AWESOME

WATER-ECOSYSTEM-FOOD

UPSCALING THE POTENTIAL OF SOILLESS TECHNOLOGIES

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Table of Content

LIST OF ACRONYMS

Abbreviations

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

EXECUTIVE SUMMARY

Deliverable 5.3 presents a comprehensive analysis of the economic and spatial factors critical to the successful scaling of hydroponic and aquaponic technologies. This analysis is based on the results obtained from experiments conducted at both lab-scale and pilot-scale within the state-of-the-art AWESOME test facilities.

The lab-scale experiments focused on two hydroponic trials, centring on optimal planting spacing for lettuce cultivation. Additionally, an aquaponic experiment integrating Nile tilapia aquaculture was conducted, highlighting the importance of planting spacing for lettuce growth. Moving to the pilot-scale, the study examined the feasibility of mass-producing lettuce, a key leafy vegetable.

Furthermore, the report underscores the potential of soilless systems as a sustainable alternative to new land reclamation in addressing food production challenges. By reducing the reliance on traditional soil-based agriculture, these technologies offer a promising solution to bridge the food gap.

Moreover, the report explores avenues for local manufacturing and automation integration. Establishing production facilities for critical components and implementing specialized monitoring devices can enhance system efficiency, reduce dependence on imports, and stimulate regional economic growth.

In conclusion, this deliverable provides a comprehensive overview of the potential for scaling hydroponic and aquaponic technologies. Through rigorous experimentation and economic analysis, valuable insights have been gained into their feasibility, efficiency, and economic viability. These findings serve as a crucial resource for stakeholders and decision-makers in the agricultural industry, offering a sustainable path forward in modern agriculture.

1. INTRODUCTION

Deliverable 5.3 is focusing on upscaling opportunities and specifics and entails a comprehensive report detailing the economic and spatial considerations essential for the successful extension of hydroponic and aquaponic technologies. It also provides an outlook on potential opportunities for local manufacturing and automation.

Hydroponics and aquaponics are innovative soilless cultivation techniques. Hydroponic systems represent a forward-thinking approach to plant cultivation, devoid of traditional soil usage. Instead, plants receive vital nutrients directly through their roots from a nutrient-rich water solution. This method confers distinct advantages over conventional soil-based agriculture. Precise control over nutrient levels ensures optimal growth conditions, while water usage is significantly reduced thanks to efficient recirculation. Moreover, hydroponics can be implemented under compact spaces, even vertically, making it particularly suitable for urban environments with limited arable land. The absence of soil minimizes the prevalence of common pests and diseases, leading to healthier and more robust plant growth. Furthermore, with the right environmental controls, hydroponic systems enable year-round cultivation, mitigating the impact of seasonal fluctuations[1–3].

In contrast, aquaponic systems represent a harmonious integration of aquaculture and hydroponics. This sustainable agricultural model involves cultivating aquatic animals, such as fish, alongside hydroponically grown plants. Fish waste serves as an organic nutrient source for the plants, while the plants reciprocate by acting as natural filters, purifying the water before it returns to the fish tank. This symbiotic relationship yields a range of benefits. Nutrient recycling is a central feature, as fish waste is continuously repurposed, creating a self-sustaining ecosystem. Additionally, the efficiency and productivity of aquaponics surpass standalone aquaculture or hydroponic systems. The model's reduced water consumption and waste production contribute to a smaller environmental footprint compared to traditional farming methods. The versatility of aquaponic systems allows for the cultivation of various plants and fish species, resulting in a diverse array of produce. Its inherent sustainability and adaptability make aquaponics a viable solution for urban settings and regions with limited access to arable land, such as in dry coastal belts and deserts[4–6].

Nonetheless, in the soilless cultivation systems under consideration, display a dual nature, presenting both an advantage and a challenge. This duality arises from the necessity to finely manipulate a multitude of influencing factors, which is vital for realizing the yield potential of plants grown in soilless systems. However, this task is intricately linked with the crucial requirement of providing a technically proficient system for regulating factors and maximizing year-round production, which includes factors such as growing season and planting density[7–9]. As a result, the commercialization of hydroponic and aquaponic systems is met with substantial hurdles[10]. These hurdles are primarily characterized by significant upfront investments and the critical need to acquire profound insights into the optimization of these cultivation systems for mass production. Soilless systems prompt contemplation that operational expenditures typically surpass those associated with traditional agriculture. This arises from the notably heightened energy demands, the increased necessity for precise measuring and regulating instrumentation, and the obligatory inclusion of maintenance expenses in the overall calculation[11–13]. Furthermore, establishing market demand and distribution channels, ensuring compliance with local regulations and zoning requirements, and addressing potential scepticism or unfamiliarity among traditional agriculture stakeholders are among the hurdles to be overcome[14]. Achieving economies of scale and effectively managing supply chain logistics can be complex in these specialized systems. Balancing these considerations while striving for profitability underscores the intricate nature of commercializing hydroponic and aquaponic technologies. The primary goal of this report is to assess economic and spatial factors influencing the scalability of hydroponic and aquaponic systems. Furthermore, it aims to evaluate prospects for local manufacturing and automation integration. In section 2, the lab and pilot-scale experiments were briefly reported as methodology. Economic factors and spatial considerations are presented in sections 3 and 4, respectively. It is followed by section 5 which demonstrates local manufacturing opportunities and the automation potential of soilless systems. Lastly, we concluded our work in section 6.

2. METHODOLOGY AND EXPERIMENTATION

The lettuce (*Lactuca sativa*), which is one of the leafy vegetables and can easily be grown in soilless systems, is tested in the AWESOME test facility [15]. The aquaponic experiment centred on utilizing Nile tilapia (*Oreochromis niloticus*) as aquaculture to nourish lettuce growth.

2.1 EXPERIMENTAL DESIGN

In AWESOME test facilities, special attention is directed towards specific subsystems commonly utilized in hydroponics, namely Deep Water Culture (DWC), Nutrient Film Technique (NFT), Media-bed system (MB), and Sandponic (SP). These hydroponic subsystems were subjected to testing within the context of an aquaponic environment. Additionally, comparisons were made between soil-based cultivation (SC) and Integrated Vegetable Aquaculture (IVA) using various hydroponic subsystems in laboratory-scale aquaponic experiments. Employing Multi-Criteria Decision Analysis (MCDA) based on the outcomes of these experiments, the most effective hydroponic subsystems were identified. Subsequently, the most successful hydroponic and aquaponic configurations for large-scale lettuce production were put to the test in the AWESOME pilot testing facilities as Figure 1.

2.1.1 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 test planting spacing for both hydroponic and aquaponic systems, (4) to investigate the adaption of subsystems with seasonal nuances under different growing seasons, and (5) to compare the crop outcomes from soilless with soil-based cultivation under closed greenhouse conditions.

