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Systematic Review of Technology in Aeroponics: Introducing the Technology Adoption and Integration in Sustainable Agriculture Model

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Abstract: Technology has transformed aeroponics, providing numerous advantages over traditional soil-based agriculture. However, there remains a need for comprehensive information on the types of technology employed in aeroponics and their impact on the growing process. This paper presents a literature review of 47 studies published between 2012 and 2023 in peer-reviewed journals and conference proceedings. As a result, it identifies the status and tendencies in the usage of technology in aeroponics as well as the main opportunities and challenges. Furthermore, this paper introduces the Technology Adoption and Integration in Sustainable Agriculture (TAISA) model. TAISA is a model that identifies the degree of technology integration in any sustainable agriculture system to determine how technology affects production and quality. Overall, the systematic review suggests that technology can play a vital role in improving the efficiency and sustainability of aeroponic farming. However, careful consideration must be given to the costs and technical requirements associated with using these technologies. Moreover, the TAISA model reveals that technology has primarily been employed in creating new processes that are not possible to implement without the help of technology. Therefore, we conclude that technology use has taken root in aeroponics and can be promoted to improve sustainable agriculture.

Keywords: aeroponics; sustainable agriculture; sustainable development goals; sustainability; systematic literature review; TAISA model; technology integration

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1. Introduction

The global population is constantly increasing, which implies the need to increase food production. As food production increases, the planet's sustainability is at risk as greater use of energy, water, and soil resources is required. In the same way, overuse of land and intensive farming practices can lead to soil erosion, nutrient depletion, and a loss of soil fertility, which can reduce the productivity of the land over time [1]. To alleviate this situation, the Food and Agriculture Organization-[FAO] (2017) proposed implementing sustainable agriculture techniques, such as aquaponics, hydroponics, and aeroponics. These are soilless-based techniques that use technology to improve food production efficiency without risking the planet's sustainability [3,4]. Aquaponics refers to producing fish and plants using water tanks and hydroponic systems. Hydroponics refers to growing plants using a water-based nutrient solution instead of soil, and aeroponics refers to growing plants in the air or a mist environment. Aquaponics is the most popular technique when there is a need to produce fish and plants. Conversely, if there is no interest in producing fish, hydroponics is very popular if sufficient water resources are available. Finally, if there is no interest in producing fish, and the water resources are insufficient, aeroponics is the technique to implement [5].

1.1. Aeroponics

Aeroponics is a method of growing plants in a soil-free environment where the plant roots are suspended in air and are misted with a nutrient-rich water solution [6]. Aeroponic systems typically use pumps, timers, and spray nozzles to deliver a highly oxygenated mist of water and nutrients to the plant roots. The mist is delivered at timed intervals, allowing the roots to absorb nutrients and water.

Aeroponics offers several advantages over traditional soil-based agriculture, including faster growth rates, higher crop yields, and more efficient use of resources [7,8]. The soil-free environment also reduces the risk of soil-borne diseases and pests, allowing for a more sustainable and environmentally friendly approach to agriculture [9]. Aeroponics is a relatively new technology, but it has already been successfully used to grow a wide range of crops, including lettuce, tomatoes, and strawberries (Gour et al., 2020). One of the main advantages technology has provided to aeroponics is that plants can be grown throughout the year, as environmental conditions such as humidity, temperature, airflow, and light intensity can be artificially controlled using specific tools and systems [10,11].

1.2. Technology in Aeroponics

Technology plays a crucial role in the success of aeroponics, enabling precise control of environmental factors, water conservation, space optimization, and pest and disease control, all of which contribute to improved food production. Additionally, by leveraging technology, aeroponics can produce high-quality, nutrient-rich crops with a reduced environmental footprint compared to traditional farming methods [8]. Four groups of technologies have been identified as critical in most aeroponic systems: sensors, Industry 4.0-related technologies, dispenser-related technology, and renewable energy technologies [5,12,13].

One of the primary applications of technology in aeroponics is the use of sensors to monitor environmental conditions [14]. For example, sensors provide real-time monitoring of environmental conditions (e.g., temperature, humidity, and nutrient levels), which allows farmers to make data-driven decisions about adjusting conditions to optimize plant growth [15]. This can include adjusting nutrient levels, controlling temperature and humidity, and monitoring plant health. Moreover, sensors can be integrated with automated control systems to adjust environmental conditions to address the changing conditions [16]. This reduces the risk of human error and ensures that environmental conditions are always optimized for plant growth. Additionally, sensors can detect issues such as nutrient deficiencies, pests, and diseases before they become visible to the human eye [13]. This early detection can help prevent crop loss and ensure that plants are healthy and productive.

