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Review

The role of automation and robotics in transforming hydroponics and aquaponics to large scale

Milon Selvam Dennison[1] · P. Sathish Kumar[1] · Fwangmun Wamyil[2] · M. Abisha Meji[3] · T. Ganapathy[4]

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Abstract
Automation and robotics are revolutionizing hydroponic and aquaponic farming techniques and also enhancing their efficiency, sustainability, and scalability within the Controlled Environment Agriculture (CEA). This review explores the integration of key technologies, such as automated nutrient and pH management systems, advanced lighting solutions, and IoT-enabled smart farming practices. These innovations significantly boost productivity, optimize resource utilization, and reduce labor dependency, although with challenges like high initial capital investment, technical complexity, and energy demands. The paper examines case studies showcasing improvements in yield and resource efficiency while addressing scalability and energy limitations. Emerging technologies, including AI-driven analytics and off-grid power solutions, are identified as promising avenues to overcome these hurdles. By presenting actionable insights and emphasizing the importance of energy-efficient equipment and sustainable practices, this review underscores the potential of automation and robotics to transform hydroponic and aquaponic systems. Ultimately, this work supports global food security, environmental conservation, and the advancement of circular economy principles.
Clinical Trial This research does not involve clinical trials.

Keywords Smart Farming · Controlled Environment Agriculture · Hydroponic · Aquaponic · Food Security

Abbreviations

AI	Artificial intelligence
CAP	Coupled aquaponic systems
CE	Circular economy
CEA	Controlled environment agriculture
CO_2	Carbon dioxide
COD	Chemical oxygen demand
DB-SMOTE	Density based synthetic minority over-sampling TEchnique
DCAP	Decoupled aquaponic systems
DLI	Daily light integral
DO	Dissolved oxygen

✉ Milon Selvam Dennison, milonds.mf@gmail.com; milon.selvam@kiu.ac.ug; P. Sathish Kumar, sathishpauto@kiu.ac.ug; Fwangmun Wamyil, fwamyil@gmail.com; M. Abisha Meji, abisha.meji@kiu.ac.ug; T. Ganapathy, ganaskctmech@gmail.com | [1]Department of Mechanical Engineering, School of Engineering and Applied Sciences, Kampala International University, Western Campus, Ishaka-Bushenyi, Uganda. [2]Department of Civil Engineering, School of Engineering and Applied Sciences, Kampala International University, Western Campus, Ishaka-Bushenyi, Uganda. [3]Department of ETC Engineering, School of Engineering and Applied Sciences, Kampala International University, Western Campus, Ishaka-Bushenyi, Uganda. [4]Department of Mechanical Engineering, P.S.R. Engineering College, Sivakasi, Tamilnadu, India.

DWC	Deep water culture
FDR	Frequency domain reflectometry
ft^2	Square feet
HCS	Hydroponic cropping systems
HLR	Hydraulic loading rate
IoT	Internet of things
IRR	Internal rate of return
ISEs	Ion selective electrodes
kg/m^2	Kilograms per square meter
LED	Light emitting diode
m^2	Square meter
MES	Manufacturing execution system
MFCs	Microbial fuel cells
ML	Machine learning
NFT	Nutrient film technique
NH_3	Ammonia
NPV	Net present value
NUE	Nutrient use efficiency
PGPM	Plant growth promoting microorganisms
pH	Potential of hydrogen
RAS	Recirculating aquaculture systems
TDS	Total dissolved solids
UAV	Unmanned aerial vehicles
WNS	Waste nutrient solutions
WSN	Wireless sensor networks
WUE	Water use efficiency

1 Introduction

Sustainable food production and Controlled Environment Agriculture (CEA) are increasingly important in addressing the challenges caused by global population explosion, urbanization, and climate change [1, 2]. The CEA which includes plant factories and vertical farming offers a promising solution by enabling consistent and predictable crop yields independent of external weather conditions [3, 4]. These systems are particularly advantageous in urban settings, where they can contribute to localized food production, reducing the need for long-distance transportation and associated emissions [5, 6]. However, the high energy demands of CEA systems pose significant sustainability challenges, necessitating innovations in energy management and the integration of renewable energy sources [3, 4]. Advances in technology, such as the use of deep learning for optimizing energy use and crop growth, are crucial in enhancing the sustainability of these systems [4]. Moreover, the integration of Circular Economy (CE) principles, such as composting and nutrient recovery, can further improve the environmental performance of CEA by closing resource loops and reducing waste [6]. Despite these advancements, there are still research gaps, particularly in the economic viability of growing staple crops and the social and cultural dimensions of sustainability, which are often unnoticed [3, 7].

Hydroponic and aquaponic systems represent innovative approaches to CEA, offering solutions to the challenges posed by traditional soil-based farming. Hydroponics involves growing plants in a nutrient-rich water solution without soil, allowing for precise control over nutrient delivery and water usage, which can give higher yields at reduced resource consumption [8]. Figure 1 shows the illustration of a general hydroponics and aquaponics system.

Whereas, aquaponics, on the other hand, integrates hydroponics with aquaculture, creating a symbiotic environment where fish waste provides nutrients for plant growth, and plants help filter and clean the water for the fish [9, 10]. This closed-loop system demonstrates the principles of the CE by minimizing waste and maximizing resource efficiency [11, 12]. Both the hydroponic and aquaponic systems are gaining attention due to their potential to conserve water, reduce pollution, and enhance food security, particularly in urban settings where space and resources are limited [8, 12].

The integration of automation into these farming methods further amplifies their efficiency and sustainability while influencing the social and economic dynamics of urban farming communities. Automation boosts productivity and

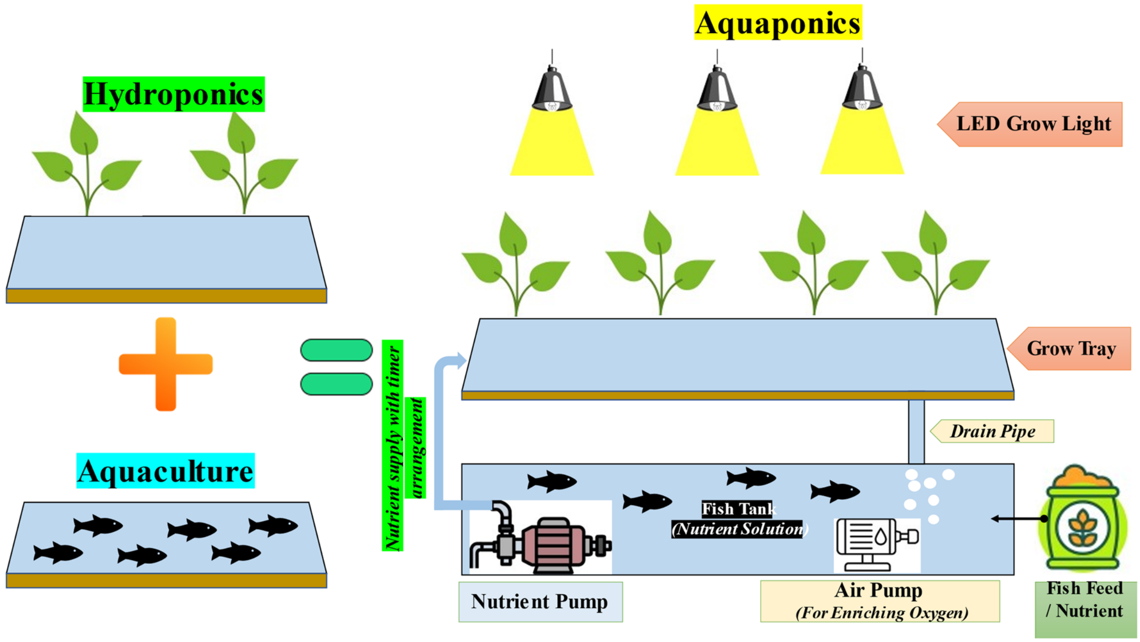

Fig. 1 Illustration of a Hydroponics and Aquaponics System

resource efficiency, allowing urban farmers to increase yields while relying less on labor. This is especially advantageous in densely populated city areas where both land and manpower are scarce. Additionally, automation creates fresh economic opportunities, including precision farming consultancy, technology maintenance, and agri-tech entrepreneurship. However, it brings about challenges concerning workforce displacement, as conventional farming jobs might diminish, highlighting the need for reskilling and digital literacy initiatives to promote inclusivity during the shift to smart farming. The expenses associated with automation technologies could pose financial challenges for small urban farmers, which might result in a market landscape that benefits larger companies. To address these challenges, implementing policies that support subsidized automation tools, cooperative farming models, and financial incentives can make smart farming solutions more accessible to everyone. By harmonizing technological progress with social inclusivity, automation can promote sustainable urban agriculture and strengthen economic resilience in farming communities [5, 6, 8, 10].

Complementing these advancements, the use of Plant Growth Promoting Microorganisms (PGPM) in hydroponics and aquaponics has shown promise in addressing challenges associated with nutrient uptake by the plant as it enhances nutrient uptake and disease resistance [13]. In aquaponics, the integration of fish and plant production can lead to improved growth rates and resource utilization compared to separate systems, although issues such as nutrient imbalances and off-flavor compounds in fish can arise [9, 14]. Additionally, aquaponics systems can be optimized through various feeding and fasting regimes, as demonstrated in studies with the fish 'Nile tilapia' and the green 'spinach', which showed that strategic feeding schedules can enhance nutrient utilization and productivity, thereby increasing economic efficiency [15]. The integration of aquaponics into eco-industrial food parks and CE models further demonstrates its potential for large-scale sustainable food production, with systems designed to achieve near zero waste and high nutrient use efficiency [11]. Moreover, aquaponics can support the cultivation of medicinal plants, reducing pressure on natural reserves and providing continuous pharmacological resources [16]. The development of innovative aquaponic systems, such as those incorporating insect larvae for nutrient recycling, highlights the potential for further closing nutrient cycles and enhancing sustainability [17]. Despite these challenges, aquaponics is being explored for its potential to diversify agricultural practices and contribute to food security, particularly in regions with limited agricultural land [18, 19]. As research and technology advance, these systems are likely to play a crucial role in the future of sustainable agriculture, offering innovative solutions for efficient and eco-friendly food production and promoting the implementation of Sustainable Development Goals (SDGs) 2, 6, 12, 13 and 15 while ensuring achieving CE goals [14, 20, 21].

The hydroponic and aquaponic CEA systems differ significantly in terms of resource use, primarily due to their structural and operational characteristics. Hydroponics is a soilless plant cultivation method that relies on nutrient solutions, which often require substantial inputs of water and mineral fertilizers. In contrast, aquaponics integrates aquaculture with hydroponics, utilizing fish waste as a nutrient source for plants, thereby reducing the need for external fertilizers and promoting a circular resource use model [9, 18, 22]. Aquaponic systems, particularly decoupled ones, have been shown to save up to 62.8% of mineral fertilizers compared to conventional hydroponics, significantly reducing greenhouse gas emissions associated with fertilizer production [22]. Moreover, aquaponics can achieve higher nutrient use efficiency, with studies indicating up to 83.51% nitrogen and 96.82% phosphorus efficiency in integrated systems, compared to hydroponics [23]. This efficiency is partly due to the recycling of nutrients within the system, which also minimizes waste and enhances sustainability [11, 24]. However, aquaponics requires careful balancing of fish and plant needs, which can complicate system management and necessitate more sophisticated control mechanisms [20, 25]. Despite these challenges, aquaponics offers a more sustainable approach by converting fish waste into plant nutrients, thus reducing the environmental footprint compared to hydroponics, which relies heavily on synthetic inputs [26, 27]. Additionally, aquaponics can be integrated into eco-industrial food parks, further enhancing resource efficiency and self-sufficiency by utilizing waste streams from other industrial processes [11]. The hydroponic and aquaponic systems are suitable for urban agriculture, offering solutions to land scarcity and environmental pollution, but they require careful management to optimize their respective benefits and minimize drawbacks [28, 29]. The choice between hydroponics and aquaponics often depends on specific goals, such as maximizing plant yield, integrating fish production, or reducing environmental impacts, and can be influenced by technological advancements like IoT and machine learning for system monitoring and optimization [29, 30].