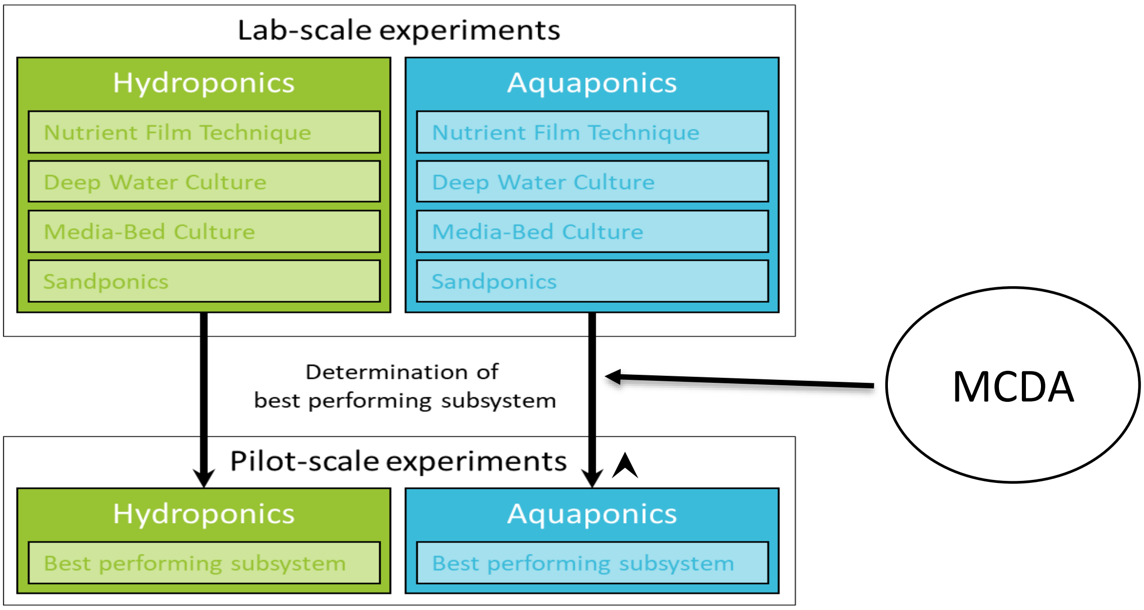

Figure 1 – Hierarchical experimental flow in the AWESOME test facilities

Lab-scale experiments comprise of three trials (two hydroponic experiments and one aquaponic experiment). In the hydroponic experiments, the interaction between hydroponic subsystems and plant spacing for lettuce growth were tested as Table 1 shows. The same variations were tested in aquaponic concept. Planting spacing variations were explored to ascertain the most conducive arrangement for optimal results. In the final trial, the adaptation of subsystems to the growing seasons was investigated in hydroponically grown lettuces. The system specifications and technical details of both soilless systems are submitted in D5.1. The moreover, all experimental steps and outputs are presented in D5.2.

Table 1 – The detailed list of experimental design with treatments in lab-scale facility

Soilless systems	Experiments	Treatments
Hydroponic	Planting spacing and hydroponic subsystems	**Cultivation systems:** DWC, NFT, MB, SP **Planting spacings:** 20 X 25 and 24X25 cm
Aquaponic	Planting spacing and hydroponic subsystems	**Cultivation systems:** DWC, NFT, MB, SP, IVA and SC. **Planting spacings:** 20 X 25 and 24X25 cm

Tested cultivation systems: DWC: Deep water culture, NFT: Nutrient Film Technique, MB: Media-bed system, SP: Sandponic, Integrated Vegetable Aquaculture (IVA) and SC: Soil Cultivation.

In hydroponic experiments, Deep water culture (DWC), Nutrient Film Technique (NFT), Media-bed system (MB), and Sandponic (SP) subsystems were tested for lettuce growth, as Figure 2 shows.

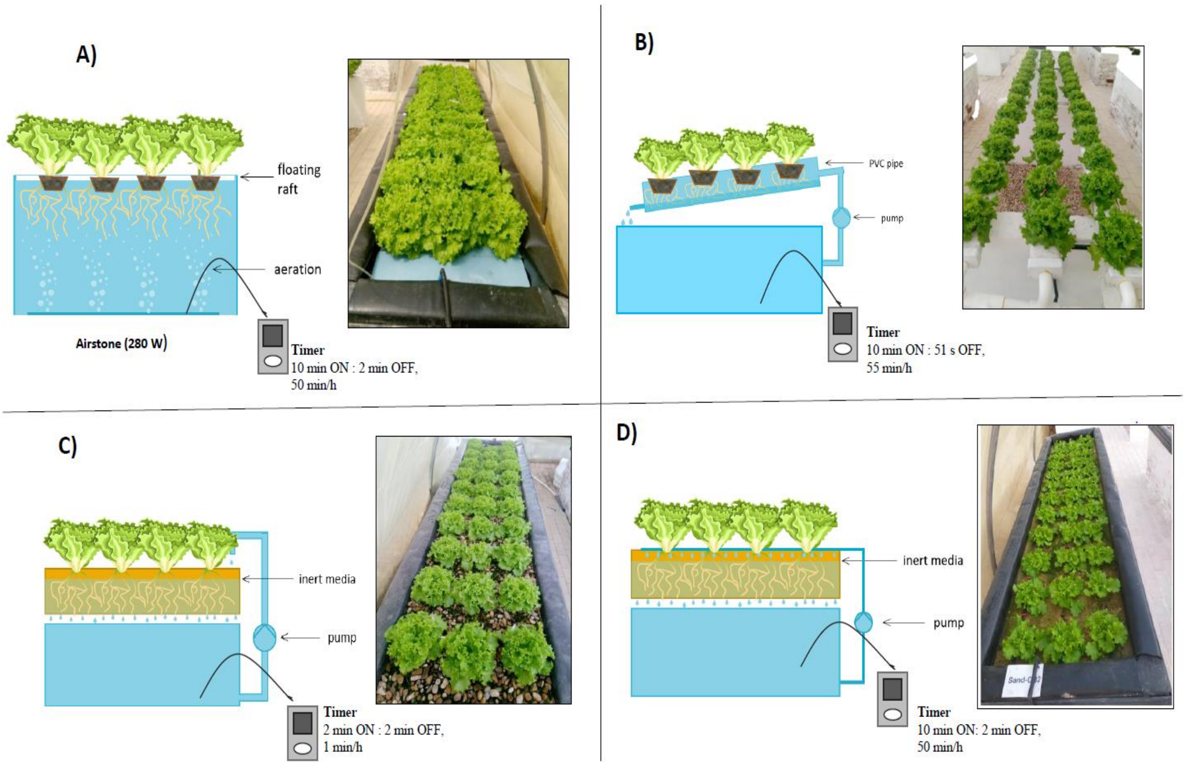

Figure 2. The various closed hydroponic sub-systems tested for lettuce growth. These systems: (A)- DWC: Deep Water Culture, (B)- NFT: Nutrient Film Technique, (C)- MB: Media- Bed system and (D)- SP: Sandponic

The number of transplanted lettuces is kept the same in aquaponic experiments. Figure 3 shows the general components of the aquaponic experiment. In addition to the above- mentioned hydroponic subsystems, Integrated Vegetable Aquaculture (IVA) and Soil cultivation (SC) were compared for lettuce growth.

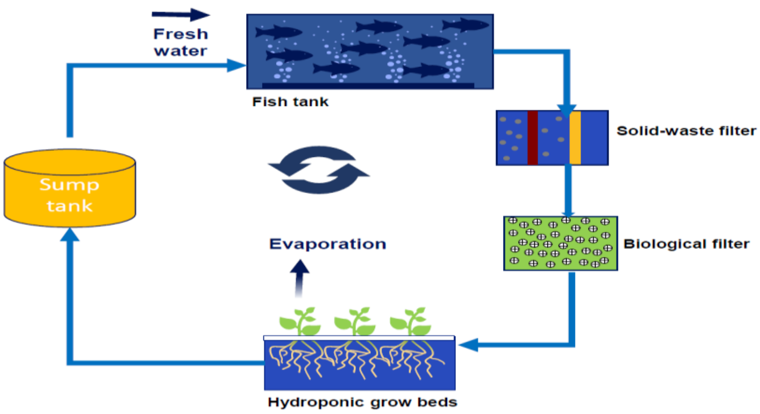

Figure 3. The components of the one-loop closed aquaponic systems, which is the combination of hydroponics and aquaculture.

In this soilless cultivation technique, Media-bed systems with gravel (MB) and sand (SP) can serve as biological and mechanical filters without adding them as shown Figure 4A. In the IVA system, nutrient-rich wastewater from flow-through aquaculture is used to irrigate and fertilize crops in soil as illustrated in Figure 4B.

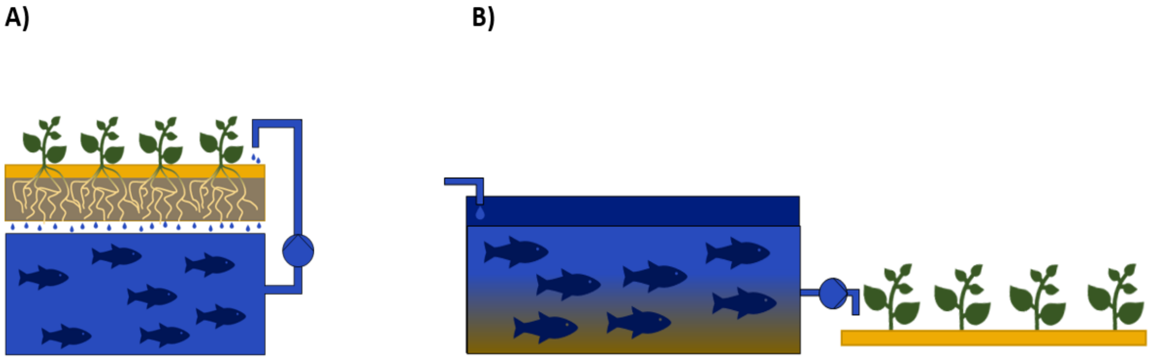

Figure 4. A- Aquaponic system design with media without adding any mechanical and biological filter (MB and SP), B- and Integrated Vegetable Aquaculture (IVA) design.