Another technological alternative that has gained relevance in aeroponics is Industry 4.0. It refers to using technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and data analytics to create smart production processes. In aeroponics, Industry 4.0 technologies are becoming increasingly important as they offer a range of benefits for optimizing plant growth and improving efficiency [13]. For example, IoT can be used to automate various tasks, such as nutrient delivery, environmental control, and pest management [17]. This reduces the need for human intervention and ensures that plants receive the optimal conditions for growth at all times. On the other hand, AI can be used to detect plant diseases early on by analyzing images of plants and identifying symptoms that may not be visible to the naked eye [18]. This can help farmers take prompt action to prevent the spread of diseases and maintain healthy crops. Similarly, data analytics can be implemented to analyze vast amounts of data on plant growth, weather patterns, and nutrient levels to accurately predict the ideal conditions for plant growth [19]. This can help farmers optimize their aeroponic systems and achieve better yields.

Dispenser-related technology is also essential to aeroponic systems, as dispensers deliver nutrients and water to plants [20]. This includes atomizers, sprayers, nebulizers, ultrasonic dispersion, water pumps, and centrifugal pumps that are automatically controlled according to the needs detected by the sensors. Dispenser technology allows for precise dosing of nutrients and water to plants [21]. This ensures that the plants receive the optimal amount of nutrients and water, which is critical for their growth and development. Moreover, dispenser technology can be automated to deliver nutrients and water at set intervals or based on real-time sensor data [22]. This reduces the need for manual labor and ensures that the plants receive consistent care. Additionally, it allows for the customization of nutrient and water delivery based on the specific needs of each plant [23], thus ensuring that each plant receives the optimal conditions for growth and development.

Another group of technologies that make aeroponics a sustainable technique is related to renewable energy. Alternative energy sources, such as solar or wind power, can be used to power aeroponic systems, providing a range of benefits for reducing energy consumption and improving sustainability [16]. This reduces the reliance on grid power, which can be expensive and environmentally damaging. Renewable energy also helps reduce energy costs associated with running an aeroponic system [24], which makes it more affordable for growers to operate and maintain their systems. Additionally, alternative energy sources are typically cleaner and more sustainable than traditional energy sources [25], making them a more environmentally friendly choice for aeroponic growers.

1.3. Related Work

Some literature review studies have analyzed the uses of different technologies on the whole panorama of sustainable agriculture. For example, the study by Abbasi et al. (2022) investigated the emerging trends of digital technologies in sustainable agriculture techniques. The review included 148 empirical studies to identify the extent of digital technologies adoption, service type, technology readiness level, and farming type (hydroponics, aquaponics, aeroponics). Out of the total sample, only three studies were related to aeroponics, whereby the study did not draw any conclusion on this type of sustainable agricultural technique. Similarly, the study by Fussy and Papenbrock (2022) compared soil and soilless cultivation techniques (aquaponics, hydroponics, aeroponics). The study concludes that implementing technological developments related to monitoring and automation gives the advantage to soilless techniques, making them much more profitable, well-organized, effective, secure, and nature friendly. Finally, the study by Basso and Antle (2020) investigated the affordances of digital technologies such as sensors, robotics, AI, and data analytics as key developments to secure sustainable food production. The study argues that while complex climate changes put food production at risk, digital technologies are key to controlling such changes and achieving truly sustainable agriculture. However, as well as with the other studies, this one also did not specify any conclusions about the impact of technology on aeroponics.

On the other hand, many empirical studies have reported how the use of specific technologies helps aeroponics improve food production [21,28], how aeroponics technology uses natural resources efficiently [29,30], and what specific technologies are implemented in aeroponic systems [14,31]. However, to the best of our knowledge, no systematic review has been conducted to identify the whole panorama of the use of technology in aeroponics. A systematic review of aeroponics is important because it can identify research gaps, evaluate existing evidence, provide guidance for practitioners, and inform policy and decision-making. Moreover, it can help advance technology and optimize plant growth while ensuring that researchers and policymakers have access to the best available evidence.

1.4. Purpose of the Study

Aiming to fill the literature gap, the purpose of this study is twofold. First, we conduct a systematic literature review to identify the status and tendencies in the usage of technology in aeroponics, as well as the main opportunities and challenges in the field. Second, we propose a model to identify the level of technology integration to determine how technology affects production and quality. Specifically, the study answers the following research questions:

1. What are the trends regarding the use of technology in aeroponic systems?
2. What are the main advantages that the integration of technology can bring to aeroponic systems compared to conventional agriculture systems?