Automation and robotics provide transformative potential for addressing the major challenges in hydroponic and aquaponic systems. Automated nutrient delivery systems and climate control technologies enable precise management of water, nutrients, and environmental conditions, reducing resource wastage and ensuring optimal plant growth [31, 32]. Robotics, including planting and harvesting robots, streamline labor-intensive tasks, enhancing efficiency and scalability [33, 34]. Moreover, IoT and AI-driven solutions allow real-time monitoring and predictive maintenance, further improving productivity and system reliability [33, 35, 36]. These advancements are critical for transitioning hydroponic and aquaponic farming to large-scale operations while ensuring sustainability and economic viability.

The objective of this review is to systematically explore the role of automation and robotics in transforming hydroponic and aquaponic smart farming techniques to a larger scale with a focus on enhancing efficiency, productivity, and sustainability in CEA. By addressing the integration of advanced technologies, this study aims to uncover how automated nutrient management, climate control systems, and robotics for planting, harvesting, and maintenance are reshaping these systems.

2 Methodology of review

Among the components of the methodology is the methodical collecting and examination of the existing literature concerning environmentally responsible and intelligent farming in a controlled setting. The initial step involved using the 'Scopus' database to compile a representative selection of articles published to date. Keywords such as 'hydroponic farming' and 'aquaponic farming' were utilized in the search process. One of the benefits of this keyword search is that it provides a broad understanding of the research conducted in the field. More specifically, this method enables the identification of developments, themes, and patterns associated with the application of CEA. The results of the search were refined using filters that restricted the inclusion to journal publications categorized as 'articles' or 'reviews' and written in the English language. This approach improved both the overall quality and the consistency of the outcomes. A total of 590 papers were selected for further analysis.

Figure 2 illustrates the trend and dynamics of research by presenting the analysis of papers, which is shown by the yearly number of articles selected and the trend of innovations. This analysis provides insights into the evolution of research activities and technological advancements in the field. Through the examination of the papers that were chosen, it was possible to determine the most significant findings, approaches, and conclusions that offered a thorough understanding of advancements and applications in the subject matter, including both historical context and recent developments.

Following the completion of the preliminary search, a stringent screening procedure was carried out. Based on the titles and abstracts of the papers that were retrieved, a thorough examination was performed to determine whether they were relevant to the review topic. All the articles that did not fulfill the criterion for inclusion were not taken into consideration. Additionally, any duplicates that were discovered during this stage were removed in order to maintain the integrity of the dataset. Performing a comprehensive full-text examination of the remaining papers was the next

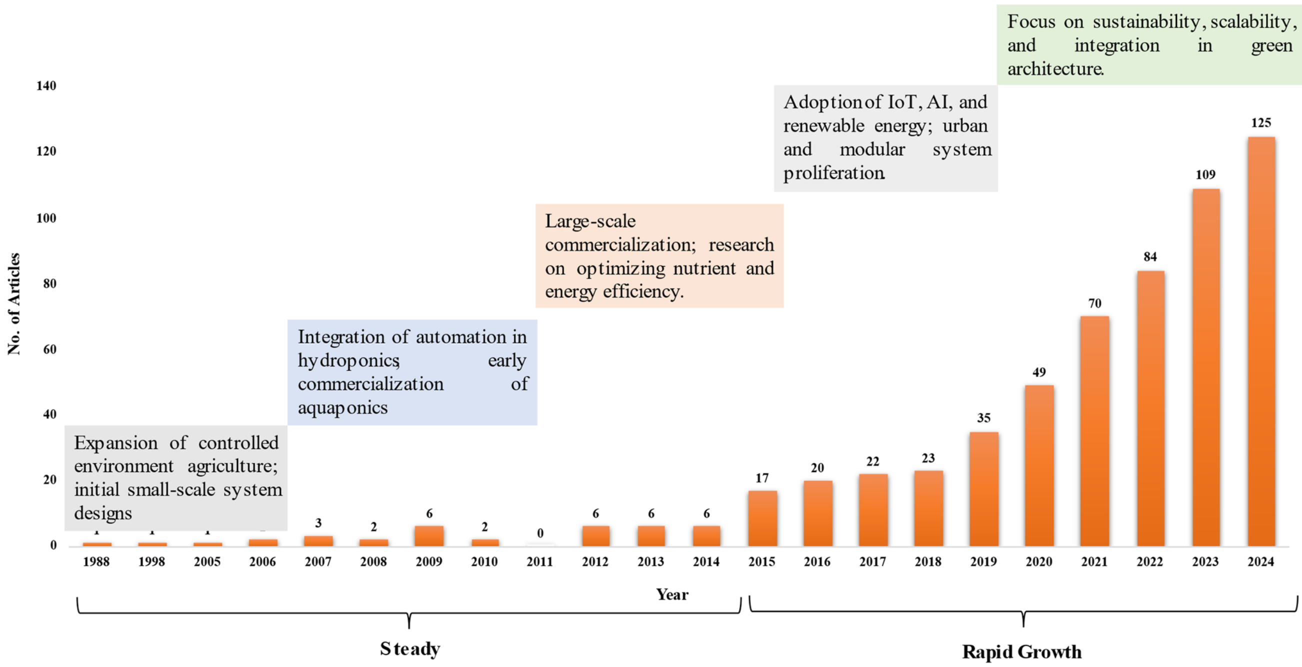

Fig. 2 Year-wise publication and research trend

step in the process. At this stage, it was necessary to verify that every selected item met all of the predetermined inclusion criteria. Each of the papers was evaluated according to how well they were able to provide sufficient information regarding the subject of the research. When conducting the final analysis, we did not include any articles that did not possess this necessary level of depth.

The eradication of these duplicate articles was carried out with the assistance of Zotero, a reference management application that made it possible to effectively identify and remove duplicates from the search results. During the process of evaluation, numerous criteria were applied in order to ensure that the papers selected were of high relevance and quality, based on their alignment with the research objectives and the credibility of the journals in which they were published. The studies were examined to determine whether they adhered to a consistent methodology, which included determining whether or not the research design and data analysis methodologies were appropriate. Following the conclusion of the paper selection process, a comprehensive data extraction and analysis procedure was initiated. Important information, such as the objectives of the study, the methodology that was employed, the most important findings, the difficulties that were recognized, creative ideas, and helpful recommendations, were collected in a methodical manner from the papers that were chosen. Following its retrieval, the data underwent a thorough analysis in order to identify patterns, identify emerging trends, and identify any gaps in the existing body of knowledge. A solid awareness of the current state of the research was achieved as a result of this meticulous method, which allowed for the establishment of the foundation for additional study into this significant topic. Figure 3 illustrates the review approach that was chosen to be evaluated.

Using VOSviewer software version 1.6.20, the collected papers were analyzed to evaluate each country's contributions to the global research landscape. A co-country analysis was conducted to provide a quantitative summary of the geographical distribution of articles. The top 41 nations were selected for each period to visualize the co-country networks, as depicted in Fig. 4. Figure 4 and Table 1 reveal the involvement of 41 distinct countries in the publications, with the size of each node representing the volume of research output. Larger nodes correspond to countries with more extensive contributions, underscoring their influence in the field, while the thickness of the connecting lines between countries illustrates the frequency and intensity of collaborations, emphasizing the importance of international partnerships in driving progress in this field.

Notably, significant contributors to hydroponics and aquaponics are India, the United States, the United Kingdom, Malaysia, and Italy (based on the number of articles); while United Kingdom, United States, Germany, Spain and Belgium (based on citations); and the United States, India, United Kingdom, Germany and China (based on

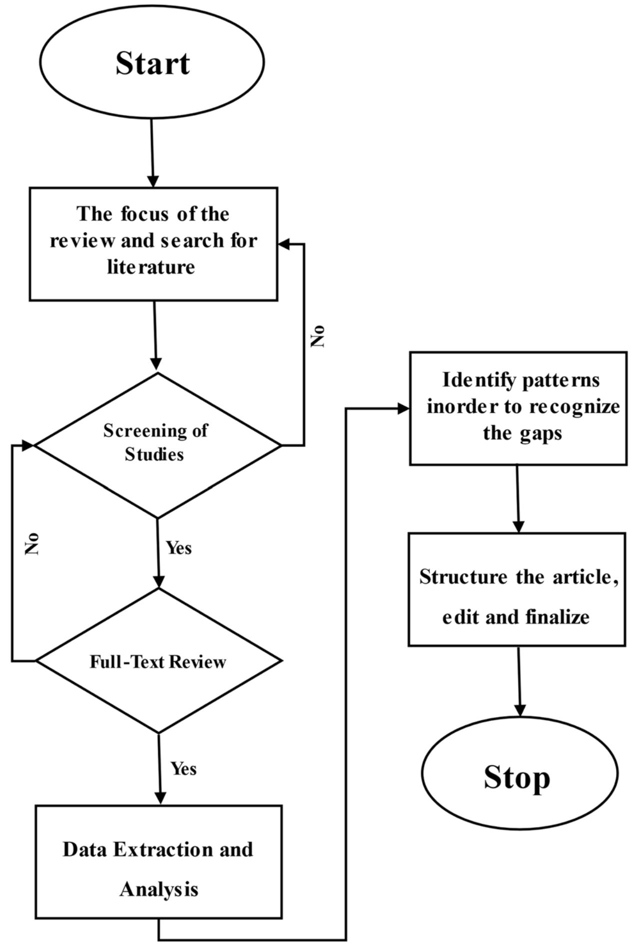

Fig. 3 Review method used in the study

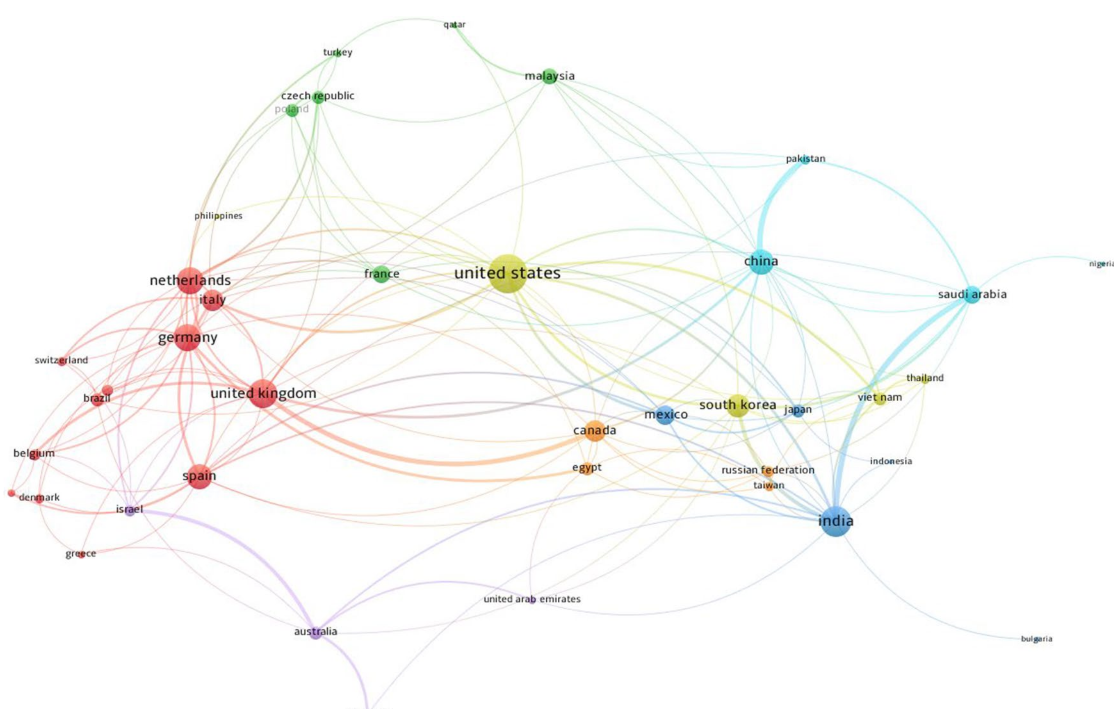

Fig. 4 Country Co-authorship Links in the study

Table 1 Country data

Sl. No	Country	No. of documents	Citations	Total link strength
1	United Kingdom	35	1181	26
2	United States	75	1093	34
3	Germany	28	1037	23
4	Spain	27	886	19
5	Belgium	9	812	9
6	India	79	769	30
7	Italy	31	659	18
8	China	28	453	23
9	Brazil	27	448	7
10	Denmark	7	432	5
11	Sweden	17	375	6
12	Netherlands	14	368	21
13	Malaysia	34	323	9
14	Canada	21	292	16
15	Israel	8	268	11
16	South Korea	16	266	19
17	Saudi Arabia	15	249	17
18	Indonesia	31	243	2
19	Australia	14	228	14
20	Switzerland	5	226	7
21	Pakistan	18	216	11
22	Mexico	16	203	15
23	Greece	16	174	4
24	Egypt	11	140	9
25	Turkey	12	137	5
26	Portugal	7	132	5
27	Vietnam	10	115	12
28	Japan	12	98	9
29	South Africa	6	83	0
30	Qatar	8	76	4
31	Russian Federation	5	70	6
32	Bulgaria	5	66	1
33	United Arab Emirates	7	65	5
34	Czech Republic	5	60	9
35	France	5	57	9
36	Philippines	6	56	2
37	Thailand	11	53	6
38	Taiwan	8	52	5
39	Nigeria	6	49	1
40	Singapore	10	45	4
41	Poland	7	35	8

link strength); which reflects the leadership of the countries in advancing research in this domain. Many other nations have recently increased their research efforts, signaling a growing recognition of the importance of CEA, particularly in hydroponics and aquaponics. This heightened interest aligns with the global need to address food security challenges.