2.1.2 Pilot Scale Experiments

The pilot-scale experiments in AWESOME have been conducted to assess the feasibility and efficiency of upscaling two distinct subsystems: DWC (Deep Water Culture) in hydroponics and sandponics within an aquaponic setup (Figure 5). The primary goal is to evaluate their adaptability for mass production and identify potential challenges during scaling.

The DWC hydroponic subsystem involves suspending plant roots directly in a nutrient-rich water solution, maximizing nutrient uptake and encouraging rapid growth. Multiple DWC units equipped with precise nutrient delivery, oxygenation, and environmental monitoring systems were established in the pilot-scale system. Performance is closely monitored for growth rate, nutrient consumption, and water quality. Scalability is evaluated based on maintaining consistent and robust growth across a larger area.

The sandponic subsystem (SP) integrates aquaponics and sand-based plant cultivation, using nutrient-rich water from an aquaculture system to irrigate plants grown in sand beds. The SP subsystem is equipped with mechanisms for controlled water flow, filtration, and nutrient cycling. Scalability is assessed by analyzing its capacity to handle increased water flow and nutrient distribution while supporting healthy plant growth.

Both subsystems are integrated into a shared aquaculture unit, forming a closed-loop aquaponic system. Fish waste provides nutrients for plants, and plants filter and purify the water for the fish. Comprehensive data is collected, including plant growth metrics, water quality parameters, energy consumption, and maintenance requirements, allowing for a thorough assessment of scalability. By subjecting the DWC and SP subsystems to pilot-scale testing, this initiative aims to establish a foundation for determining their feasibility in large-scale aquaponic production. The knowledge gained will inform decisions regarding the potential adaptation of these subsystems for mass production in hydroponic and aquaponic contexts.

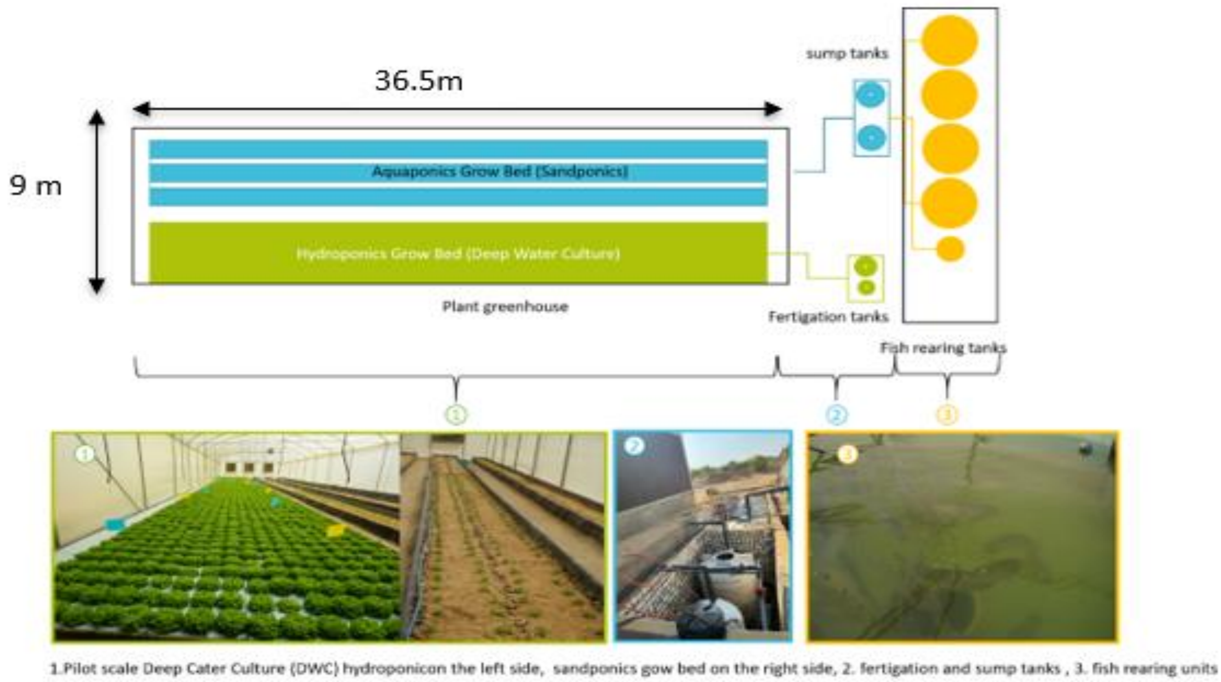

Figure 5. An illustrated schematic view of the pilot-scale greenhouse design, and a layout of the subsystems: (1) Plant Green House, (2) Fertigation and circulation tanks unit, (3) Fish greenhouse and rearing tanks.

2.2 DATA COLLECTION AND ANALYSIS

Prior to the initiation of all experiments, detailed records of the investment costs incurred in each enlargement system were meticulously maintained. This encompassed both laboratory and pilot-scale trials. Furthermore, precise quantifications of the seeds, fertilizers, and fish feed utilized throughout the experimental phases were meticulously documented. In addition to these parameters, the quantities of water introduced into the system and the corresponding energy expenditures were systematically recorded.

For yield of lettuce in each experimental test, all statistical analyses were conducted using SPSS Statistics 29 (IBM Software, Chicago, USA). 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. Probabilities of significance among treatments and LSD ($P \leq 0.05$) were used to compare means among treatments.

3. SPATIAL CONSIDERATIONS

Spatial considerations play a pivotal role in the successful upscaling of hydroponic and aquaponic technologies. This section delves into the intricate details of the spatial requirements essential for accommodating larger-scale production systems. In 2017, land rental rates for agricultural purposes exhibited a range from USD 158 to 317 per acre annually. Conversely, the rental fee for utilizing the AWESOME test facility stood at 700 euros per acre. It is worth noting that these rates are applicable to traditional agricultural lands and those designated for soilless cultivation. The distinguishing factor lies in the fact that soilless systems do not necessitate specific land qualities. They can be implemented on terrains characterized by rockiness, salinity, or any type of land unsuitable for conventional agricultural production[16].

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 under different planting spacings, and (4) to compare the crop outcomes from soilless with soil-based cultivation under closed greenhouse conditions.

In the lab experiment, we tested the lettuce growth and yield interaction between different subsystems of hydroponics and different planting densities as well and we tested the same interaction in an aquaponic context. 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 experiments, whereas 72 plants were cultivated in aquaponic experiments by maintaining the fish stoking density stable.

We hypothesized that the leaf yield of lettuce per unit area increases with increased plant density, while leaf yield per plant decreases with increasing plant density. Table 2 shows the yield of lettuce grown in narrow and larger plating spacing for both hydroponic and aquaponic experiments at lab-scale level.