3. What are the main challenges that technology integration can bring to aeroponic systems compared to conventional agriculture systems?
4. What has been the purpose of technology integration in aeroponics?

To identify the trends regarding technology usage in aeroponic systems (1), we consider the type of technology implemented, the type of cultivated product, the country of the research, the publisher of the study, and the publication date. Advantages of aeroponic systems (2) refer to positive outcomes compared to conventional agriculture systems. In contrast, disadvantages (3) refer to negative outcomes encountered in aeroponic systems. Finally, to establish the purpose of technology integration in aeroponics (4), we propose a model to assess the level of technology use in a sustainable agriculture system. This model is based on the Substitution, Augmentation, Modification, and Redefinition (SAMR) model and helps identify the purpose of integrating technology into the system.

2. The Model

2.1. Theoretical foundation

The proposed model is based on the SAMR educational framework. Initially developed by Dr. Ruben Puentedura in 2006, this model was proposed to analyze and evaluate technology integration in the classroom [32]. The primary purpose of the SAMR model is to help teachers and instructional designers understand how technology can transform teaching and learning experiences. It provides a framework for categorizing different levels of technology integration, ranging from basic substitution to more advanced redefinition. At the "substitution" level, technology is used as a direct substitute for traditional pedagogical tools without any significant functional changes. At the "augmentation" level, technology enhances the learning process by providing additional functionalities. At the "modification" level, technology allows for significantly redesigning the learning task. Finally, at the "redefinition" level, technology creates entirely new learning experiences, transforming the learning task into something previously unimaginable without technology [33]. While the SAMR model is primarily designed to analyze and evaluate the integration of technology in education, it could also be adapted to be applied in other fields.

2.2. The Proposed Model

In this study, we introduced the Technology Adoption and Integration in Sustainable Agriculture (TAISA) model. TAISA is a framework to assess and evaluate the level of technology integration in the context of sustainable agriculture. It focuses on understanding how technology is adopted and integrated into farming practices to promote sustainable and environmentally friendly approaches. It promotes innovation, efficiency, and collaboration, leading to advancements in agriculture techniques and the potential for sustainable and optimized crop production. Therefore, the TAISA model can help assess how technology is being utilized to enhance and transform the overall cultivation process.

2.2.1. Definition of the Levels of Technology Integration

The TAISA model evaluates the level of technology integration using a four-point rating scale: Limited, Basic, Moderate, and Advanced. Figure 1 summarizes the significance of each level, and subsequently, we present a general description and some specific examples.