3 Nutrient flow and water recycling mechanisms

Hydroponic and aquaponic systems focus on nutrient flow and water recycling, but their mechanisms and efficiencies differ. In aquaponics, nutrients primarily originate from fish feed, with fish excretions providing soluble nutrients directly available for plant uptake, while solid waste requires microbial mineralization to become accessible [37]. The integration of aquaculture and hydroponics allows for the recycling of nutrient-enriched water, reducing water use and production costs, and offering a sustainable solution for food production [38]. However, controlling nutrient concentrations in aquaponics is more challenging than in hydroponics due to the variability introduced by factors such as pH and temperature [37]. Additionally, advanced systems like the three-level ecological cycle aquaponic system further enhance nutrient recycling by categorizing cycles into low, medium, and high nutrition levels, thereby increasing nutrient utilization rates and offering economic and environmental benefits. These innovations highlight the potential of aquaponics to improve nutrient and water use efficiencies, contributing to sustainable agricultural practices.

3.1 Nutrition flow mechanism

The nutrient flow mechanisms in hydroponic and aquaponic systems are distinct yet interconnected processes that optimize plant growth through different strategies. In hydroponic systems, nutrients are delivered directly to plant roots via a nutrient solution, with flow rates influencing root morphology and hormone synthesis, thereby affecting plant growth and yield [39]. In contrast, aquaponic systems integrate aquaculture and hydroponics, utilizing fish waste as a nutrient source for plants. This waste, primarily from fish feed, is metabolized by fish and excreted as soluble and solid waste, with the former being readily available for plant uptake and the latter requiring microbial mineralization [37, 40]. The Coupled Aquaponic Systems (CAP) operate in a single loop where water continuously circulates between fish tanks and plant units, leading to nutrient imbalances but higher Nutrient Use Efficiency (NUE) compared to hydroponics [24]. Decoupled Aquaponic Systems (DCAP), on the other hand, separate the aquaculture and hydroponic units, allowing for independent control and potentially higher NUE than hydroponics, though similar water quality parameters are observed [24, 41]. The CAP and DCAP systems are shown in Fig. 5.

These systems can be optimized using technologies like reverse osmosis to balance nutrient concentrations without harming beneficial microorganisms [41]. Additionally, innovative treatments for fish solids can reduce carbon and nitrogen loads, producing a liquid fertilizer that enhances nutrient bioavailability and reduces biofouling in hydroponic systems [40]. The integration of aquaponics and hydroponics offers ecological benefits by recycling nutrients and water,

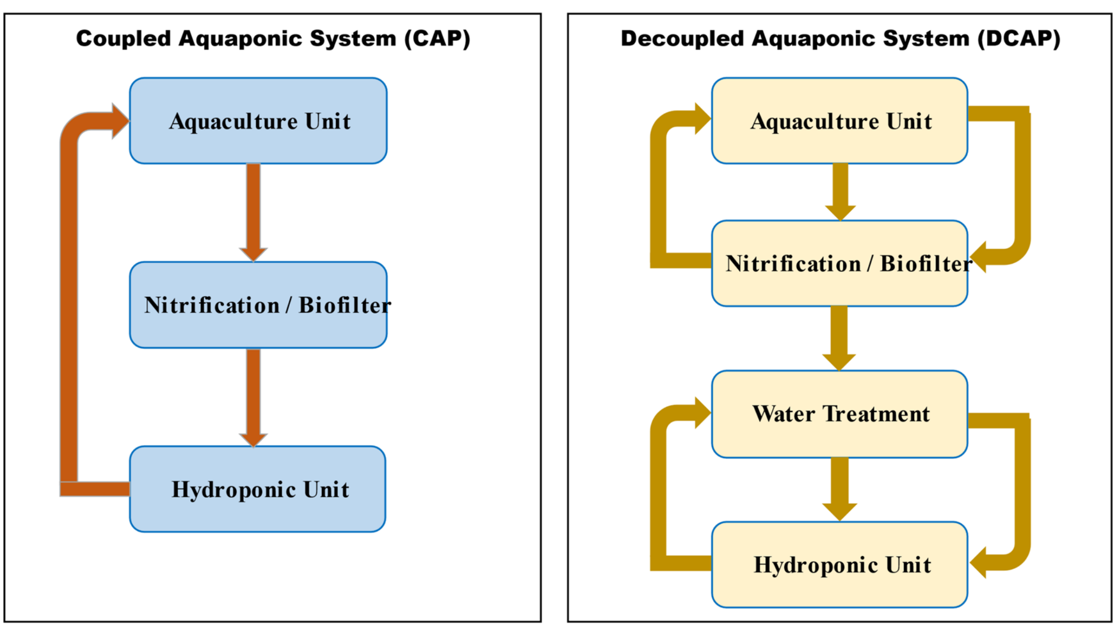

Fig. 5 Block diagram illustrating CAP and DCAP systems, reproduced from [33]

but challenges remain in managing nutrient concentrations to meet the differing needs of fish and plants [42]. Overall, understanding and controlling nutrient cycles and flow environments are crucial for improving the efficiency and productivity of both hydroponic and aquaponic systems [37, 39].

3.2 Water recycling mechanisms

Water recycling mechanisms in hydroponic and aquaponic systems are integral to enhancing sustainability and efficiency in food production. In aquaponic systems, water is recirculated between fish tanks and plant beds, allowing nutrients from fish waste to be utilized by plants, thus reducing the need for external fertilizers, and minimizing water discharge. This integration is exemplified in decoupled multi-loop aquaponics, where desalination technologies like reverse osmosis are employed to optimize nutrient concentrations for both fish and plants, thereby eliminating the need for periodic nutrient and water discharges [41]. In a study conducted in Saudi Arabia, an aquaponic system demonstrated effective water reuse, with only 1.4% of the total system water added daily to compensate for evaporation and transpiration losses; while maintaining high productivity of both fish and plants [43]. Additionally, Microbial Fuel Cells (MFCs) have been integrated with hydroponic systems to treat wastewater, generate electricity, and recover nutrients, showcasing a novel approach to water recycling and energy production [44]. The potential of using reclaimed water in aquaponics has also been explored, although public acceptance remains a challenge, suggesting that ornamental plants and fish might be more suitable for such systems until safety is thoroughly verified [45]. Wastewater hydroponics has been effective in pollutant removal, achieving high removal rates for COD, nitrogen, and phosphorus, although it faces challenges such as high energy consumption and public acceptance [46]. In hydroponic systems, nutrient recycling is crucial, with technologies like aerobic mineralization being used to treat aquaculture effluent, making nutrients more available for plant uptake [47]. The presence of bacterial communities capable of degrading complex polysaccharides and phytate further enhances nutrient cycling in aquaponics, contributing to the mineralization of plant nutrients [48]. The recycling mechanisms mentioned show how CE implements key SDGs in hydroponics and aquaponics.

4 Automation technologies in hydroponic and aquaponic systems

Automated nutrient and pH management systems in hydroponic and aquaponic systems have been significantly advanced by integrating various technologies, including IoT, AI, and fuzzy logic. In hydroponics, these systems are designed to optimize plant growth by precisely controlling environmental factors such as pH, temperature, and nutrient levels. For example, systems utilizing Arduino controllers and sensors can automatically adjust pH and Total Dissolved Solids (TDS) levels, ensuring optimal conditions for plant growth [49]. Similarly, systems integrating AI-based fuzzy logic algorithms enable real-time monitoring and control of nutrient solutions, enhancing the precision of nutrient dosing and temperature regulation, which are critical for plant health [50]. The use of the Nutrient Film Technique (NFT) in automated systems further reduces manual workload by regulating environmental factors like temperature and humidity, thus promoting sustainable crop production [51]. In aquaponics, the integration of fuzzy logic and machine learning models facilitates the management of water chemistry, including dissolved oxygen, TDS, and pH levels, which are crucial for maintaining the symbiotic relationship between fish and plants [52, 53]. These systems can automatically adjust nutrient concentrations and environmental conditions, thereby reducing human intervention and improving efficiency [54, 55]. Moreover, decision tree logic has been applied to automate the control of water temperature, pH, and lighting in aquaponics, achieving high accuracy and precision in maintaining optimal conditions for both plant and fish growth. Overall, the integration of these advanced technologies in automated nutrient and pH management systems not only enhances the efficiency and sustainability of hydroponic and aquaponic farming but also provides scalable solutions to meet the growing food demands amid challenges such as climate change and urbanization [56].

4.1 Use of sensors in hydroponic and aquaponic systems

The integration of sensors in hydroponic and aquaponic systems has significantly advanced the efficiency and sustainability of these agricultural practices. In hydroponics, sensor fusion and IoT technologies are employed to autonomously monitor and regulate environmental conditions, thereby enhancing plant yield and reducing human intervention. For example, a smart hydroponic system utilizing sensor fusion and the Random Forest algorithm can prioritize and adjust ambient parameters, achieving substantial energy savings in temperature, water level, and light regulation

[57]. Additionally, the use of spectroscopic sensors, such as the AS7265x, in micro indoor smart hydroponics allows for precise monitoring of nutrient concentrations, particularly nitrogen, which is crucial for plant growth. This system has demonstrated significant accuracy in predicting nutrient levels, thereby optimizing plant growth [58, 59]. Ion Selective Electrodes (ISEs) are also pivotal in hydroponics, offering precise monitoring of specific nutrients like nitrates and potassium, which are essential for crop optimization [60, 61]. In aquaponics, sensors play a crucial role in maintaining the health of both fish and plants. Advanced IoT monitoring systems can track water quality and fish behavior, ensuring optimal conditions for aquaculture and plant cultivation. These systems utilize wireless sensor networks to monitor parameters such as water quality and fish activity, which are essential for sustainable aquaponic operations [36, 62]. Moreover, modular IoT systems with edge computing capabilities have been developed to facilitate remote monitoring and intelligent control of aquaponic environments, ensuring the optimal balance between fish and plant growth [63]. Overall, deploying sensors in hydroponic and aquaponic systems not only enhances productivity and sustainability but also reduces resource consumption, making these systems viable solutions for addressing food security challenges in urban settings [64].

Various sensors are employed in hydroponics and aquaponics systems to monitor critical water quality parameters essential for the health and productivity of plants and aquatic life. Commonly monitored parameters and their sensors used in smart farming are shown in Table 2, which include temperature, pH, dissolved oxygen (DO), turbidity, ammonia, TDS, and so on.