Table 2 – The yield of lettuce grown from several cultivation systems under 2 different planting spacing for hydroponic and aquaponic experiments

Hydroponic experiment				Aquaponic experiment			
Treatments	**CS**	**Number of plants**	**Shoot fresh mass per plant (g)**	**Treatments**	**CS**	**Number of plants**	**Shoot fresh mass Per plant (g)**
Narrow spacing 20x25 cm	DWC	108	160.63 ± 37.01[a]	Narrow spacing 20x25 cm	DWC	72	109.03 ± 4.76[c]
	NFT	135	165.28 ± 25.14[a]		NFT	72	126.64 ± 4.76[b]
	MB	108	100.94 ± 9.54[b]		MB	72	77.11 ± 4.76[d]
	SP	108	78.61 ± 14.76[b]		SP	72	142.31 ± 4.76[a]
	IVA	0	-		IVA	72	10.17 ± 5.83[e]
	SC	0	-		SC	72	21.19 ± 4.76[e]

Larger spacing 24x25 cm	DWC	72	204.64 ± 24.77^{a}	Larger spacing 24x25 cm	DWC	72	136.31 ± 4.76^{a}
	NFT	90	189.28 ± 19.93^{a}		NFT	72	105.03 ± 4.76^{b}
	MB	72	87.17 ± 23.23^{b}		MB	72	68.64 ± 4.76^{c}
	SP	72	51.29 ± 14.45^{c}		SP	72	145.50 ± 4.76^{a}
	IVA	0	-		IVA	72	12.75 ± 5.83^{d}
	SC	0	-		SC	72	16.17 ± 4.76^{d}

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. 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

In the soilless systems and IVA, lettuce cultivation was conducted within an area of 5.76 m^2, while soil-based cultivation necessitated a twofold larger land area of 12 m^2. Among hydroponically grown lettuce, the highest shoot mass per plant was recorded in the NFT and DWC systems with extensive planting spacing. In the aquaponic systems, the lettuce shoot mass derived from the SP system surpassed that of other systems across both planting spacings. Nevertheless, the optimal lettuce yield per unit area was achieved under narrow planting spacing conditions, particularly within hydroponic systems**.**

Pilot Scale Experiments

In the AWESOME test facility, pilot-scale experiments have been conducted to assess the feasibility and effectiveness of scaling up two distinct systems: DWC (Deep Water Culture) in a hydroponic setting (HP) and sandponic in an aquaponic context (AP). These subsystems were selected based on the outcomes of Multicriteria Decision Analysis (MCDA). The primary objective of this endeavour is to evaluate how well these subsystems can be adapted for large-scale production and to identify any potential challenges that may arise during the scaling-up process.

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. Table 3 shows the land use and properties of grow beds in hydroponic and aquaponic experiments in pilot scale.

Table 3 – The land use and properties of grow beds in hydroponic and aquaponic experiments in pilot-scale

Hydroponic growth		Aquaponic growth	
Characteristics	**Properties**	**Characteristics**	**Properties**
Subsystem	DWC	Subsystem	Sandponics
Number of grow beds (based on growth phases)	3	Number of grow bed	3
Cultivation area/system	Phase 1: 9.4 m^2 Phase 2: 36.4 m^2 Phase 3: 90.4 m^2	Grow bed area	Grow bed 1: 0.6x34 = 20.4 m^2 Grow beds 2 and 3: 1x34= 34 m^2, total: **88.4 m^2**
Numbers of plants to be transplanted	1590 per phase	Numbers of plants to be transplanted	1630
Plant spacing	Phase 1: 7.5 cm x 7.5 cm Phase 2: 14.5 cm x 14.5 cm Phase 3: 20 cm x 25 cm	Aquaculture Greenhouse	6 x 25 x3 m (Length x Width x Height), **total 150 m^2**
Total needed land:	136.2 m^2	**Total needed land:**	238.4 m^2
Annual cost for the land	23.59 €	**Annual cost for the land**	41.23 €
Total yield for a month	1590 *157.5=250.4 kg	**Total yield for a month**	1630*112=182.56 kg
Total yield for a year	3005.1 kg	**Total yield for a year**	2190.72

In the pilot-scale facility, a total of 1590 lettuces were cultivated in the hydroponic system, and 1630 lettuces were grown in the sandponic (aquaponic) system simultaneously, within a single lettuce growth period. The annual rental cost for 1 acre (4046.86 m^2) is 700 €. Consequently, the yearly expenditure for the utilized land amounts to 23.59 € in the hydroponic system and 41.23 € in the aquaponic system.

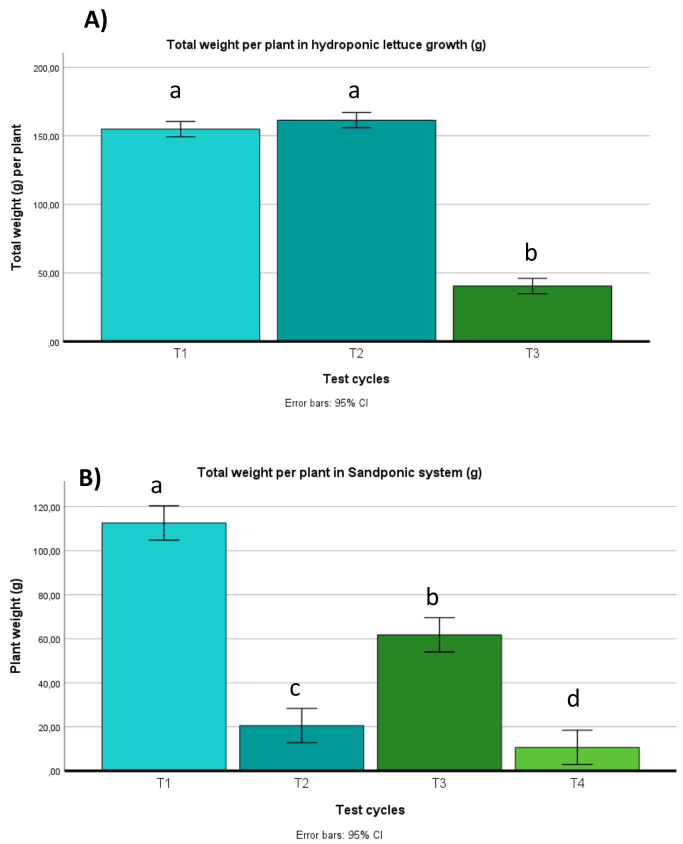

Figure 6. Total plant height per plant (g) in hydroponic (A) and aquaponic (B)

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 6 A. Similarly, after a successful test cycle of lettuce, the plant pathogens reduced the growth in the aquaponic system (Figure 6b). 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 hydroponic systems yielded a total of 250.4 kg of lettuce per month, whereas the aquaponic system exhibited a potential yield of 182.56 kg. On an annual basis, the hydroponic system produced 3005.1 kg of lettuce, while the aquaponic system yielded 2190.72 kg.

4. ECONOMIC FACTORS

This section provides an overview for the analysis on economic feasibility of hydroponic and aquaponic systems in terms of capital and operational expenditure costs by assessing the upscaling the lab-scale experiments to the pilot-scale study. Moreover, the return on investment is calculated based on lettuce yield with different scenarios.

4.1. ECONOMIC FEASIBILITY ANALYSIS

The Economic Feasibility Analysis is a crucial component of the assessment process, aiming to provide a comprehensive evaluation of the financial viability of upscaling aquaponics and hydroponics technologies. This analysis delves into both capital and operational expenditure costs associated with the transition from lab-scale modules to pilot-scale implementation.

Conventional agriculture's costs, both initial (CAPEX) and ongoing (OPEX), are variable on factors such as land location, condition, soil quality, and water availability for irrigation. Land fertility directly impacts land prices, influencing both CAPEX and OPEX. Location, whether for ownership or rental, significantly affects land pricing. The use of chemical fertilizers and soil conditioners escalates OPEX. Proximity to water sources affects land prices, with lands near running water being pricier. For lands without direct access to water sources, owners must invest in water wells, incurring a CAPEX of over USD 5500. Water salinity and well maintenance further impact OPEX. Additionally, the costs of drip irrigation network installation and maintenance should be factored into CAPEX and OPEX calculations for reclaimed lands[16].

4.1.1 Initial Set-up Costs (Capital expenditure costs- CAPEX)

This segment scrutinizes the initial investment required for the upscaling process. It encompasses an itemized breakdown of expenses covering infrastructure development, acquisition of essential equipment, and any specialized components needed for the larger-scale operation. Additionally, it conducts a comparative analysis with traditional farming methods to ascertain the cost-effectiveness and potential savings these modern technologies can offer.

Lab-Scale Experiments

Lab-scale experiments consist of hydroponic and aquaponic test cycles. Table 4 presents the capital expenditure costs (CAPEX) for various hydroponic subsystems and soil-based cultivation methods. The data is provided in euros (€), and offers a detailed breakdown of expenses, including plumbing, tanks, interlock, and electricity tools. Notably, plumbing and tanks represent a significant expense, totalling €1500.49, with fairly equal distribution across grow bed types. This indicates that initial investment costs are relatively consistent across the different cultivation methods. Understanding these CAPEX figures is crucial for making informed decisions regarding the upscaling process, ensuring a balanced allocation of resources for each subsystem.