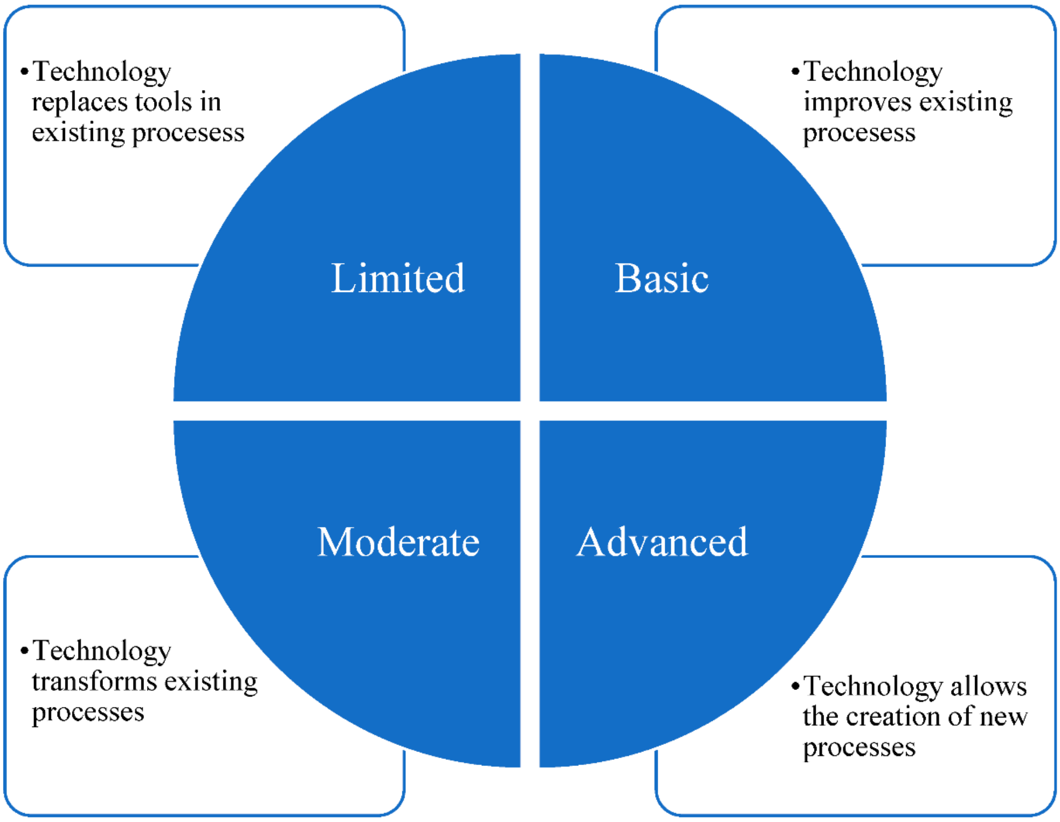

Figure 1. TAISA model.

Limited Integration: Technology plays a minimal role in sustainable agriculture practices. There is little evidence of technology being used to enhance production and sustainability efforts; instead, it replaces existing tools without any advancement in the process. Traditional farming methods are predominantly employed, with limited adoption of innovative technologies or digital tools that promote sustainable food production. For example, using electric water pumps for water and nutrition irrigation. The technology does not enhance the process; it only replaces manual irrigation.

Basic Integration: Technology is somewhat integrated into sustainable agriculture practices. There are instances where technology is utilized to support sustainability goals, but it is not consistently applied or fully leveraged. Some digital tools or precision farming techniques may be used to optimize resource management or monitor environmental impact, but their adoption is limited. However, there is evidence of technology improving efficiency or effectiveness in certain areas. For example, weather monitoring systems are utilized to make informed irrigation decisions in some areas, but not systematically across the entire farm. In this case, technology improves the process but does not fundamentally change it.

Moderate Integration: Technology is reasonably integrated into sustainable agriculture practices and is consistently used to enhance sustainability efforts and achieve desired outcomes. Digital tools, precision farming techniques, and smart agricultural systems are employed to optimize resource use, monitor and reduce environmental impact, and promote sustainable practices. There is evidence of technology being applied effectively, resulting in improved efficiency and effectiveness. However, there are still some areas where technology could be further leveraged. For example, automated irrigation systems are employed, utilizing soil moisture sensors and weather data to optimize water use efficiency and reduce waste. In this case, technology modifies the process and enhances sustainable production.

Advanced Integration: Technology is fully integrated into sustainable agriculture practices and is effectively utilized to create new processes that maximize sustainability outcomes and minimize environmental impact. There is extensive evidence of technology enabling significant improvements in efficiency and effectiveness in sustainable agriculture. Technology is seamlessly embedded throughout the process, and its use is well-optimized. For example, by integrating cutting-edge technologies, smart farming systems can monitor and manage crops, soil conditions, water usage, and environmental factors autonomously and in real time. In this case, technology redefines processes and creates new possibilities.

2.2.2. Significance of the Model

The TAISA model is valuable for evaluating the integration level of technology in sustainable agriculture for different reasons. First, this model can be implemented to identify the extent to which technology is being applied and whether it is merely replacing existing methods or truly transforming the cultivation practices. This knowledge helps us understand the true impact of technology on farming processes; thus, if technology is only replacing existing methods without providing significant improvements, it might not be worth the investment. Second, the model helps stakeholders (e.g., researchers, growers, and engineers) understand whether they are fully leveraging the capabilities of technology or if there are untapped opportunities for enhancement. This analysis can lead to innovative ideas and advancements in the field. Third, the model encourages practitioners to move beyond basic technology uses and consider how it can fundamentally transform the cultivation process. This mindset can lead to the development of groundbreaking techniques and approaches in sustainable agriculture that were not previously feasible. Fourth, technology integration in sustainable agriculture can contribute to improved efficiency and productivity in crop production. Using the TAISA model, practitioners can evaluate how technology is utilized to streamline processes, automate tasks, monitor and control environmental factors, and optimize resource utilization. This assessment helps identify areas where technology can further enhance efficiency and productivity in sustainable agriculture systems. Fifth, the TAISA model fosters a culture of innovation and collaboration within the sustainable agricultural community. By evaluating technology integration and striving for higher levels of transformation, stakeholders are encouraged to explore new ideas, share best practices, and collaborate on research and development initiatives. This can lead to technological advancements, cultivation techniques, and knowledge sharing within sustainable agriculture communities.