4.2 Lighting automation

Lighting automation in hydroponic and aquaponic systems is a critical component for optimizing plant growth and energy efficiency. The integration of IoT technologies and automatic control algorithms, as proposed by Abdelkader et al. [69], allows for precise and centralized control of lighting conditions in indoor farming, which is essential for maintaining an ideal environment for plant growth while minimizing energy consumption. In hydroponic systems, the manipulation of Daily Light Integral (DLI) and LED spectrum has been shown to significantly impact the growth and nutritional quality of crops like spinach, with specific light conditions enhancing photosynthetic rates and reducing energy consumption by over 38% compared to traditional lighting methods [70]. Similarly, Boucher et al. [71], demonstrated that extending the photoperiod while reducing light intensity can increase biomass production and light use efficiency in organically grown leafy greens, suggesting a cost-effective strategy for indoor cultivation. In aquaponic systems, Fernández-Cabanás et al. [72], found that vertical systems with optimized light distribution significantly outperformed horizontal systems in terms of productivity, highlighting the importance of strategic light supplementation in maximizing yield. Moreover, the use of sensor fusion and intelligent control systems, as described by Bhargava et al. [57], can enhance energy efficiency by prioritizing environmental parameters based on real-time data, achieving substantial power savings during light

Table 2 Sensors used to monitor different water quality parameters

Sl No	Parameter	Sensor	Literature
	Temperature monitoring	DFRobot DS18B20s	[65, 66]
		Sensirion SCD30	[67]
		DS18B20	
	Humidity	Sensirion SCD30	[67]
	CO_2	Sensirion SCD30	[67]
		DFROBOT infrared	[66]
	pH levels	GI electronic E-201-C	[65, 68]
		Grove—PH	[67]
		DFROBOT gravity analog-SEN0161	[66]
	Sunlight	SI1145	[67]
	Dissolved oxygen	DFRobot SEN0237-A	[65]
		DFROBOT analog DO	[66]
	Ammonia levels	MQ135 gas sensor	[68]
	Turbidity	DFROBOT analog	[66]
	TDS	DFROBOT analog TDS	[66]

regulation. The automation of lighting systems, such as those used in photobioreactors, also allows for precise control of light distribution and intensity, which is crucial for the growth of photosynthetic organisms [73]. Overall, the strategic automation and optimization of lighting in hydroponic and aquaponic systems not only improve plant growth and quality but also contribute to the sustainability and economic viability of indoor agriculture [74, 75].

4.3 Robotics integration

Planting and harvesting robots in hydroponic and aquaponic farming systems are increasingly being developed to enhance efficiency and productivity. In hydroponic systems, a novel grabbing mechanism has been designed for harvesting leafy vegetables like Chinese kale. This mechanism uses double-pivot rotation cross fingers to envelop and center the vegetable stalks before extraction, achieving a high grabbing success rate of over 95% when optimized for specific inclination angles and deflection speeds [76]. In aquaponics, which integrate Recirculating Aquaculture Systems (RAS) with hydroponics, the growth of plants such as spinach and fish like rainbow trout has been studied. The aquaponic system showed advantages in fish growth and water quality, with faster nitrification onset compared to separate systems, although spinach growth was similar in both aquaponic and hydroponic setups [9]. Robotic systems for selective harvesting, such as those used for strawberries, are being enhanced with technologies like 5G networks to improve processing speed and accuracy, although achieving cost parity with human labor remains a challenge [77]. Monitoring robots, particularly in hydroponic greenhouses, utilize deep learning algorithms for tasks like detecting and classifying tomato maturity, achieving high detection accuracy [78]. The integration of robotics in plant production involves various tasks, including transplanting and harvesting, with robots needing to adapt to changing plant shapes and environmental conditions [79]. Additionally, smart image recognition systems using neural networks are being developed to improve crop maturity detection and robotic arm precision in harvesting [80]. Despite these advancements, aquaponic systems face challenges in achieving commercial success due to design issues that affect economic viability, highlighting the need for better integration of water treatment and production timelines [81]. Overall, the development of robotic systems in hydroponic and aquaponic farming is a promising area that addresses labor shortages and aims to increase agricultural productivity, although further advancements are needed to overcome existing challenges [82, 83].

4.4 Use of actuators in hydroponic and aquaponic systems

Actuators play a crucial role in enhancing the efficiency and functionality of hydroponic and aquaponic systems by enabling precise control over environmental conditions and resource management. In hydroponic systems, actuators are employed to optimize parameters such as humidity and water levels, which are critical for plant growth. For example, a fuzzy logic control-based optimization scheme has been developed to manage these parameters efficiently, resulting in an 18% reduction in energy consumption compared to traditional methods [84]. Similarly, in aquaponic systems, actuators can be integrated to improve water treatment and nutrient management, as demonstrated by the use of a dynamic root floating technique that enhances both plant yield and water quality [85]. The integration of smart technologies, such as IoT-enabled systems, further enhances the precision and sustainability of these agricultural methods. For example, IoT frameworks have been successfully applied in hydroponic systems for crops like saffron, providing optimal growth conditions through real-time monitoring and control [86]. Additionally, novel actuator designs inspired by natural phenomena, such as electric-responsive water layer actuators and forward osmosis-based actuators, offer low power consumption and effective force generation, which are beneficial for sustainable agricultural practices [87, 88]. These advancements in actuator technology not only improve the operational efficiency of hydroponic and aquaponic systems but also contribute to the broader goal of meeting future food demands through high-productive agricultural technologies [83]. Overall, the integration of advanced actuators in these systems represents a significant step towards achieving sustainable and efficient agricultural practices.

4.5 Monitoring drones in large-scale operations

The integration of drones in hydroponic and aquaponic farming offers significant advancements in monitoring and management, leveraging the capabilities of unmanned systems and the IoT. Drones equipped with sensors can efficiently monitor environmental parameters such as water quality, temperature, and pollutants, which are crucial for aquaculture farm management, reducing labor costs and enhancing precision in data collection [89]. In greenhouse settings, drones can be part of a distributed environmental monitoring system that utilizes IoT technology to gather real-time data on air and water temperatures and dissolved oxygen levels, facilitating effective production management in combined hydroponic and aquaponic systems [90]. Moreover, drones can play a pivotal role in monitoring heavy metal concentrations in hydroponic solutions, using machine learning models to ensure optimal nutrient levels for plant growth, thus addressing long-standing concerns about heavy metal accumulation in aquaponic environments [91]. The use of drones extends to environmental compliance, where they provide aerial views that enhance the robustness of monitoring processes, although regulatory challenges regarding data capture and usage remain [92]. Additionally, drones can be integrated with Wireless Sensor Networks (WSNs) to improve data transmission efficiency and energy utilization, offering a comprehensive approach to long-term farmland quality assessment [93]. In agriculture, drones facilitate rapid phenotyping of plant traits, such as biomass and nitrogen content, through vegetation indices, thereby enhancing crop monitoring and yield optimization [94]. Moreover, drones are instrumental in plant disease assessment, offering high-resolution, cost-effective, and rapid detection capabilities that surpass traditional methods, thus enabling early intervention and reducing pesticide use [95]. The potential of drones in agriculture is further supported by advancements in wireless power transfer technologies, which address limitations related to drone flight time and power consumption, thereby extending their operational capabilities in smart agriculture applications [96]. Overall, drones represent a transformative tool in hydroponic and aquaponic farming, providing enhanced monitoring, data collection, and management capabilities that support sustainable agricultural practices [97].

4.6 Maintenance and cleaning robots

Maintenance and cleaning robots play a crucial role in enhancing the efficiency and sustainability of hydroponic and aquaponic farming systems. These systems, which integrate aquaculture and hydroponics, benefit significantly from automation to ensure optimal conditions for plant and fish growth. Specific examples of smart systems include the use of IoT-based systems for real-time monitoring and control of nutrient concentrations, such as calcium, sulfate, and phosphate, as demonstrated by a smart sensing and actuation system that controls heavy metal concentrations to optimize lettuce growth [91].

In aquaculture, the cleaning of large tanks is vital to prevent oxygen depletion and pathogen spread, and a modular mechanical rotary device has been developed to automate this labor-intensive task, significantly improving biosolid removal [98]. Reconfigurable robots, capable of adapting their morphology to different cleaning tasks, offer enhanced area coverage and adaptability, making them suitable for various maintenance operations in farming environments [99]. The Mark IV maintenance robot, with its multi-joint structure and shape memory alloy actuators, exemplifies advancements in robotic adaptability, allowing it to navigate complex surfaces like pipelines and storage tanks [100].

In fish processing plants, robotic cleaning systems have been shown to perform as well as or better than manual cleaning, reducing labor and contamination risks [101, 102]. The integration of smart systems, such as cable-driven parallel robots, in aquaponics supports automation by enabling tasks like sowing and irrigation, improving resource efficiency and crop quality [103].

These examples illustrate how smart systems and IoT technologies are integral to scaling aquaponics systems commercially. By enabling precise monitoring and control of environmental parameters, they significantly enhance operational efficiency and support sustainable agricultural practices. The comparison of different automation technologies and their applications in hydroponics and aquaponics is provided in Table 3.

5 Case studies of large-scale implementations

5.1 Case studies on automated hydroponic facility (AHF)

5.1.1 Operational scale, technologies used, and outcomes

Hydroponic systems, as demonstrated in various case studies, offer a promising alternative to traditional agriculture by optimizing resource use and enhancing crop yields. In Nigeria, hydroponics has proven economically viable for both small- and medium-scale operations when ten hydroponic farms were evaluated, with positive Net Present Values (NPVs) of 15% discount rate and 83% high internal rates of return (IRR), despite the high initial investment required [115]. Technological advancements, such as the use of artificial intelligence and plant growth-promoting rhizobacteria, have further enhanced hydroponic systems, particularly in the cultivation of potato mini-tubers, which are crucial for food security

Table 3 Comparison of different automation technologies and their applications in hydroponics and aquaponics

Technology	Application in hydroponics	Application in aquaponics	Benefits	Challenges	References
IoT systems	Real-time monitoring of environmental conditions (e.g., pH, temperature, humidity)	Real-time monitoring of water quality, fish health, and nutrient levels	Improved precision and control, reduced labor	Initial setup cost, maintenance	[33–35, 104]
Automated nutrient delivery	Precise delivery of nutrients based on plant needs	Automated dosing of nutrients to maintain optimal fish and plant health	Consistent nutrient supply, reduced waste	Calibration and maintenance	[33, 105]
Automated climate control	Regulation of temperature, humidity, and light	Regulation of water temperature and oxygen levels	Enhanced plant growth, energy efficiency	System complexity, cost	[106–108]
Robotics	Automated planting, harvesting, and pruning	Automated feeding, cleaning, and monitoring of fish tanks	Labor reduction, increased efficiency	High initial investment, technical expertise	[33, 109]
Data analytics	Analysis of growth data to optimize conditions	Analysis of fish growth and health data to optimize feeding schedules	Data-driven decision-making, improved yields	Data privacy, integration with existing systems	[110–112]
AI and machine learning	Predictive maintenance, anomaly detection	Predictive maintenance, optimization of aquaponic cycles	Proactive issue resolution, enhanced productivity	Data quality, algorithm training	[33, 113, 114]

in regions facing climate challenges with benefit in saving water, energy, and space [116]. The Nutrient Film Technique (NFT) is widely used globally for its efficiency in water conservation and year-round production of vegetables like tomatoes, cucumbers, and leafy greens to obtain around 70 to 90% savings of water [117]. In India, hydroponic urban farming models have been assessed for environmental sustainability, with greenhouse farming showing lower greenhouse gas emissions compared to other models (indoor farming, cabinet selling and remote monitoring, and conventional farming) [118]. In remote areas, innovations like self-fertigation systems have enabled hydroponic cultivation without electricity, as seen in the successful growth of spinach in Indonesia (with superiority in calcium, iron, phosphorus and vitamin C in green spinach, and superiority of potassium and magnesium in red spinach) [119]. In Western Greece, hydroponic tomato greenhouses have shown economic feasibility over five years resulting from the efficiency of hydroponic systems showing up to 11 ± 1.7 higher yields, although adoption remains limited [120]. Despite higher energy consumption, hydroponic systems offer significantly higher yields compared to conventional methods, making them a viable option for sustainable agriculture [121]. Smart hydroponics, utilizing real-time monitoring and smart sensing devices, have demonstrated superior growth responses in crops like lettuce, further enhancing productivity and resource efficiency [122]. The integration of nanoparticles and beneficial microorganisms in hydroponic solutions has improved nutrient management, supporting the system's role in sustainable agriculture [111]. Additionally, hydroponic systems have been explored for dual purposes, such as treating greywater while cultivating crops like lettuce, although nutrient supplementation is necessary for optimal plant growth [123]. Overall, hydroponic systems represent a versatile and sustainable approach to modern agriculture, capable of addressing food security and environmental challenges.