The lowest initial cost in soil-based cultivation is recorded as expected whereas the DWC subsystem needed more capital investment due to more components such as the aeration pump, foam.

Table 4 – Capital expenditure costs (CAPEX) for hydroponic subsystems and soil-based cultivation

Item	Total cost	Quantity for grow beds (n)					Individual costs for grow beds (€)				
Item	**Total cost (€)**	**Soil**	**NFT**	**DWC**	**SP**	**MB**	**Soil**	**NFT**	**DWC**	**SP**	**MB**
Plumbing and tanks	1500.49	1	1	1	1	1	300.10	300.10	300.10	300.10	300.10
Interlock	230.54	1	1	1	1	1	46.11	46.11	46.11	46.11	46.11
Interlock building fees	76.97	1	1	1	1	1	15.39	15.39	15.39	15.39	15.39
Electricity tools	908.25	1	1	1	1	1	181.65	181.65	181.65	181.65	181.65

Electricity board	113.92	1	1	1	1	1	22.78	22.78	22.78	22.78	22.78
Growing beds	615.76	0	0	1	1	1	0	0	205.25	205.25	205.25
Building fees	206.28	1	1	1	1	1	41.26	41.26	41.26	41.26	41.26
Air curtain	31.56	1	1	1	1	1	6.31	6.31	6.31	6.31	6.31
Plastic for grow beds	105.51	0	0	1	1	1	0	0	35.17	35.17	35.17
Cooling system	768.23	1	1	1	1	1	153.65	153.65	153.65	153.65	153.65
Greenhouse body	1381.25	1	1	1	1	1	276.25	276.25	276.25	276.25	276.25
DWC Aeration pump	74.66	0	0	1	0	0	0	0	74.66	0	0
NFT pipes	51.42	0	1	0	0	0	0	51.42	0	0	0
Foam (m^2)	70.94	0	0	5.76	0	0	0	0	70.94	0	0
Gravel media(m^3)	61.58	0	0	0	0	1	0	0	0	0	61.58
Sand media(m^3)	92.36	0	0	0	1	0	0	0	0	92.36	0
				Total cost			1037.19	1088.61	1423.21	1369.97	1339.19

DWC: Deep water culture, NFT: Nutrient Film Technique, MB: Media-bed system, SP: Sandponic, and SC: Soil Cultivation

Table 5– Capital expenditure costs (CAPEX) for hydroponic subsystems in aquaponic context, IVA and soil-based cultivation

Item	Cost (€)	Amount for shared grow beds						Total Cost for shared grow beds (€)					
		DWC	**NFT**	**MB**	**SP**	**SC**	**IVA**	**DWC**	**NFT**	**MB**	**SP**	**SC**	**IVA**
Plumbing and Tanks	1500.49	1	1	1	1	1	1	250.08	250.08	250.08	250.08	250.08	250.08
Interlock	230.54	1	1	1	1	1	1	38.42	38.42	38.42	38.42	38.42	38.42
Interlock Building fees	76.97	1	1	1	1	1	1	12.83	12.83	12.83	12.83	12.83	12.83
Electricity Tools	908.25	1	1	1	1	1	1	151.38	151.38	151.38	151.38	151.38	151.38
Electricity Board	113.92	1	1	1	1	1	1	18.99	18.99	18.99	18.99	18.99	18.99
Growing beds	615.76	1	0	1	1	0	0	205.25	0	205.25	205.25	0	0
Building fees	206.28	1	1	1	1	1	1	34.38	34.38	34.38	34.38	34.38	34.38
Air curtain	31.56	1	1	1	1	1	1	5.26	5.26	5.26	5.26	5.26	5.26
Growbeds Plastic	105.51	1	0	1	1	0	0	35.17	0	35.17	35.17	0	0
Cooling system	768.23	1	1	1	1	1	1	128.04	128.04	128.04	128.04	128.04	128.04
Greenhouse body	1381.25	1	1	1	1	1	1	230.21	230.21	230.21	230.21	230.21	230.21
DWC Aeration pump	74.66	1	0	0	0	0	0	74.66	0	0	0	0	0
NFT Pipes	51.42	0	1	0	0	0	0	0	51.42	0	0	0	0
Fish tanks+ pumps+sumps	1015.09	1	1	1	1	0	1	203.02	203.02	203.02	203.02	0	203.02
Fish	246.31	1	1	1	1	0	1	49.26	49.26	49.26	49.26	0	49.26
Biofilter	87.38	1	1	0	0	0	0	43.69	43.69	0	0	0	0

Plumbing fish greenhouse	350.89	1	1	1	1	0	1	70.18	70.18	70.18	70.18	0	70.18
ELECTRICITY tools	220.29	1	1	1	1	0	1	44.06	44.06	44.06	44.06	0	44.06
Generator	316.59	1	1	1	1	0	1	63.32	63.32	63.32	63.32	0	63.32
Airpump	61.58	1	1	1	1	0	1	12.32	12.32	12.32	12.32	0	12.32
Building fees	183.19	1	1	1	1	0	1	36.64	36.64	36.64	36.64	0	36.64
Fishhouse	0							0	0	0	0	0	0
Sand and Gravel media	157.02	0	0	1	1	0	0	0	0	78.51	78.51	0	0
Foam (m^2)	0	5.76	0	0	0	0	0	70.94	0	0	0	0	0
Heaters	982.14	1	1	1	1	0	1	196.43	196.43	196.43	196.43	0	196.43
						Total Cost:		1974.53	1639.93	1863.75	1863.75	869.59	1544.82

DWC: Deep water culture, NFT: Nutrient Film Technique, MB: Media-bed system, SP: Sandponic, IVA: Integrated Vegetable Aquaculture and SC: Soil Cultivation

Table 5 provides an itemized breakdown of capital expenditure costs (CAPEX) for hydroponic subsystems in the context of aquaponics, as well as soil-based cultivation. The costs are denominated in euros (€). Each item's cost is detailed alongside the quantity required for various grow bed types, as well as the cumulative expense for shared grow beds. Significant expenses include plumbing and tanks, with a total of €1500.49, evenly distributed across all types of grow beds, resulting in individual costs of approximately €250.08 per grow bed. Similarly, items like interlock and interlock building fees are allocated proportionately.

Grow beds play a key role, costing €615.76, with relevance for DWC and media-bed systems, amounting to €205.25 per bed. Additionally, the greenhouse body represents a substantial investment at €1381.25, distributed equally across all grow bed types, averaging €230.21 per bed.

Noteworthy aquaponic components include fish tanks, pumps, and sumps, costing €1015.09, and fish, amounting to €246.31. Both of these expenses are relevant for DWC, NFT, and media-bed systems, with individual costs specified. The total CAPEX for each subsystem is as follows: DWC (€1974.53), NFT (€1639.93), Media-bed (€1863.75), Sandponic (€1863.75), Integrated Vegetable Aquaculture (IVA) (€869.59), and Soil Cultivation (€1544.82). The highest capital cost is recorded in DWC subsystems as a component of aquaponic, while the IVA systems are needed lowest amount compared to other cultivation systems.

Pilot Scale Experiments

Table 6 provides an itemized breakdown of the capital expenditure costs (CAPEX) for lettuce growth in both hydroponic (HP) and aquaponic (AP) systems at the pilot-scale level in the AWESOME test facility. The costs are listed in euros (€). Plumbing and Tanks, for instance, incur a total expense of €3934.73, with HP accounting for €1331.25 and AP for €1967.36 when distributed among shared grow beds. Other expenses, such as Interlock, Renile Environment Controller, Electricity Tools, and others, are similarly allocated between the two systems. This table offers a comprehensive overview of the financial considerations associated with lettuce growth in both hydroponic and aquaponic systems, providing crucial insights for decision-making in the upscaling process. The total CAPEX for lettuce growth in both hydroponic and aquaponic systems at the pilot-scale level amounts to €24967,23, with €7.570,29 for HP and €17.396,94 for AP.