3. Methods

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines [34] and follows recommendations outlined by Kitchenham and Charters [35]. This procedure requires that systematic reviews go through three stages, namely planning, conducting, and reporting the review.

3.1. Planning the review

This stage entails the strategy to identify the empirical studies to answer the research questions. Journal articles and conference articles were searched in the following bibliometric databases and publishers: IEEE, MDPI, Scopus, and Web of Science (WoS). We used the following search terms “aeroponics AND technology,” “precision aeroponics,” “smart aeroponics,” “sustainable agriculture AND aeroponics,” “smart farming AND aeroponics,” “smart agriculture AND aeroponics.” The final search was performed on June 30, 2023, and allowed us to find 615 studies. After identifying and removing duplicate studies (212), a total of 403 studies were set to be further examined. Unpublished studies were not included because their quality assessment cannot be guaranteed in the absence of a peer review process. Two of the researchers examined each paper to determine its suitability for the study. Articles that did not meet the eligibility criteria were discarded.

3.1.1. Eligibility criteria

Studies were first selected based on their title and keywords. The title and keywords of all articles were scanned to remove irrelevant studies. Fifty-eight studies were deemed irrelevant and

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removed; hence, this process yielded 345 studies. The abstract of each study was then read. This allowed us to remove 243 studies either because they were review articles, reports, dissertations, work in progress articles, or did not address the aim of our study. Thus, this process resulted in 102 articles. Next, we selected the studies that met the following conditions: a) empirical studies, b) studies that specify the technology used in the production process, and c) studies that specify the cultivated product. These criteria led to a selection of 47 academic articles to be further examined and included in the analysis. The reference list of each paper was then scanned, but no additional study was found. The PRISMA flowchart of the study selection process is shown in Figure 2.