Hydroponic systems operate at various scales, each with distinct characteristics and applications, as observed in multiple case studies. The NFT and Deep Water Culture (DWC) are two prevalent designs, with DWC often outperforming NFT in terms of water quality and yield, particularly in controlled environments like greenhouses [124, 125]. These systems are part of a broader category that includes aeroponics, flood and drain, continuous drip systems, and the wick method, each offering unique advantages and risks, particularly concerning pathogen internalization in leafy vegetables [124]. The operational scale of hydroponics can range from small-scale, nonrecirculating systems suitable for low-nutrient concentration studies [126], to large-scale applications using innovative techniques like fertilizer drawn forward osmosis, which is particularly beneficial in arid regions with limited freshwater resources [127]. Vertical farming, enabled by smart sensing devices, represents another operational scale, enhancing year-round production and resource efficiency, albeit with higher energy consumption compared to substrate cultivation [122]. The choice of system and scale often depends on the specific crop and environmental conditions, as seen in the cultivation of potatoes and lettuce, where hydroponics has shown to significantly improve yield and quality while reducing water and space requirements [116, 128]. Moreover, hydroponic systems are adaptable to organic farming practices, although the compatibility of organic fertilizers with different systems requires further exploration [128]. Overall, the operational scales of hydroponic systems are diverse, ranging from small experimental setups to large commercial operations, each tailored to optimize growth conditions and resource use for specific crops and environments [129–131].

5.1.2 Case studies from different regions on AHF

Automated hydroponic facilities have been explored in various regions, each adapting to local challenges and leveraging technology to optimize plant growth. In Qatar, an indoor vertical hydroponic system was developed to overcome the harsh desert climate, utilizing IoT for remote monitoring and control, which significantly reduced water consumption (only 8–10 L) and allowed for the cultivation of food crops in limited spaces in the gulf region [132]. Similarly, a study in Southern Italy compared high-tech hydroponic greenhouses with traditional soil-based systems (using fossil fuel and fertilizers), finding that the former, with its automated climate and lighting controls, significantly reduced environmental impacts through renewable energy use and closed-loop systems [133]. In Canada, a framework was proposed for retrofitting industrial spaces with renewable energy-assisted hydroponics, aiming to provide fresh produce in rural northern communities despite high greenhouse gas emissions compared to traditional supply chains [134]. Meanwhile, a study in India highlighted the potential of hydroponics in sustainable agriculture, particularly for potato mini-tuber production, emphasizing the system's efficiency in resource use and its adaptability to climate change [116]. In another case, a smart hydroponic system using sensor fusion and the Random Forest algorithm was developed to autonomously regulate environmental conditions, achieving significant energy savings in India [57]. These case studies collectively demonstrate the versatility and potential of automated hydroponic systems across different regions, addressing local agricultural challenges through innovative technological solutions.

Robotics in hydroponic systems has been explored through various case studies across different regions, showcasing diverse applications and technological advancements. In South Korea, a real-time monitoring robot system was developed for hydroponic tomato greenhouses, utilizing Faster R-CNN for fruit detection and a centroid-based tracking algorithm for counting, achieving a detection accuracy of 90.2% when excluding obscured fruits [78]. In Iran, a robot was designed for monitoring iron nutrient levels in spinach within greenhouses, employing artificial neural networks and support vector regression to detect deficiencies with an accuracy of 96% and taking corrective actions through foliar spraying [135]. In China, a mobile robotics platform was developed for precision indoor farming of strawberries, integrating perception systems and a soft gripper for nondestructive harvesting, achieving a mean average precision of 96.4% for ripe strawberries [136]. In Japan, a miniature robot was created for seedling transplantation in tissue culture vessels, using shape memory alloy actuators to handle delicate plant stalks, thus improving efficiency and reducing manual labor [137]. In Qatar, an IoT-based automated vertical hydroponics system was constructed to address the challenges of growing food in arid climates, allowing for remote monitoring and control of environmental parameters, thereby optimizing plant growth and resource use [132]. These studies highlight the potential of robotics to enhance efficiency, precision, and sustainability in hydroponic systems, addressing challenges such as labor shortages, resource management, and environmental constraints across different agricultural circumstances.

5.1.3 Productivity metrics of pre- and post-automation in AHF

The integration of automation in hydroponic systems has significantly impacted productivity metrics, as evidenced by various studies. In strawberry cultivation, the use of a Frequency Domain Reflectometry (FDR) sensor-automated irrigation system resulted in a 1.2 fold increase in Water Use Efficiency (WUE) compared to conventional timer-based irrigation, with a 41% reduction in fertilizer costs, while maintaining similar plant growth and fruit yield [138]. Similarly, an IoT-based automated vertical hydroponic system in Qatar demonstrated efficient resource use, consuming only 8–10 L of water monthly while circulating 104,000 gallons of nutrient solution, highlighting the system's capability to maintain optimal growing conditions with minimal human intervention [132]. In plant factories, automated weight measurement systems have been developed to continuously monitor plant growth, providing precise data that can enhance productivity by optimizing growth conditions [139]. Moreover, a sensor-fusion based intelligent hydroponic system employing the Random Forest algorithm has shown a 20.4% reduction in peak power consumption during temperature and water level regulation, and an 82.1% reduction during light regulation, thus improving energy efficiency [57]. In terms of nutrient management, a low-cost spectroscopic system for microscale smart hydroponics has been effective in maintaining nutrient levels, resulting in superior plant growth compared to traditional methods [59]. Automation in fertigation using electrotensiometers has also improved water and nutrient productivity in horticultural crops by optimizing irrigation based on soil moisture levels [140]. Additionally, the use of robotic systems in greenhouses, although initially less efficient than skilled human labor, offers the advantage of continuous operation, potentially increasing daily production significantly with improvements in technology [141]. These advancements in automation and digital technologies in hydroponics not only enhance productivity but also contribute to sustainable agricultural practices by optimizing resource use and reducing environmental impact [142]. Overall, the adoption of automated systems in hydroponics presents a promising avenue for increasing efficiency and productivity in agricultural practices [143].

5.2 Case studies on automated aquaponic facility (AAF)

5.2.1 Case studies on operational scale, technologies used, and outcomes

Aquaponic systems, which integrate aquaculture and hydroponics, have been explored across various operational scales, employing diverse technologies, and yielding distinct outcomes. The operational scale of aquaponic systems varies significantly, from small-scale setups for personal use to large commercial operations. For example, in the United States, system sizes range from 50 to 3,000 ft^2, with hobbyists and educators typically operating smaller systems compared to producers [144]. In Berlin, a large-scale urban aquaponic scenario was proposed to meet the city's annual demand for fish and vegetables, requiring 370 facilities covering 224 hectares [145]. In Egypt, pilot-scale investigations demonstrated the potential of aquaponics as a sustainable alternative to conventional agriculture, highlighting its long-term profitability and significant water savings [146]. Technologically, aquaponic systems often utilize coupled systems integrating recirculating aquaculture systems with deep-water culture or media bed hydroponics [144]. Advanced systems incorporate technologies like moving bed bioreactors and sand filters for efficient nutrient cycling and water treatment, as seen in marine aquaponics [147]. In urban settings, digital twin systems and machine learning have been employed to enhance decision-making and system management [148]. The outcomes of aquaponic systems are promising, with high-quality organic produce and efficient use of resources being common benefits. For example, in Egypt, aquaponics produced safe organic food with reduced capital and operational costs compared to conventional methods [146]. In Brazil, a marine aquaponics system demonstrated economic feasibility, particularly when premium pricing strategies were applied [149]. However, challenges remain, such as the need for increased knowledge and institutional support to ensure sustainable outcomes [150]. Despite these challenges, aquaponics continues to grow as a viable solution for sustainable food production, with potential economic gains from organic certification and renewable energy integration [151]. Overall, aquaponics presents a multifaceted approach to addressing food security and sustainability, with diverse applications and outcomes across different circumstances.

Aquaponic systems operate at various scales, each with distinct characteristics and applications, as observed in multiple case studies. Small-scale systems, often used for educational purposes or as hobbies, typically range from 50 to 500 ft^2 and are prevalent among hobbyists and educators in the United States [144]. These systems are frequently homemade incorporating commercially available technology, and are adapted for urban settings, such as rooftops, particularly in Spain and Latin America [152]. Medium-scale systems, which range from 500 to 3,000 ft^2, are more common among producers who aim for commercial viability. These systems often employ coupled designs integrating Recirculating Aquaculture Systems (RAS) with hydroponic units like DWC or media beds [144]. In contrast, larger commercial systems, exceeding 500 m^2, are increasingly adopting decoupled multi-loop designs, which separate the RAS and hydroponic units to optimize resource use and improve crop and fish cultivation [153]. These systems are being integrated into greenhouse farming, as seen in Iceland, where they support both fish and plant production, leveraging local market conditions and environmental factors such as long daylight hours. Upscaling aquaponics to meet urban demands, such as in Berlin, involves extensive planning and resource allocation, with potential facilities covering hundreds of hectares to meet the food needs of millions [145]. The transition to commercial scales is supported by advancements in nutrient management, as demonstrated by the use of RAS effluents, which provide sufficient nutrients for plant growth, although supplementation with potassium and certain micronutrients may be necessary [154]. Overall, the operational scales of aquaponic systems are diverse, ranging from small educational setups to large commercial operations, each tailored to specific environmental, economic, and social circumstances [155].

5.2.2 Case studies from different regions on AAF

Automated aquaponic facilities have been explored in various regions, each with unique challenges and innovations. In Jordan, the Khodra facility exemplifies regional adaptation by optimizing cooling and heating systems to suit local climates, demonstrating that ventilation and shading can significantly reduce temperatures, while HVAC systems manage humidity effectively in different environments like Qatar [156]. In Spain and Latin America, small-scale aquaponic systems are primarily driven by motivations such as producing high-quality food and environmental concerns, with many facilities located in urban settings like rooftops, utilizing techniques like the nutrient film technique for hydroponics [152]. In the U.S. Midwest, a techno-economic analysis of a tilapia-lettuce system highlights the economic viability of aquaponics, emphasizing the importance of labor and facility costs, and showing that automated water quality monitoring can enhance profitability [157]. IoT-based predictive analytics have been integrated into aquaponics to enhance monitoring and control, as demonstrated by projects with multiple demonstration sites, which use IoT to improve remote maintenance and economic optimization [158]. The integration of smart systems and IoT technologies is crucial for the automation of aquaponics, with recent advancements focusing on precision farming techniques to make commercial-scale operations feasible [102]. In terms of resource optimization, process monitoring and graph-theoretical approaches have been used to enhance profitability and energy efficiency, with techniques like reflective foils improving light energy use [159]. Multi-loop aquaponics systems, which separate aquaculture and hydroponic units, have been modeled to optimize system sizing across different climates, showing the importance of plant transpiration dynamics in system design [153]. Additionally, latitude-dependent lighting regimes have been studied to understand their impact on plant physiology and resource utilization, indicating that geographic differences in solar radiation significantly affect aquaponics design and efficiency [160]. Finally, Machine Learning (ML) models have been applied to optimize nutrient supply in commercial aquaponic operations, identifying key nutrient predictors and using sensors and actuators to maintain optimal conditions for plant and fish growth [161]. These case studies collectively illustrate the diverse approaches and technological innovations being applied to automate and optimize aquaponic facilities across different regions.