Table 6 – Capital expenditure costs (CAPEX) for lettuce growth in hydroponic (HP) and aquaponic (AP) systems at pilot-scale level.

Item	Total cost €	Amount for shared grow beds		Cost for shared grow beds (€)	
		HP	AP	HP	AP
Plumbing and Tanks	3934.73	1	1	1331.25	1967.36
Interlock	292.49	1	1	98.96	146.24
Renile environment controller	431.03	1	1	145.83	215.52
Electricity tools	1808.5	1	1	611.88	904.25
Growing beds	1610.22	1	1	544.79	805.11
Air curtain	277.09	1	1	93.75	138.55
Cooling system	1570.2	1	1	531.25	785.1
Greenhouse body	5118.32	1	1	1731.7	2559.16
Fish House body	1381.25	0	1	0	1381.25
Aeration pump	2278.33	1	1	770.83	1139.16
Heaters	1281.07	0	1	0	1281.07
Fish tanks	2463.05	0	1	0	2463.05
Fish	369.46	0	1	0	369.46
Nursery area	4984.61	1	1	1686.46	2492.3
Sand	708.13	0	1	0	708.13
Land use	700 € per acre	136.2 m^2	238.4 m^2	23.59	41.23
Total:	24.967,23			7.570,29	17.396,94

4.1.2 Operational Expenditure Costs (OPEX)

The Operational Expenditure Costs analysis examines the ongoing costs involved in running the aquaponics and hydroponics systems at the lab and pilot scale. This includes expenses related to resources like water, energy, maintenance, and any other recurring operational costs. By providing a detailed view of the long-term financial commitments. This analysis offers valuable insights into the sustainability and efficiency of the scaled-up operation.

Lab-Scale Experiments

The operational expenses (OPEX) of soilless systems primarily depend on the system design. For instance, the initial water fill in a soilless system is estimated to be 0.23 m^3 for each square meter of plants, substituting from 5 to 7% of the water capacity per week. This, of course, depends on agricultural practices, system design, and weather conditions. In Egypt, water costs amount to USD 33 per month, and the effective maximum capacity of water to be withdrawn ranges from 1500–1800 m^3 per month, incurring a cost of USD 0.02 per m^3. Electrical consumption varies from 50 kW and could reach up to 8000 kWh per month. Seed expenses are contingent on factors such as crop variety, source, supplier, and specifications including coating, breed, and genetic traits. In total, the OPEX for a well-equipped soilless system can amount to as much as USD 975 per acre each month[16].

In our studies, energy consumption is one of the high costs. The price for electricity is 0.05 € (1.50 Egyptian pound) per kWh. The total energy consumption and cost for hydroponic and aquaponic experiments are presented in table 7.

Table 7a – Energy consumption for hydroponic subsystems and soil-based cultivation for a month

Electricity		Total usage (kWh)	Quantity for grow beds (n)					Individual costs for grow beds (€)				
Device	**Its watt**	**Total cost (€)**	**Soil**	**NFT**	**DWC**	**SP**	**MB**	**Soil**	**NFT**	**DWC**	**SP**	**MB**
Cooling Pads	247.50	74.25	0.00	0.00	0.00	0.00	0.00	0.69	0.69	0.69	0.69	0.69
Fans *2	90.00	660	0.00	0.00	0.00	0.00	0.00	6.1	6.1	6.1	6.1	6.1
Submerged pumps	2200.00	0	0.00	59.40	54.00	1.08	54.00	0	2.74	2.49	0.05	2.49
Water pump	420.00	0	1.05	0.00	0.00	0.00	0.00	0.05	0	0	0	0
Air pump	280.00	0	0.00	0.00	100.80	0.00	0.00	0	0	4.66	0	0
						Total cost:		6.83	9.53	13.93	6.83	9.28

Table 7b – Energy costs for hydroponic subsystems in aquaponic context, IVA and soil-based cultivation

Item	For Greenhouse	Energy consumption for shared grow beds					
		DWC	**NFT**	**MB**	**SP**	**SC**	**IVA**
Illuminated lights	126.00	21.00	21.00	21.00	21.00	21.00	21.00
Fan motors	792.00	132.00	132.00	132.00	132.00	132.00	132.00
Cooling pad pumps	167.85	27.98	27.98	27.98	27.98	27.98	27.98
Vaccum	86.40	14.40	14.40	14.40	14.40	14.40	14.40
Water pumps	0.00	335.90	321.60	328.70	314.40	1.70	4.20
Total Energy	1172.25	531.28	516.98	524.08	509.78	197.08	199.58
	Total cost (€):	26.56	25.85	26.20	25.49	9.85	9.98

Table 8 –Water consumption and cost for both hydroponic and aquaponic experiments

Hydroponic experiments					Aquaponic experiments				
CS	**Water per plant (l)**	**Number of plants**	**Total water (l)**	**Cost**	**CS**	**Water per plant (l)**	**Number of plants**	**Total water (l)**	**Cost**
DWC	12.09	108	1305.72	0.01	**DWC**	6.3	72	453.6	0.04
NFT	6.07	135	819.45	0.07	**NFT**	5.4	72	388.8	0.03
MB	11.54	108	1246.32	0.1	**MB**	4.7	72	338.4	0.03
SP	9.26	108	1000.08	0.08	**SP**	9.4	72	676.8	0.05
SC	41.7	90	3753	0.3	**SC**	516.7	72	37202.4	2.86
					IVA	19.4	72	1396.8	0.11

Table 8 outlines water consumption and costs for hydroponic and aquaponic experiments, categorized by cultivation system. In hydroponics, the Deep Water Culture (DWC) system uses 12.09 liters per plant, totaling 1305.72 liters for 108 plants (0.01 Euro cost), while the Nutrient Film Technique (NFT) system consumes 6.07 liters per plant, totaling 819.45 liters for 135 plants (0.07 Euro cost). In aquaponics, DWC utilizes 6.3 liters per plant, totaling 453.6 liters for 72 plants (0.04 Euro cost). Soil-based Cultivation (SC) requires significantly more water, with 41.7 liters per plant, totaling 3753 liters for 90 plants (0.30 Euro cost). These insights assist in evaluating water efficiency and costs for different cultivation systems, essential for large-scale production considerations.

Table 9a – Operational costs for hydroponic subsystems and soil-based cultivation for a month

Item	Price	Quantity					Costs				
	(€)	**Soil**	**NFT**	**DWC**	**Sand**	**Mediabed**	**Soil**	**NFT**	**DWC**	**Sand**	**Mediabed**
Seeds	0.01	90.00	135.00	108.00	108.00	108.00	0.90	1.35	1.08	1.08	1.08
Cups	0.02	0.00	135.00	108.00	0.00	0.00	0.00	2.70	2.16	0.00	
Nutrient solution	0.62	50.00	24.00	37.50	24.00	24.00	31.00	14.88	23.25	14.88	14.88
Energy (kW)	0.05	136.60	190.60	278.60	136.60	185.60	6.83	9.53	13.93	6.83	9.28
Water (m^3)	0.08	3.75	0.82	1.31	1.00	1.25	0.30	0.07	0.01	0.08	0.10
						Total:	39.03	28.53	40.43	22.87	25.34

Table 9b – Operational costs for aquaponic systems

Item	Price	Quantity						Costs					
	(€)	**DWC**	**NFT**	**MB**	**SP**	**SC**	**IVA**	**DWC**	**NFT**	**MB**	**SP**	**SC**	**IVA**
Energy (kW)	0.05	531.28	516.98	524.08	509.78	197.08	199.58	26.56	25.85	26.20	25.49	9.85	9.98
Water (m^3)	0.08	0.45	0.39	0.34	0.68	37.2	1.4	0.04	0.03	0.03	0.05	2.98	0.11
Seed	0.01	72	72	72	72	72	72	0.72	0.72	0.72	0.72	0.72	0.72
Cups	0.02	72	72	0	0	0	0	1.44	1.44	0	0	0	0
Fish forage	0.45	3.6	5	6.7	4.5	0	4.7	1.62	2.25	3.015	2.025	0	2.115
Fertilizer	0.62	0	0	0	0	25	0	0	0	0	0	15.5	0
							Total:	30.38	30.29	29.97	28.29	29.05	12.93

Table 9a provides a comprehensive breakdown of operational costs for hydroponic subsystems (NFT, DWC, Sand, and Mediabed) alongside soil-based cultivation, evaluated on a monthly basis. The costs are itemized for seeds, cups, nutrient solutions, energy consumption (in kWh), and water usage (in cubic meters). The total monthly operational costs for each cultivation method are meticulously calculated.