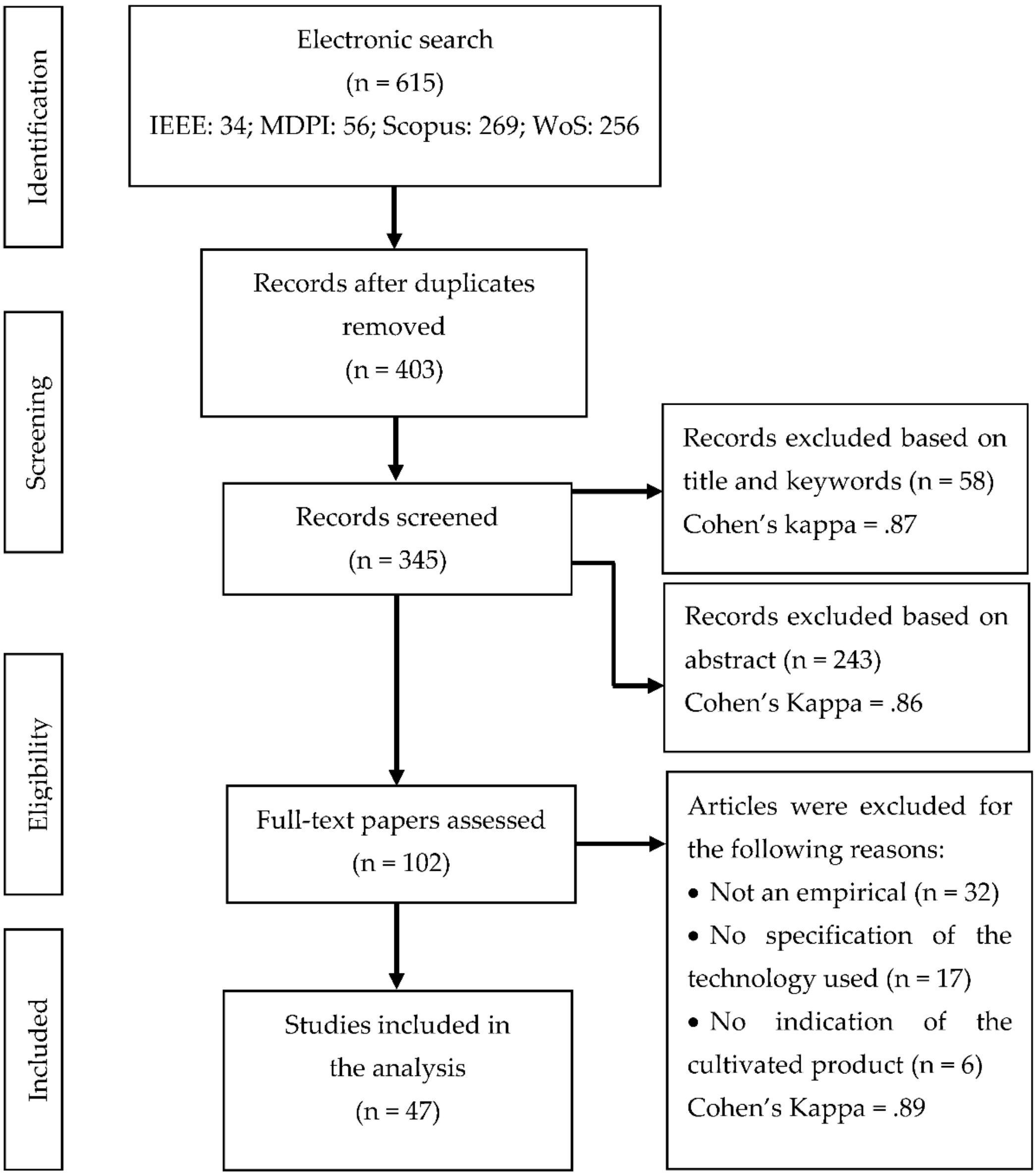

Figure 2. PRISMA flowchart of the study selection process.

3.2. Conducting the review

We designed a data extraction form to collect the information to address the research questions. The data form included the following information: title, year, type of technology used, cultivated product, country of the study, publisher, reported advantages, reported disadvantages, and main findings. Two of the researchers read each paper individually and extracted the information using the content analysis method to extract the data [36]. These researchers have degrees related to electronic engineering and a combined experience of more than ten years in aeroponic systems. Intercoder reliability was measured using Cohen's Kappa statistic. This value was 0.92, which

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corresponds to almost perfect agreement [37]. Disagreements were discussed and resolved through consensus among the researchers.

3.3. Reporting the review

This stage refers to the process of documenting and presenting the findings of the review in a clear and transparent manner. This stage is crucial for ensuring the reproducibility and reliability of the review, as it allows readers to assess the rigor and credibility of the review findings. The results of this stage are presented in Section 4.

4. Results

This section presents and discusses the systematic review results to answer the research questions. These results are based on the analysis of 47 empirical studies that focused on the uses of technology in aeroponic systems. Table 1 summarizes the information about the studies included in the review. A file with all the information about the studies can be solicited to the corresponding author of this study.

Table 1. Summary of the studies included in the review.

Study	Authors (Year) [Cite]	Cultivated product	Technology level
1	Idris and Sani (2012) [38]	Tuber	Advanced
2	Reyes et al. (2012) [39]	Vegetable	Moderate
3	Pathania et al. (2012) [40]	Tuber	Moderate
4	Sani et al. (2016) [10]	Fruit	Advanced
5	Pathania et al. (2016) [41]	Tuber	Advanced
6	He (2017) [42]	Vegetable	Advanced
7	Dannehl et al. (2017) [43]	Fruit	Limited
8	Montoya et al. (2017) [44]	Vegetable	Moderate
9	Belista et al. (2018) [45]	Vegetable	Advanced
10	Rahman et al. (2018) [46]	Vegetable	Moderate
11	Chang et al. (2018) [47]	Vegetable	Moderate
12	Jamshidi et al. (2019) [31]	Fruit	Basic
13	Klarin et al. (2019) [25]	Fruit, Vegetable	Advanced
14	Hoyos et al. (2019) [48]	Aromatic plant	Advanced
15	Vera et al. (2019) [49]	Flower	Advanced
16	Lakhiar et al. (2019) [50]	Vegetable	Basic
17	Argo et al. (2019) [51]	Vegetable	Advanced
18	Lucero et al. (2020) [29]	Vegetable	Advanced
19	Rahmad et al. (2020) [15]	Vegetable	Advanced
20	Jamhari et al. (2020) [52]	Vegetable	Advanced
21	Torres et al. (2020) [53]	Vegetable	Advanced
22	Ríos et al. (2020) [28]	Vegetable	Advanced
23	Cabascango et al. (2020) [54]	Tuber	Basic
24	Caya et al. (2021) [55]	Vegetable	Advanced
25	Karuniawati et al. (2021) [56]	Vegetable	Moderate
26	Kuncoro et al. (2021) [57]	Tuber	Moderate
27	Devederkin et al. (2021) [23]	Tuber	Basic