Robotics in aquaponic systems has been explored through various case studies across different regions, highlighting the integration of technology to enhance efficiency and sustainability. In the Faroe Islands, the Netherlands, and Namibia, a simulation model was developed to optimize aquaponic system sizing based on plant transpiration dynamics, demonstrating the importance of adapting system components to regional climates for optimal resource use and productivity [153]. In Jordan and Qatar, energy-efficient cooling and heating strategies were evaluated, showing that regional climate considerations are crucial for maintaining optimal conditions for plant and fish growth in aquaponic systems [156]. The integration of IoT and predictive analytics has been shown to significantly enhance aquaponic management by enabling robust remote monitoring and predictive maintenance, as demonstrated in a project with five demonstration sites across different geographical locations [158]. In Spain and Latin America, small-scale aquaponic facilities have been characterized, revealing that these systems are often used for educational purposes and self-consumption, with a focus on producing high-quality, healthy food [152]. The use of digital twin technology in urban aquaponics has been explored as a decision support system, providing adaptive capabilities and data-driven analytics to optimize production in urban settings [148]. Additionally, the application of deep learning algorithms, such as YOLO v4, has been utilized to monitor fish locomotion in aquaponic systems, offering insights into fish health and system optimization [162]. These case studies collectively illustrate the diverse applications and benefits of integrating robotics and advanced technologies in aquaponic systems across different regions, emphasizing the potential for these systems to contribute to sustainable food production and resource management.

5.2.3 Productivity metrics pre- and post-automation in aquaponic system

The integration of automation in aquaponic systems has significantly influenced productivity metrics, enhancing both efficiency and economic viability. Pre-automation, aquaponic systems relied heavily on manual labor and traditional monitoring methods, which were labor-intensive and less precise. For example, a techno-economic analysis of a recirculating aquaponics system highlighted labor as a major cost, constituting 52% of annual operating expenses, with profitability hinging on labor and facility costs [157]. Post-automation, the introduction of IoT-based predictive analytics and automated monitoring systems has revolutionized aquaponics. These technologies enable real-time monitoring and control, reducing labor costs and increasing NPV significantly, as seen in a study where automated water quality monitoring increased NPV 9,000 to over 52,000 [157]. IoT systems, when integrated with existing frameworks like MES, enhance process control and responsiveness, ensuring optimal execution in aquaponics plants [158]. Moreover, automation has improved resource optimization, with techniques like process network synthesis and real-time crop monitoring leading to a ninefold increase in annual net income and significant energy savings [159]. Automated systems also facilitate precise monitoring of plant growth and health, as demonstrated by computer vision systems estimating crop size and weight with minimal error [163]. Additionally, specific smart technologies have led to improved water and energy use efficiency. For example, the implementation of sensor-based automated irrigation systems has optimized water use by delivering precise amounts of water to plants based on real-time soil moisture data, reducing water waste significantly. Similarly, the adoption of energy-efficient LED grow lights, combined with automated dimming controls, has minimized energy consumption during plant growth cycles, achieving significant energy savings when compared to traditional lighting systems [164]. Overall, the shift towards automation in aquaponics has not only enhanced productivity metrics but also contributed to the sustainability and economic feasibility of these systems, making them a viable solution for modern agricultural challenges.

6 Benefits of automation and robotics

6.1 Data on yield improvement and consistency in hydroponic systems

Hydroponic systems have demonstrated significant potential for yield improvement and consistency across various crops, as evidenced by multiple studies. The modified hydroponic kit designed for remote areas, which operates without electricity, successfully cultivated spinach with notable productivity, particularly for the green variety, which yielded 1.34 kg/m^2 compared to 0.71 kg/m^2 for the red variety [119]. In lettuce cultivation, nutrient solution deprivation three days before harvest enhanced nutritional quality with minimal yield loss, suggesting a strategy for improving sustainability and quality in hydroponic systems [165]. The integration of plasma-nanobubble hybrid technology in hydroponics resulted in a 60% yield increase for lettuce, attributed to improved nutrient solution properties and antimicrobial effects

[166]. In tomato cultivation, closed hydroponic systems significantly enhanced water productivity by 54.3% compared to open systems, without compromising yield, highlighting the efficiency of nutrient and water use [167]. Aquaponic systems, which combine aquaculture and hydroponics, showed that hydraulic loading rates significantly affect crop yield and quality, with higher rates improving nutrient uptake and biomass production in fast-growing crops like lettuce [168]. The inoculation of lettuce with Bacillus subtilis in hydroponic systems increased yield and nutrient acquisition, demonstrating the potential of microbial inoculants to enhance hydroponic crop performance [169]. Comparisons between aquaponic and hydroponic systems revealed that while aquaponics generally resulted in lower yields for basil and lettuce, it maintained similar yields for tomatoes, suggesting crop-specific responses to nutrient availability [168]. In cannabis cultivation, recirculation systems in hydroponics achieved higher yields of cannabinoids with reduced water and nutrient consumption, although with longer cultivation times [170]. Hydroponic cultivation of soybeans improved nutritional quality by increasing fat and dietary fiber content, indicating the system's ability to enhance specific nutritional attributes [171]. Lastly, intercropping in aquaponic systems improved the sweetness of lettuce and altered the taste profile of red chicory, suggesting a method for enhancing vegetable quality through species interactions [172]. Collectively, these studies underscore the versatility and effectiveness of hydroponic systems in improving yield and consistency across diverse crops, while highlighting the importance of system-specific optimizations for maximizing benefits.

6.2 Data on reduced labor and labor cost requirements in hydroponic farming

Hydroponic farming has demonstrated significant reductions in labor and labor costs, primarily through automation and efficient resource management. Automated systems, such as those developed for controlling pH and nutrient concentrations in hydroponic lettuce production, have been shown to reduce labor requirements by enabling precise and continuous monitoring and adjustment of growing conditions, leading to faster harvests and increased productivity compared to conventional soil farming [173]. The concept of 'hydroponic capital' further elucidates how hydroponics has intensified production efficiencies by reducing labor inputs and overcoming biophysical barriers, thus rationalizing labor use in agrifood production systems [174]. Various hydroponic techniques, including the Nutrient Film Technique (NFT), have been highlighted for their ability to minimize labor-intensive tasks such as weeding and watering, contributing to labor cost savings [117]. Additionally, the integration of IoT technologies in hydroponics has optimized resource usage and reduced operational costs, including labor, by automating environmental controls and energy consumption [84]. Moreover, the economic assessment of hydroponic systems, such as those in the UAE, suggests that local production can enhance employability while reducing dependency on imports, indirectly lowering labor costs associated with logistics and distribution [175]. Overall, the integration of advanced technologies and innovative practices in hydroponic farming significantly reduces labor requirements and costs, making it a viable and efficient alternative to traditional agriculture.

6.3 Data on yield improvement and consistency in aquaponic system

Aquaponic systems, which integrate aquaculture and hydroponics, have shown potential for improving yield and consistency in crop production, though challenges remain. Studies have demonstrated that aquaponics can be more efficient than traditional systems, with fish production being 29% and 75% more efficient than recirculatory and static aquaculture systems, respectively, and pumpkin yield in aquaponics being significantly higher than in irrigated and non-irrigated land [176]. However, nutrient management is crucial, as aquaponic systems often face deficiencies in essential nutrients like magnesium and calcium, which can limit crop yield and quality. Supplementing these nutrients, particularly magnesium before transplanting and calcium before fruiting, can enhance growth and quality, especially in high-quality water systems [168]. Tailored fish feeds enriched with potassium have been shown to improve plant growth without negatively impacting fish health, addressing nutrient imbalances inherent in conventional feeds [177]. Additionally, the use of decoupled aquaponic systems, which separate fish and plant production loops, has been found to eliminate bottlenecks such as pH management, resulting in a 36% increase in fruit yield compared to coupled systems [178]. The Hydraulic Loading Rate (HLR) also plays a significant role, with higher rates improving water quality and nutrient availability, thus enhancing crop growth and yield, particularly for fast-growing species [179]. Moreover, uniform feeding regimes can improve water quality and nutrient use efficiency, leading to better crop performance and yield comparable to hydroponics [179]. Despite these advancements, aquaponic systems still face challenges in achieving consistent yields across different crop types, as seen in the reduced yields of basil and lettuce compared to hydroponics, though tomato yields remain comparable [179]. Overall, optimizing nutrient management, feed composition, system design, and operational parameters are key to improving yield and consistency in aquaponic systems.

6.4 Data showing reduced labor and labor cost requirements in aquaponic farming

Aquaponic farming has shown potential for reducing labor and labor costs, although the extent varies across different systems and circumstances. In small-scale aquaponic systems, personal labor input is typically less than 20 h per week, indicating a relatively low labor requirement compared to traditional farming methods [144]. However, the economic sustainability of these systems can be challenging, as demonstrated by a study where small-scale aquaponic systems showed positive accounting profit but negative economic profit when labor costs were included, suggesting that while labor requirements are reduced, the cost of labor can still impact overall profitability [180]. In larger, commercial aquaponic systems, labor remains a significant cost contributor, alongside infrastructure and heating, accounting for over 89% of total costs [181]. Optimizing operational aspects such as aeration can further reduce costs; for example, semi-aeration techniques have been shown to improve energy efficiency and reduce aeration costs without significantly impacting product yields [182]. Additionally, urban aquaponics farms can benefit from optimized equipment operating schemes to minimize energy consumption, thereby indirectly reducing labor costs associated with energy management [183]. In coastal Bangladesh, cost-effective aquaponic systems using locally available inputs have demonstrated good returns on investment, suggesting that such systems can be economically viable with reduced labor costs, especially in regions vulnerable to climate change [184]. Overall, while aquaponic systems can reduce labor requirements, achieving economic sustainability often requires careful management of labor costs and optimization of system operations.

7 Environmental and economic analysis

7.1 Water and nutrient savings in hydroponic systems

Hydroponic farming systems have demonstrated remarkable efficiency in conserving water and nutrients. Studies highlight that smart nutrient solution management strategies, such as the NUTRISENSE (NTS) software, significantly optimize nutrient supply and prolong recirculation under saline conditions, leading to improved water conservation [185]. Similarly, automated irrigation systems utilizing FDR sensors in strawberry cultivation reduce irrigation volumes by 1.7 times and achieve 41% cost savings in fertilizers compared to conventional methods [138]. Vertical hydroponic systems for crops like lettuce save up to 88% of water while boosting yields [186]. Circular economy approaches, including drainage solution reuse, enhance water efficiency, reducing freshwater consumption by 30% and nitrate disposal by 40% [187]. Emerging technologies, such as nutrient recovery techniques and hybrid electrodialysis-forward osmosis processes, further highlight the potential of hydroponics to minimize environmental impacts and maximize sustainability [188, 189].

7.2 Water and nutrient savings in aquaponic systems

Aquaponic systems, which integrate aquaculture and hydroponics, provide significant environmental benefits by reusing fish waste as a nutrient source for plants, thereby reducing water consumption and minimizing the need for inorganic fertilizers [190]. Coupled Aquaponics (CAP) systems demonstrate nutrient use efficiency up to 42% higher than decoupled aquaponic systems (DCAP) or hydroponics, though nutrient imbalances in CAP can pose challenges [24]. DCAP systems, allowing independent control of aquaculture and hydroponics, show reduced greenhouse gas emissions while maintaining water and nutrient efficiencies similar to hydroponics [22]. Additionally, nutrient remineralization and innovative waste management practices enhance water quality and nutrient bioavailability, ensuring efficient resource utilization [40, 191]. These features make aquaponics particularly viable in regions with water scarcity and stringent environmental requirements.

7.3 Economic viability

The economic viability and cost–benefit analysis of hydroponic and aquaponic systems reveal distinct advantages and challenges for each approach. Hydroponic systems, as demonstrated in a study conducted in Brazil, show promising economic viability with an Net Present Value (NPV) of $177,845.74 and an Internal Rate of Return (IRR) of 30.45%, indicating a strong potential for profitability in emerging markets like Brazil [192].

In comparison, aquaponic systems integrate aquaculture with hydroponics, providing unique environmental benefits such as reduced water consumption and the use of fish waste as a nutrient source for plants, minimizing reliance on chemical fertilizers [16]. Despite these advantages, aquaponic systems face challenges related to high initial costs and the need for reliable electricity and nutrient management [10]. Larger aquaponic systems tend to be more economically viable, with profitability influenced by factors such as retail prices and business planning [193]. A life cycle assessment further highlights that aquaponic systems have about half the environmental cost of separate production systems, making them a more sustainable choice [194].

Innovations like the integration of biofloc technology in aquaponics (FLOCponics) have demonstrated potential for cost reduction through improved nutrient cycling and reduced feed costs, although the economic feasibility depends on achieving a high percentage of marketable produce [195]. Additionally, optimizing aeration patterns in aquaponics can enhance energy efficiency and lower greenhouse gas emissions, thereby improving both economic and environmental outcomes [182]. When evaluating nutrient efficiency, aquaponics demonstrates superior nitrogen and phosphorus use efficiency when considering both fish and plant biomass, although hydroponics remains more efficient when focusing solely on plant biomass [196]. While hydroponics offers a simpler economic model, aquaponics presents a sustainable alternative with significant long-term benefits, provided operational and market challenges are effectively addressed.