Table 9b offers a detailed analysis of monthly operational costs for various aquaponic systems, including DWC, NFT, Media Bed (MB), Sandponics (SP), Soil-based Cultivation (SC), and Integrated Vertical Aquaponics (IVA). The expenses encompass energy consumption (in kWh), water usage (in cubic meters), seeds, cups, fish forage, and fertilizer. The total monthly operational costs are presented for each aquaponic cultivation method, aiding in comprehensive financial assessment and decision-making.

Pilot Scale Experiments

The pilot-scale experiments focused on optimizing lettuce growth for mass production, employing both hydroponic (HP) and aquaponic (AP) systems. This phase of the project involved the cultivation of 1590 lettuce plants in the hydroponic system and 1630 lettuce plants in the aquaponic system, within a controlled environment. The objective was to achieve robust growth and high yield rates in order to assess the potential for large-scale lettuce production.

Table 10 outlines the operational costs associated with conducting the pilot-scale experiments for both hydroponic (HP) and aquaponic (AP) systems. These costs encompass various components including seeds, cups, nutrient solutions, energy consumption, water usage, fish forage, and generator usage.

For the hydroponic system, the monthly operational costs amounted to €262.17, with an annual total of €3,146.04. In comparison, the aquaponic system incurred higher monthly costs at €848.75, resulting in an annual total of €10,185.01. These OPEX costs are crucial in evaluating the financial feasibility and sustainability of lettuce production at a pilot scale, providing essential insights for potential large-scale implementation.

Table 10 – Operational costs for hydroponic (HP) and aquaponic systems (AP) at pilot scale

Item	Price	Quantity	Costs (€)		
	(€)	**HP**	**AP**	**HP**	**AP**
Seeds	0.01	1590.00	1630.00	15.90	16.30
Cups	0.02	1590.00	0.00	31.80	0.00
Nutrient solution (L)	1.10	160.00	0.00	176.00	0.00
Energy (kW)	0.05	763.80	8935.20	38.19	446.76
Water (m3)	0.08	3.51	14.87	0.28	1.19
Fish forage (kg)	0.45	0.00	101.87	0.00	45.84
Generator + gas	338.66	0.00	1.00	0.00	338.66
		Monthly total cost:		262.17	848.75
		Annual total cost:		3.146,04	10.185,01

4.2 RETURN ON INVESTMENT (ROI)

The Return on Investment (ROI) is a pivotal financial metric indicating the efficiency and profitability of the lettuce mass production conducted at pilot scale using both hydroponic (HP) and aquaponic (AP) systems. ROI was calculated by first multiplying the profit and then diving it to total investment cost (CAPEX: the capital expenditure costs). Pay-back period of the investment was calculated by dividing the total investment by operational profit as following[17]

$$ROI = \frac{Total\ annual\ profit}{Total\ costs} \text{x } 100$$
I

$$Payback\ period = \frac{CAPEX}{annual\ gain}$$
II

In the hydroponic system, a monthly lettuce yield of 250.4 kg and an annual yield of 3005.1 kg were achieved, resulting in a yearly gain of €5559.43. The ROI for the hydroponic system stands at an impressive 51.83%. This indicates that for every euro invested, the hydroponic system yields a return of approximately €1.52.

For the aquaponic system, a monthly lettuce yield of 182.56 kg and an annual yield of 2190.72 kg were attained, resulting in a yearly gain of €4754,35. The ROI for the aquaponic system is 31.25%, reflecting a return of approximately € 5.44 for every euro invested.

These ROI figures demonstrate that the hydroponic system exhibits higher profitability compared to the aquaponic system at the pilot scale. This financial assessment is crucial in making informed decisions regarding the scalability and implementation of lettuce production using these technologies as shown table 11.

Table 11 – The comparation for efficiency of lettuce mass production from hydroponic (HP) and aquaponic systems (AP) at pilot scale

Hydroponic systems		Aquaponic systems	
Total lettuce yield for a month	1590 *157.5=250.4 kg	**Total yield for a month**	1630*112=182.56 kg
Total lettuce yield for a year	3005.1 kg	**Total yield for a year**	2190.72
Yearly gain	€5559.43=1.85 €*3005.1	**Yearly gain**	4052.83=1.85*2190.72
Total monthly fish production	0	**Total monthly fish production**	27.19 kg
Total annual fish production	0	**Total annual fish production**	326.28 kg
Yearly gain	€5559.43	**Yearly gain**	€701,52
Total yearly gain from food production	€5559.43	**Total yearly gain from food production**	€ 4754,35
CAPEX	7.570,29	**CAPEX**	17.396,94
Total yearly OPEX	3.146,04	**Total yearly OPEX**	10.185,01

Total costs:	10.716,33	**Total costs:**	27.581,95
ROI$_{hydroponic}$	51.83%	**ROI$_{aquaponic}$**	31.25 %
Payback$_{hydroponic}$	1.36 years	**Payback$_{aquaponic}$**	3.66 years

The payback period for the hydroponic system is approximately 1.36 years, while for the aquaponic system it is approximately 3.66 years. This means that the hydroponic system is expected to recoup the initial investment in a shorter period compared to the aquaponic system.

5. LOCAL MANUFACTURING OPPORTUNITIES AND AUTOMATION

The exploration of local manufacturing opportunities in hydroponic and aquaponic systems presents a promising avenue for sustainable agricultural development. This involves the establishment of production facilities within the vicinity of cultivation sites, potentially reducing reliance on imports and promoting regional economic growth. Local manufacturing can encompass the production of key components such as growth substrates, nutrient delivery systems, aquaculture equipment, and specialized monitoring devices. This strategy not only bolsters the resilience of the agricultural sector but also fosters job creation and skill development within the local community. Furthermore, it can lead to the customization of products to suit specific environmental conditions and cultivation methods, ultimately enhancing system efficiency and productivity. **In Egypt, while soil remains the primary growing medium, continuous cropping in open fields or plastic houses leads to soil-borne diseases.** This poses a challenge, particularly in plastic houses, as they represent a substantial investment and are better suited for higher value crops like tomato, cucumber, pepper, eggplant, and melon, which also require crop rotation. **Therefore, transitioning from soil to soilless systems in greenhouse vegetable production is becoming imperative.** This shift is not only relevant to greenhouses but also crucial in open fields, especially concerning water usage, fertilizer, and pesticide efficiency. Commercial adoption of soilless greenhouse culture in Egypt has been gradual over the past two decades, with less than 2% of the total cultivated area utilizing various soilless culture systems. Deep water culture is the most prevalent technique, and nutrient film technique is implemented using an "A" shaped configuration of pipes. However, broader attention to proper soilless culture methods remains limited among growers, except those supplying leafy crops to larger establishments like restaurants, hotels, and hypermarkets. Egyptian researchers have been pioneers in this field since the early 1990s[18].

The pursuit of local manufacturing opportunities in hydroponic and aquaponic systems is poised to revolutionize the agricultural landscape. By harnessing regional resources and expertise, we have the potential to mitigate supply chain vulnerabilities and promote self-sufficiency. The establishment of manufacturing facilities for essential components not only streamlines production processes but also engenders a sense of empowerment and ownership within the local community. Moreover, it offers the flexibility to tailor products to unique environmental and operational requirements, thereby optimizing system performance. Through strategic investments in local manufacturing, we embark on a trajectory towards a more sustainable and resilient agricultural future.

Egypt's urban population constitutes nearly half of its total population, surpassing the African average of 40%. Greater Cairo alone hosts more than 40% of Egypt's urban residents, presently numbering around 20 million. Projections estimate that by 2050, the population in this area will exceed 30 million.