28	Chowdhury et al. (2021) [58]	Vegetable	Moderate
29	Narimani et al. (2021) [59]	Flower	Advanced
30	Tang et al. (2021) [60]	Vegetable	Advanced
31	Tunio et al. (2021) [61]	Vegetable	Basic
32	Rahman et al. (2021) [62]	Tuber	Advanced
33	Riswandi et al. (2022) [63]	Vegetable	Advanced
34	Martinea et al. (2022) [64]	Vegetable	Moderate
35	Bolivar et al. (2022) [65]	Fruit; Vegetable	Moderate
36	Estuita et al. (2022) [66]	Vegetable	Advanced
37	Qi et al. (2022) [67]	Vegetable	Moderate
38	Méndez et al. (2022) [68]	Vegetable	Advanced
39	Yang et al. (2022) [9]	Vegetable	Moderate
40	Mehmood et al. (2022) [69]	Fruit	Moderate
41	Mohamed et al. (2022) [70]	Vegetable	Advanced
42	Setiowati et al. (2022) [71]	Vegetable	Advanced
43	Dhanasekar et al. (2023) [72]	Vegetable; Tuber; Fruit	Advanced
44	Sadek et al. (2023) [73]	Vegetable	Advanced
45	Calzita et al. (2023) [74]	Vegetable	Advanced
46	Paponov et al. (2023) [75]	Aromatic plant	Moderate
47	Guo et al. (2023) [76]	Fruit	Moderate

4.1. Trends in the use of technology in aeroponic systems

To identify the trends in technology use in aeroponics, we evaluated a) the technology type, b) the cultivated product, c) the country of the research, d) the publisher of the study, and e) the publication date.

4.1.1. Technology type

We coded each study according to the criteria in Table 2. We selected this group of technologies because they have been identified as the most prominent technologies in sustainable agriculture, specifically in aeroponics [5,12,13]. It is important to mention that a single study can report the use of multiple technologies. In such cases, all technologies were assigned to the study. Figure 3 depicts the number of studies that implemented each specific technology.

Table 2. Description of the categories of implemented technology.

Category	Description	Examples
Sensing technology	Devices that detect and measure physical or environmental conditions, converting them into electrical signals for analysis.	Temperature sensors, flow sensors, cameras, and microphones
Industry 4.0	Digital transformation of processes through advanced technologies based on smart automation.	AI, IoT, machine learning, microcontrollers, robotics, artificial lighting.
Dispenser technology	Systems that automatically dispense liquids, solids, or gases in controlled quantities and precise locations.	Sprayers, nebulizers, ultrasonic dispersion, and pumps.
Renewable energy	Energy derived from naturally replenishing sources such as sunlight, wind, water, and	Biomass, fuel cells, solar panel, wind turbines, and hydropower.

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	geothermal heat, with minimal ecological impact.

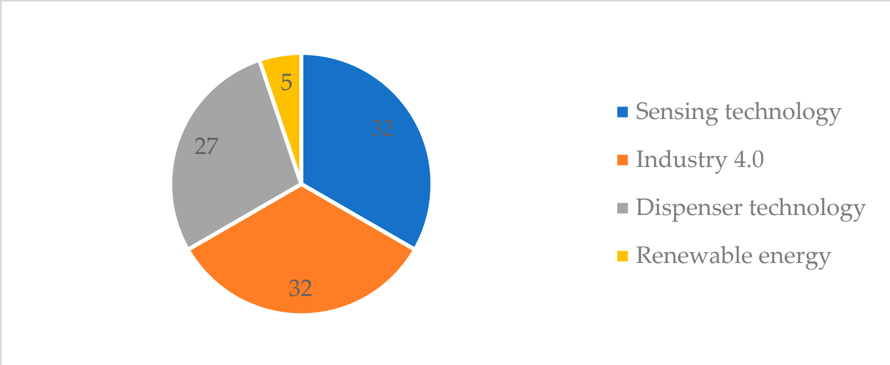

Figure 3. Distribution of the studies sorted by the implemented technology.

Figure 3 indicates that 68% of the studies implemented technologies related to industry 4.0 $(N = 32)$ or sensing technologies $(N = 32)$. Industry 4.0-related technologies bring precision, efficiency, and sustainability to plant cultivation. These technologies empower growers with data-driven insights, enable remote management, and enhance resource efficiency, ultimately leading to higher yields, better quality crops, and a more environmentally conscious approach to agriculture. Similarly, sensing technologies play a crucial role in optimizing aeroponic systems. These technologies provide real-time data that enables precise control, early issue detection, resource efficiency, and informed decision-making, ultimately leading to improved crop yields, reduced resource consumption, and more sustainable agricultural practices.