7.4 Integration of circular economy principles

Both hydroponic and aquaponic systems can incorporate circular economy principles to achieve sustainability goals. In hydroponics, practices like nutrient recycling and reusing waste streams significantly enhance resource efficiency. For instance, drainage solution reuse reduces freshwater consumption by 30% and nitrate disposal by 40% [187]. Similarly, aquaponics leverages waste streams from aquaculture to nourish crops, reducing dependency on external inputs and fostering a closed-loop system. These integrated approaches not only lower environmental costs but also align with sustainable agricultural practices that promote resource efficiency and environmental stewardship.

8 Challenges and limitations

8.1 Challenges in hydroponic farming

Hydroponic farming, while offering numerous advantages such as efficient resource management and year-round production, presents several challenges related to maintenance complexity and the need for technical expertise. One of the primary challenges is the requirement for precise control over environmental conditions, such as pH levels and nutrient concentrations, which necessitates the use of advanced technologies like auto-calibrated pH sensors and wireless sensor networks to ensure optimal plant growth [197]. The complexity of these systems can be daunting, requiring significant technical knowledge and expertise to manage effectively. Additionally, the integration of hydroponics with other systems, such as aquaponics, further complicates maintenance due to the need to balance water chemistry and manage potential infections in both plants and fish [10, 198]. The initial setup and operational costs can be high, and the systems often require stable electricity and continuous monitoring, which can be a barrier to adoption, especially in regions with less reliable infrastructure [10]. Moreover, the risk of rapid microbial contamination in hydroponic systems, due to the recirculating water, demands stringent phytosanitary measures and regular monitoring to ensure the microbial safety of the produce [199]. Despite these challenges, innovations such as IoT-based automated systems are being developed to reduce human intervention and simplify maintenance tasks, although these solutions still require a level of technical proficiency to implement and manage effectively [132]. Overall, while hydroponic systems offer sustainable agricultural solutions, their complexity and the technical expertise required for their maintenance remain significant hurdles that need to be addressed to facilitate broader adoption [117].

8.2 Challenges in aquaponic farming

Aquaponic farming, which integrates aquaculture and hydroponics into a closed-loop system, faces significant challenges in maintenance complexity and the need for technical expertise. One of the primary challenges is the intricate balance required to maintain optimal water chemistry and pH levels, which are crucial for the health of both fish and plants. This complexity is compounded by the need to convert toxic ammonium from fish waste into nitrate through bacterial biofilters, a process that requires precise management to ensure plant health and system sustainability [198, 200]. Additionally, aquaponic systems must manage microbial communities effectively, as these microorganisms play a critical role in nutrient cycling but can also compete with plants for essential micronutrients, necessitating careful supplementation and increasing operational complexity [201, 202]. The integration of microbial community-assisted technologies is emerging as a potential solution to these challenges, offering improved water quality control and nutrient recovery, yet these technologies are still in the developmental phase and not widely implemented [202]. Moreover, the lack of standardized operational and management practices poses a barrier to the widespread adoption and commercial viability of aquaponics, as systems must be tailored to specific environmental and biological conditions [203]. The economic feasibility of aquaponics is also a concern, with many systems struggling to achieve profitability due to high initial setup costs and the need for skilled labor to manage the complex interactions within the system [204]. Despite these challenges, aquaponics holds promise for sustainable food production, particularly in arid regions where water conservation is critical, but overcoming these technical and expertise-related hurdles is essential for its broader adoption [106].

8.3 Economic barriers to implementing hydroponic farming

Implementing hydroponic farming faces several economic barriers, as highlighted by various studies. One significant challenge is the high initial investment required, which can be a deterrent for small-scale farmers and entrepreneurs. For example, in Brazil, small farmers face difficulties in securing initial financing, which limits their ability to adopt hydroponic systems despite their interest in sustainable practices [205]. Similarly, in Nigeria, while hydroponic systems have shown economic viability with positive NPVs and internal rates of return, the high sensitivity to changes in running costs and revenue poses a risk, particularly for small-scale farmers [115]. In Greece, hydroponic systems are economically viable under most scenarios, but extreme scenarios with high installation and production costs can negate these benefits, highlighting the volatility and risk associated with agricultural markets [120]. Additionally, the energy costs associated with hydroponic systems, particularly in human-powered setups, contribute significantly to the overall economic burden, making them more expensive than conventional methods unless yields are significantly improved [206]. In emerging markets like Brazil, the economic viability of hydroponic systems is confirmed through financial metrics, but the sensitivity to price variations remains a concern [192]. Moreover, the lack of knowledge and experience among new entrants into the hydroponics and aquaponics sectors can lead to inefficiencies and increased costs, as many entrepreneurs lack prior training in these systems [207]. These barriers are compounded by the need for public intervention to support the industry, as some benefits of hydroponics, such as environmental sustainability, are external to the growers and not directly monetizable [207]. Overall, while hydroponic farming presents a promising alternative to sustainable agriculture, overcoming these economic barriers is crucial for its widespread adoption and success.

8.4 Economic barriers to implementing aquaponic farming

Aquaponic farming, while promising as a sustainable agricultural practice, faces several economic barriers that hinder its widespread implementation. One of the primary challenges is the high initial capital investment required to establish aquaponic systems, which is a significant deterrent for both small-scale farmers and commercial enterprises. This is compounded by the lack of large-scale projects that can demonstrate profitability, as seen in the EU and UK circumstances, where regulatory complexities further worsen the economic challenges [204, 208]. In Brazil, small farmers express interest in aquaponics due to its potential profitability and environmental benefits, yet they face barriers such as limited access to financing, insufficient human resources, and challenges in product placement [205]. Similarly, in India, the slow adoption of aquaponics is attributed to financial constraints and the need for better financial planning and risk management strategies [209]. The economic viability of aquaponics is also influenced by the scale of operations, with larger systems being more economically favorable due to economies of scale and sensitivity to retail prices [193]. Moreover, the environmental benefits of aquaponics, such as reduced water usage and lower environmental costs compared to separate systems, are often external to the grower, necessitating public intervention to internalize these benefits for profitability [194]. In Egypt, while aquaponics offers long-term profitability and significant water savings, the high initial and operational costs compared to conventional agriculture remain a barrier [146]. To overcome these economic barriers, policy interventions such as grants, organic certification, and streamlined licensing processes have been proposed, particularly in the UK, to enhance the economic feasibility of aquaponics [208]. Additionally, improving consumer perception and willingness to pay for aquaponic products, along with innovative business models, could further support the economic sustainability of aquaponics [193]. Overall, addressing these economic barriers through strategic planning, policy support, and consumer engagement is crucial for the successful implementation of aquaponic farming on a commercial scale.

8.5 Scaling up issues of hydroponic farming

Scaling up hydroponic farming presents several challenges, primarily related to cost, environmental impact, and technical feasibility. High initial investment and operational costs are significant barriers, as highlighted in studies from Nigeria and the UAE, where economic viability is contingent on subsidies and financial incentives [115, 175]. Energy consumption and greenhouse gas emissions are also critical concerns, with hydroponic systems often requiring substantial energy inputs for lighting and climate control, which can negate some of their environmental benefits [210]. Waste management is another pressing issue, as hydroponic systems generate Waste Nutrient Solutions (WNS) that contain high concentrations of nitrogen and phosphorus, leading to potential environmental degradation if not properly treated [211]. Innovative solutions, such as integrating bio-electrochemical systems, have been proposed to mitigate these issues by improving nutrient recovery and reducing wastewater generation [210]. Additionally, the use of municipal wastewater in hydroponics offers a dual benefit of waste treatment and nutrient recycling, although it poses health risks that need careful management [212, 213]. Technological advancements, such as the use of nanoparticles and plant growth-promoting rhizobacteria, are being explored to enhance nutrient uptake and system efficiency [111]. However, the scalability of these technologies remains uncertain, as they require further research and development to ensure stability and cost-effectiveness on a larger scale [210]. Moreover, the adoption of smart agriculture tools, including multi-element sensors and machine learning algorithms, could optimize nutrient management and reduce resource use, but these technologies also add complexity and cost to the systems [111]. Finally, the potential for hydroponics to contribute to food security, especially in arid regions, is significant, yet it requires supportive policies and infrastructure to overcome the initial hurdles of scaling up [175]. Overall, while hydroponics offers promising solutions for sustainable agriculture, its expansion is hindered by economic, environmental, and technical challenges that need to be addressed through integrated and innovative approaches.

8.6 Scaling up issues of aquaponic farming

Scaling up aquaponic farming presents several challenges that need to be addressed to achieve commercial viability. One of the primary issues is the complexity of system design, which requires a balance between aquaculture and hydroponics to optimize nutrient recycling and water use efficiency. Traditional linear designs often fail to meet the specific needs of both fish and plant production, leading to economic inefficiencies and limited scalability [81, 214]. The integration of RAS with Hydroponic Cropping Systems (HCS) into a single system, while beneficial for water conservation and nutrient recycling, often lacks the necessary optimization for hydraulic retention times, which is crucial for intensive production [214]. Moreover, the selection of appropriate fish and crop species, along with the development of salt-water aquaponics systems, remains a significant challenge [215]. Economic sustainability is another critical issue, as many aquaponic ventures struggle to achieve profitability due to high initial setup costs and the need for efficient supply chain management [216]. In Europe, for example, the commercial aquaponics sector has not yet reached economic viability, with many companies facing disillusionment due to these challenges [204]. Additionally, there is a need for clear guidelines and nomenclature to help stakeholders understand the different system designs and their potentials, which is essential for setting business priorities and regulations [155]. Technical challenges such as energy efficiency, pathogen control, and effective value chains also need to be addressed to enhance the adoption of aquaponics as a sustainable farming practice [216, 217]. Despite these challenges, aquaponics offers significant potential for sustainable food production, particularly in urban and resource-constrained environments, by providing a closed-loop system that reduces water usage and reliance on synthetic fertilizers [218]. Addressing these scaling issues through improved system designs, policy support, and stakeholder education could accelerate the adoption and success of aquaponics on a commercial scale [217].

8.7 Overview of challenges, their impact, and potential solutions

Hydroponic and aquaponic smart farming face several significant challenges. The high initial costs of setting up these systems can be prohibitive, especially for small-scale farmers. Additionally, the technical expertise required to manage these systems effectively can be a barrier, as they necessitate a deep understanding of both aquaculture and hydroponics.

The integration of IoT and AI in hydroponic and aquaponic systems enhances monitoring and resource efficiency, but it also brings challenges like cybersecurity risks, high costs, and the possibility of system failures. Moreover, the rise of automation could result in a decrease in conventional farming skills, highlighting the importance of training. To address these challenges, embracing secure, cost-effective, and farmer-centric technology solutions will promote sustainable and inclusive smart farming practices. Energy consumption is another critical issue, as maintaining optimal conditions for plant and fish growth can require substantial power. Moreover, managing pests and diseases in these closed systems can be difficult, as any infestation or infection can spread rapidly. Lastly, balancing the nutrients to meet the needs of both plants and fish demands constant monitoring and adjustments.

These challenges have notable impacts. Economically, the high costs and ongoing energy requirements (sensors, lighting, robotics, drones and actuators) can make smart farming systems less viable for smaller operators, especially in developing countries. Environmentally, while hydroponic and aquaponic systems generally use less water than traditional farming, their energy consumption can mitigate some of their environmental benefits. Additionally, the need for specialized knowledge and skills can limit the adoption of these technologies, potentially affecting food security in regions that could benefit most from innovative farming solutions. Addressing these issues requires multiple strategies. Reducing costs through technological innovation and economies of scale can help make these systems more accessible. Education and training programs are essential to equip farmers with the necessary skills. Enhancing energy efficiency by developing more efficient systems (through research and development) and integrating renewable energy sources (or off-grid solutions) can also mitigate the high energy demands. Implementing integrated pest management strategies can help manage pests and diseases effectively. Finally, utilizing automated monitoring systems to maintain optimal growing conditions can ensure nutrient levels and other critical parameters are consistently managed.