Green roofs offer a multitude of advantages for neighbourhoods and communities, particularly benefiting vulnerable groups. Research demonstrates that urban vegetation lowers temperatures and reduces energy expenses for associated buildings. Consequently, the need for urban green spaces, such as green roofs, is evident in Cairo. While there's yet to be a large-scale rooftop food production initiative in the city, some companies have turned to cultivating leafy greens in hydroponics systems housed in greenhouses. Although this approach has succeeded in popularizing the concept of rooftop food production throughout Cairo, it means that producers are distanced from their own yield, which is consumed in other suburbs of the city. The final destination for rooftop produce is the high-end market, including prominent supermarket chains and specialty grocery stores catering to expatriates and the affluent segment of Egyptian society. Here, the prices range from four to 40 times that of conventionally grown produce, placing it out of reach for most of the population, including the rooftop farmers themselves. Even with an increasing number of rooftop units potentially leading to economies of scale, this model offers little direct contribution to enhancing food security or dietary quality for vulnerable populations in Cairo. Furthermore, the authors estimate that the upscale market constitutes only about 2-5% of the total market, severely limiting the potential for this model to expand. This specialized market niche will likely reach saturation before the full social and environmental benefits of urban farming can be fully realized[19].

Automation Prospects in Hydroponic and Aquaponic Systems

Automation stands as a pivotal frontier in advancing the efficiency and productivity of hydroponic and aquaponic systems. It involves the integration of cutting-edge technologies such as IoT (Internet of Things), sensors, robotics, and AI-driven analytics to optimize various facets of cultivation. Automation can encompass tasks ranging from precise nutrient delivery, environmental monitoring, and pest control to the harvesting and packaging of produce. This not only minimizes resource wastage but also enables real-time data-driven decision-making. The potential benefits of automation extend to labor savings, enhanced crop quality, and the ability to operate cultivation facilities with greater precision and consistency[20].

The integration of automation technologies represents a quantum leap in the evolution of hydroponic and aquaponic systems. By leveraging the power of advanced sensors, artificial intelligence, and robotics, we unlock new levels of efficiency and precision in agricultural practices. Automation mitigates human error, allowing for optimal resource allocation and significantly reducing operational costs. Furthermore, it equips cultivators with invaluable real-time data, enabling swift and informed decision-making. The adoption of automation not only revolutionizes the way we cultivate but also positions us at the forefront of sustainable agriculture, poised to meet the demands of a dynamic and evolving global food landscape[20,21].

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6. CHALLENGES

Scaling up hydroponic and aquaponic systems from lab-scale and pilot-scale experiments to large-scale production poses several challenges that need careful consideration for successful implementation. One significant challenge lies in infrastructure scaling, which entails upgrading facilities to accommodate increased production capacities while ensuring optimal environmental control, water management, and nutrient delivery. This requires substantial investment and meticulous planning to meet the technical requirements of large-scale operations.

Another crucial aspect is resource management, which is becoming increasingly complex at larger scales. Efficient water recycling systems, nutrient recovery methods, and energy-efficient technologies must be developed to minimize resource consumption and environmental impact. Additionally, maintaining operational efficiency becomes more challenging with scale, necessitating the streamlining of processes, optimization of workflow, and implementation of automation technologies to maximize productivity and minimize labor costs.

Crop diversity and variability present additional challenges when scaling up hydroponic and aquaponic systems. Accommodating a diverse range of crops requires research into crop-specific requirements, nutrient formulations, and cultivation techniques to ensure consistent yields and quality across different varieties. Moreover, large-scale production facilities are more susceptible to pest infestations and plant diseases, which can significantly impact crop health and yield. Implementing integrated pest management strategies, biosecurity measures, and disease surveillance protocols are crucial for combating these threats and safeguarding production.

In aquaponic systems, fish health is paramount to the success of the operation. Disease outbreaks among fish populations can have devastating effects on the entire ecosystem. Monitoring fish health, maintaining optimal water quality, and implementing preventive measures such as quarantine protocols are essential for disease prevention. Additionally, prompt identification and treatment of fish diseases through appropriate veterinary interventions are necessary to minimize losses and ensure the sustainability of aquaponic operations.

On the plant side, diseases such as root rot, powdery mildew, and various bacterial and fungal infections can pose significant challenges in hydroponic systems. Maintaining a sterile growing environment, proper sanitation practices, and regular monitoring for early signs of disease are essential for prevention. Implementing disease-resistant plant varieties, as well as biological control methods such as beneficial microorganisms and biopesticides, can help mitigate disease risks and minimize crop losses.

Compliance with regulatory standards and certification requirements becomes increasingly important as operations expand. Ensuring adherence to food safety regulations, environmental guidelines, and industry standards is crucial for market access and consumer confidence. Additionally, aligning production levels with market demand and integrating supply chain logistics pose challenges in large-scale hydroponic and aquaponic operations, requiring effective market forecasting, distribution strategies, and partnerships with retailers to achieve market competitiveness and profitability.

Furthermore, developing a skilled workforce proficient in hydroponic and aquaponic techniques is essential for successful large-scale operations. Training programs and educational initiatives should be implemented to equip personnel with the knowledge and skills required for efficient system management and maintenance.

By addressing these challenges through collaborative efforts from researchers, industry stakeholders, policymakers, and technology providers, the expansion of hydroponic and aquaponic technologies can contribute to sustainable agricultural development, food security, and environmental conservation on a global scale.

7. CONCLUSIONS

In conclusion, this comprehensive study delves into the potential of hydroponic and aquaponic technologies as innovative and sustainable approaches to modern agriculture. Through meticulous lab-scale and pilot-scale experiments, we evaluated various subsystems and configurations, shedding light on their feasibility for large-scale production.

The lab-scale experiments demonstrated the adaptability of different hydroponic subsystems, including Deep Water Culture, Nutrient Film Technique, Media-bed System, and Sandponics, in both hydroponic and aquaponic setups. These experiments also assessed factors such as planting spacing, seasonal variations, and the comparison with traditional soil-based cultivation. The results underscored the efficiency and potential benefits of soilless cultivation, particularly in terms of resource utilization and productivity.

Moving to the pilot-scale experiments, we further validated the feasibility of two distinct subsystems: Deep Water Culture in hydroponics and sandponics within an aquaponic setup. These experiments provided crucial insights into the scalability and efficiency of these systems, paving the way for potential large-scale implementation.

Economic factors were meticulously analyzed, covering both capital expenditure (CAPEX) and operational expenditure (OPEX) costs. The detailed breakdown of expenses for infrastructure development, equipment acquisition, and ongoing operational costs provided a comprehensive view of the financial implications of scaling up hydroponic and aquaponic technologies. Additionally, the Return on Investment (ROI) calculations highlighted the potential profitability of these systems, with the hydroponic approach exhibiting higher returns at the pilot scale. Specifically, in the hydroponic system, a monthly lettuce yield of 250.4 kg and an annual yield of 3005.1 kg were achieved, resulting in a yearly gain of €5559.43. The ROI for the hydroponic system stands at an impressive 51.83%. This indicates that for every euro invested, the hydroponic system yields a return of approximately €1.52.

For the aquaponic system, a monthly lettuce yield of 182.56 kg and an annual yield of 2190.72 kg were attained, resulting in a yearly gain of € 4754,35. The ROI for the aquaponic system is 31.25%, reflecting a return of approximately €5.44 for every euro invested.

The hydroponic system is forecasted to regain its initial investment in just 1.36 years, whereas the aquaponic system is expected to take about 3.66 years to do the same. In simpler terms, the hydroponic system is set to recoup the initial investment much faster compared to the aquaponic system.

Spatial considerations played a pivotal role in assessing the potential for large-scale production. The flexibility of soilless systems in terms of land suitability and the reduced requirement for specific land qualities further emphasized their adaptability to diverse terrains.

Furthermore, the exploration of local manufacturing opportunities and automation integration presents a promising avenue for sustainable agricultural development. By establishing production facilities for key components and specialized monitoring devices, we can enhance system efficiency, reduce reliance on imports, and promote regional economic growth.

Overall, this deliverable provides a comprehensive foundation for the potential expansion of hydroponic and aquaponic technologies. Through rigorous experimentation and economic analysis, we have gained valuable insights into their feasibility, efficiency, and economic viability. These findings serve as a crucial resource for stakeholders and decision-makers in the agricultural industry, offering a sustainable path forward in modern agriculture.

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