subsystem's strengths with the specific priorities and unique considerations at hand.

Pilot-scale experiments validated these conclusions and underscored the real-world scalability of the chosen subsystems. The DWC hydroponic subsystem and the SP subsystem in aquaponic were subjected to comprehensive testing, confirming their potential for large-scale food production while factoring in water consumption and energy efficiency. As a result, the hydroponic (HP) system shows promising reductions in water consumption for lettuce cultivation compared to traditional agriculture. In the lettuce growth, hydroponic systems can save up to **8 times** more water compared to soil-based cultivation, and in the NFT system, during the winter season, water savings can be as much as 10-fold compared to traditional agriculture. Additionally, the potential for multiple cropping cycles in HP systems could significantly increase yields per unit of land area, optimizing land utilization. According to our findings, while in soil-based cultivation, on a 4 square meter area, 90 lettuce plants (spaced at 35 x 45 cm planting spacing) can be grown, hydroponic systems can accommodate the growth of 150 lettuce plants. Furthermore, lettuce grown in soil may take anywhere from 45 to 90 days to mature, whereas in soilless farming, they can be harvested in just 28 days. This also means that when **year-round production is carried out on the same unit area, at least a 5-fold increase in yield is achieved.**

In Aquaponic experiments, we chose the Nile Tilapia, since it has resistance to diseases and can a large range of water temperature can tolerate. In the Aquaponic (AP) sub-system, diversifying fish species holds the potential for enhanced system resilience and meeting broader market demands, though careful research is crucial to determine the most suitable species for integration.

For policy-makers and potential investors, these findings offer valuable insights for informed decision-making. We propose a multi-faceted approach, including the promotion of hydroponic (HP) systems to optimize water usage and land efficiency, as well as allocating resources towards research and development in aquaponics. Establishing robust regulatory frameworks, providing economic incentives, and encouraging market diversification in aquaponics products are further recommendations to advance sustainable and efficient agricultural practices in both hydroponic (HP) and aquaponic (AP) systems.

In summary, this study not only underscores the viability of hydroponic and aquaponic cultivation techniques but also emphasizes the importance of tailored approaches. The DWC subsystem excelled within hydroponics, showcasing its potential for efficient water usage and bountiful yields. Similarly, the SP subsystem, thriving within aquaponics, demonstrated an integrated and resource-efficient methodology. By embracing these innovative systems, we move closer to a future where sustainable food production, optimized water utilization, and environmental harmony converge in unison.

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