9 Technological innovations and future prospects

9.1 AI-driven predictive analytics for nutrient management

AI-driven predictive analytics for nutrient management in hydroponics and aquaponics is a burgeoning field that leverages ML and IoT technologies to optimize nutrient supply and improve plant growth. In aquaponics, where nutrient regulation is crucial for both plant and fish health, ML models have been developed to manage nutrient concentrations effectively. For example, techniques like Density-Based Synthetic Minority Over-sampling TEchnique (DB-SMOTE) and ExtraTreesClassifier have been used to handle small datasets and select relevant features for nutrient control, enhancing yield optimization [219]. Similarly, in commercial aquaponic operations, ML models utilizing XGBoost and Recursive Feature Elimination have identified ammonium and calcium as key nutrient predictors, with IoT sensors and actuators maintaining optimal concentrations for plant and fish growth [161]. In hydroponics, low-cost IoT-based spectroscopic systems have been developed to monitor and adjust nutrient levels, demonstrating significant improvements in plant growth compared to traditional methods [59]. Moreover, ML models such as Linear Support Vector Machines have been applied to small datasets to regulate nutrients in hydroponic environments, showing promising results in optimizing plant growth [113]. The integration of AI with sensor technology, as seen in the use of pre-trained convolutional neural networks for detecting nutrient deficiencies in hydroponic basil, further exemplifies the potential of AI in enhancing nutrient management systems [220]. Despite these advancements, challenges such as data scarcity, model reproducibility, and explainability remain, necessitating further research to improve the practical application of these technologies [221]. Overall, AI-driven predictive analytics holds significant promise for transforming nutrient management in hydroponics and aquaponics, contributing to sustainable agricultural practices and food security [222].

9.2 Blockchain for transparency in food supply chains

Blockchain technology holds promise for enhancing transparency and traceability in food supply chains, including its potential applications in hydroponics and aquaponics systems. By leveraging a decentralized and tamper-proof ledger, blockchain enables all stakeholders from producers to consumers to access verifiable information about the origin, production methods, and distribution of food products [223–225]. This capability aligns with the overarching goals of food safety, quality assurance, and sustainability in the context of modern agricultural practices.

In hydroponics and aquaponics, where precision control over environmental parameters is essential, blockchain can integrate with IoT sensors and data analytics to automate data monitoring and logging. This integration ensures real-time tracking of key metrics such as water quality, nutrient levels, and crop health, fostering operational efficiency while maintaining transparency [226]. Additionally, blockchain's immutable record-keeping can substantiate sustainability claims, mitigating risks of greenwashing and information misrepresentation. This feature empowers consumers to make informed choices and promotes trust within the supply chain [227].

Blockchain also enhances accountability by creating a secure, verifiable trail of transactions. In the agri-food sector, where food quality and safety are critical, this functionality helps maintain integrity across the supply chain. For example, in cases of food recalls or safety breaches, blockchain's traceability enables swift identification and resolution of issues, minimizing economic and reputational losses [228, 229]. Despite these advantages, challenges remain. High implementation costs, the need for regulatory alignment, and the interoperability of blockchain systems with existing supply chain technologies are significant hurdles [223, 230]. However, ongoing advancements in digital technology and the growing demand for transparent and sustainable food systems indicate that blockchain could become an integral component of future supply chains.

In conclusion, while blockchain may not yet be widely adopted in hydroponics and aquaponics, its potential to revolutionize food supply chains through improved traceability, transparency, and sustainability merits consideration. As these technologies evolve, their integration with blockchain could contribute meaningfully to achieving broader Sustainable Development Goals [224, 230].

9.3 Research gaps

Hydroponics, as a soilless cultivation system, presents numerous opportunities for sustainable agriculture, yet several areas require further research to optimize its potential. One critical area is the management of nutrient solutions, particularly the processes and mechanisms that ensure optimal nutrient acquisition without causing nutritional disorders. This includes understanding nutrient solubilization, precipitation, and interactions among nutrients, which are crucial for maintaining crop quality. Additionally, the occurrence and management of root exudates in closed hydroponic systems pose challenges, as these organic acids can inhibit plant growth. Effective methods for removing these phytotoxic substances, such as adsorption and photocatalysis, need further exploration to enhance system efficiency. The integration of wastewater treatment with hydroponics for nutrient recovery is another promising area. Current nutrient recovery processes from wastewater treatment plants are insufficient, meeting less than 11.5% of hydroponic nutrient demands. Developing multi-nutrient concentrates and improving recovery processes could significantly enhance nutrient supply for hydroponics [231]. Moreover, the high energy consumption associated with wastewater hydroponics and the complexity of control parameters necessitate research into reducing energy use and simplifying system management [46]. The potential of nutrient solution deprivation as a strategy to improve crop quality, as demonstrated in lettuce, also warrants further investigation across different crops to optimize yield and nutritional content. Moreover, the tolerance of various plant species to high pH and low nutrient conditions in aquaponics systems needs to be better understood to improve the integration of aquaculture and hydroponics. Finally, the application of emerging technologies such as artificial intelligence, nanoparticles, and plant growth-promoting rhizobacteria could revolutionize hydroponic systems, enhancing productivity and sustainability [116]. Addressing these research gaps will be crucial for advancing hydroponics as a viable solution for modern agriculture.

Aquaponics, an integrated system combining aquaculture and hydroponics, presents numerous opportunities for sustainable food production, yet several areas require further research to enhance its viability and efficiency. One critical area is the optimization of system construction and nutrient management, which includes understanding the microbial community structure to improve system performance and sustainability. The economic aspects of aquaponics also demand attention, particularly in developing robust financial planning and risk management strategies to encourage initial grower engagement and improve profitability through better business models. Additionally, consumer perception and willingness to pay for aquaponic products need exploration to enhance market acceptance. The integration of aquaponics into eco-industrial food parks offers a promising avenue for achieving near-zero waste and high resource use efficiency; but requires further investigation into system design and optimization under varying climatic conditions [11]. Moreover, the diversity of aquatic and plant species, as well as the environmental and economic impacts of co-products, are under-researched areas that could significantly influence the scalability and sustainability of aquaponics systems. The potential of incorporating insect larvae production to recycle waste streams and develop sustainable aquafeeds also presents a novel research direction, with implications for nutrient cycling and fish performance [17]. Moreover, the role of root-released organic compounds in influencing system microbiomes and fish health is an emerging field that could unlock new pathways for system optimization. Addressing these research gaps will be crucial for advancing aquaponics as a commercially viable and environmentally sustainable food production system.

9.4 Future trends

The integration of 5G and IoT in smart farming systems represents a transformative advancement in agricultural technology, promising to enhance efficiency, productivity, and sustainability. The high-speed, low-latency capabilities of 5G networks facilitate real-time data transmission and processing, which are crucial for precision agriculture. This enables the deployment of IoT devices and sensors that monitor crop health, soil conditions, and environmental factors, allowing for data-driven decision-making in irrigation, fertilization, and pest control [232, 233]. The use of IoT in agriculture, combined with blockchain technology, further enhances data integrity and traceability, addressing issues of data security and management inefficiencies [234]. In Colombia, the deployment of 5G is seen as a pivotal step towards implementing smart farming practices, particularly in remote areas lacking current mobile network coverage, thus improving production and efficiency [235]. Additionally, 5G technology supports the development of intelligent farming platforms, as demonstrated in animal husbandry, where it aids in disease prevention and control through advanced monitoring systems [236]. The integration of AI and machine learning with IoT and 5G networks allows for the automation of agricultural tasks, such as precision irrigation and crop monitoring, which can significantly reduce resource use and environmental impact [237, 238]. Unmanned Aerial Vehicles (UAVs) and robotics, enabled by these technologies, further enhance monitoring capabilities and operational efficiency in both crop and livestock management [239]. Overall, the synergy of 5G and IoT in smart farming systems not only optimizes agricultural practices but also aligns with global sustainability goals by promoting more efficient and environmentally friendly farming methods [240]. However, challenges such as data privacy, scalability for small farms, and the need for user-friendly interfaces remain and require ongoing research and development to fully realize the potential of these technologies in agriculture [233, 240].

9.4.1 Fully automated farm and recommendations

An entirely automated, IoT-integrated hydroponic and aquaponic farm represents the future of sustainable agriculture, merging advanced technology with eco-friendly techniques. IoT sensors track essential characteristics like as water pH, nutrient concentrations, temperature, and humidity, while actuators modify systems in real time to sustain optimal conditions. In the hydroponic subsystem, plants are cultivated in a nutrient-dense aqueous solution in a soil-less environment, while vertical farming configurations optimize spatial efficiency. The aquaponic subsystem introduces an interdependent relationship, wherein fish waste is transformed into nutrients for plants, which then cleans the water for the fish. Collectively, these systems constitute a self-sustaining cycle, overseen by robotics for planting, harvesting, and maintenance.

This revolutionary strategy has substantial advantages, such as increased crop yields, less resource usage, and urban adaptability. Precision agriculture, enabled by IoT, guarantees that plants obtain the precise quantity of water and nutrients required, reducing waste, and conserving up to 90% of water relative to conventional approaches. Solar panels and intelligent energy systems can improve sustainability, while mobile applications offer real-time monitoring and remote management for agriculturalists. These farms can mitigate food security concerns in metropolitan regions, reduce agricultural runoffs, and minimize the carbon footprint of food production, rendering them optimal for tackling global environmental challenges.

However, obstacles such as elevated startup expenses and system complexity must be resolved for extensive adoption. Advancements in AI may further improve growth optimization, predicting plant health and harvest timelines, while the incorporation of renewable energy could render farms energy-independent. Whereas it is important to make automation accessible in small-scale and resource-limited markets by using affordable, modular, and open-source technologies. Using budget-friendly sensors, simple automation systems, and materials sourced from nearby can really help to cut down expenses. Moreover, working together in farming, along with supportive policies and training programs, can help in embracing smart farming solutions. By putting these strategies into action, small-scale farmers can leverage automation to boost their productivity and promote sustainability.

To alleviate the long-term environmental impact of automation in hydroponic and aquaponic systems, several strategies can be implemented. First, adopting energy-efficient technologies such as low-power sensors, optimized LED lighting, and energy-efficient actuators can significantly reduce power consumption. Additionally, integrating renewable energy sources like solar panels and wind turbines can reduce reliance on fossil fuels. Second, closed-loop resource management through advanced monitoring systems can enhance water and nutrient recycling, reducing waste and environmental pollution. Third, conducting lifecycle assessments (LCA) of automation equipment can help optimize material selection, improve recyclability, and extend the operational lifespan of components, thereby minimizing electronic waste. Fourth, decentralized smart farming approaches tailored to regional climatic and economic conditions can help reduce transportation emissions and energy consumption associated with large-scale operations. Lastly, AI-driven predictive analytics can optimize irrigation, nutrient dosing, and environmental control, ensuring precision management with minimal resource wastage. These strategies collectively enhance the sustainability of automation in hydroponic and aquaponic systems, aligning with Circular Economy (CE) principles and long-term environmental conservation. Ongoing progress in completely automated hydroponic and aquaponic farms could transform agriculture, guaranteeing a sustainable and resilient food supply for future generations.

10 Conclusion

The key conclusions drawn from this review article are as follows:

- Integration of automation and robotics such as nutrient management systems, climate control, and robotic planting/harvesting has significantly improved productivity and efficiency in hydroponic and aquaponic systems.
- Monitoring drones and maintenance robots enhance operational scalability and reduce human labor dependency.
- Automated systems minimize water, energy, and nutrient wastage, addressing environmental concerns in modern agriculture.
- These technologies contribute to sustainable food production by optimizing resource usage.
- High initial costs, maintenance complexities, and scalability issues hinder widespread adoption.
- Targeted innovations, such as AI-driven analytics and IoT integration, are essential to overcoming these barriers.
- Focus on research and development to enhance cost-effective, scalable solutions.
- Stakeholders are encouraged to adopt advanced technologies to ensure resilient and sustainable agricultural practices.
- Automation and robotics in hydroponics and aquaponics can play a pivotal role in addressing global food security challenges supporting a circular food economy and achieving the Sustainable Development Goals.

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