On the other hand, dispenser-related technologies were implemented in 57% of the studies $(N = 27)$. Integrating dispenser technologies into aeroponic systems enhances nutrient delivery precision, reduces resource wastage, minimizes human errors, and facilitates remote management. These technologies contribute to improved plant growth, higher yields, and more efficient use of resources in controlled environment agriculture.

Finally, 11% $(N = 5)$ of the studies implemented renewable energy-related technologies. Incorporating renewable energy-related technologies into aeroponics aligns with sustainability goals, reduces energy costs, and minimizes environmental impact. These technologies offer financial benefits, energy security, and a strong market position for growers committed to responsible and forward-looking agricultural practices.

4.1.2. Cultivated products

The variety of products that can be cultivated in aeroponics is extensive; therefore, we grouped the products according to their nature: vegetables, fruits, tubers, flowers, and aromatic plants (See Table 3). We selected these categories because they involve the products most commonly cultivated in aeroponics [8,21]. Some aeroponic systems cultivated more than one product. In such cases, all the products were assigned to the corresponding category. Aeroponics can be implemented to grow various vegetables, fruits, tubers, flowers, and aromatic plants. However, space and nutrient requirements make some products more challenging to grow. Figure 4 shows the number of studies related to the cultivation of each type of product.

Table 3. Description of the categories of implemented technology.

Category	Product examples
Vegetable	Lettuce, spinach, and arugula
Fruit	Tomato, mulberry, and strawberry
Tuber	Potato, yucca, and yam
Flowers	Lily; sunflower, and anthurium

Aromatic plant	Coriander, artemisia, and mint

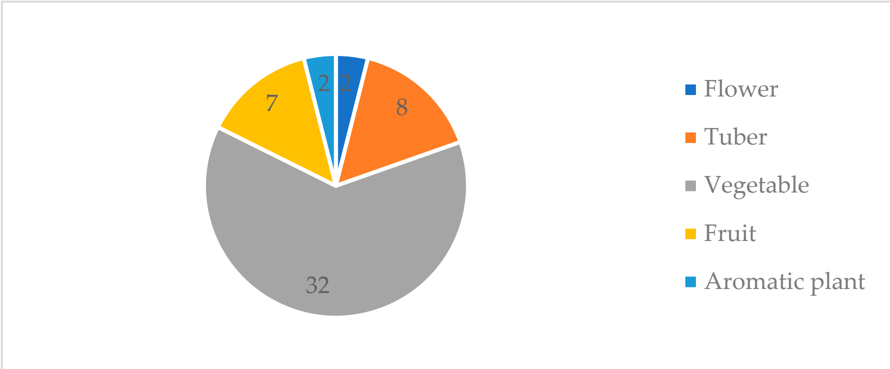

Figure 4. Distribution of the studies by cultivated product.

The results of our study indicate that the most common cultivated product was vegetables $(68\%, N = 32)$. Specifically, in the vegetable category, lettuce was the number one cultivated product (29 studies). Other cultivated products were spinach, arugula, and garlic. Tubers $(17\%, N = 8)$ and fruits $(15\%, N = 7)$ were the second and third most cultivated products. All tuber-related studies referred to the cultivation of potatoes. On the other hand, the most popular fruit was tomato (4 studies), but there were also studies related to the cultivation of mulberries, strawberries, and chili peppers. Finally, flowers and aromatic plants were grown in four percent of the studies, which represents two studies in each category. Regarding flowers, the studies were related to lilies and sunflowers, while regarding aromatic plants, the studies were related to coriander and artemisia.

The results show that various types of plants can be grown using aeroponics. However, this technique is particularly well-suited for crops requiring specific oxygen, moisture, and nutrients at the root level. It is worth noting that, while aeroponics is more commonly associated with plants that have shallow root systems, there is an increasing interest in growing certain root vegetables like potatoes. These efforts aim to optimize the conditions to encourage healthy root growth and tuber formation.

While aeroponics offers numerous advantages for growing various types of plants, certain crops may not be well-suited for this cultivation method due to their growth habits, root structures, or other specific requirements. Hence, large root crops, woody plants and trees, vining plants, plants with high water needs, and plants with fragile stems are not traditionally suited for aeroponics. This is reflected in the lack of evidence found in our study and has been stated in previous studies [21,26].

4.1.3. Country of the research

This variable corresponds to the country where the aeroponic system was implemented. In cases where the study did not report this information, we coded the country of the first author of the paper as the country of the research. This analysis is essential because it informs about the leading countries in aeroponics. Thus, stakeholders can find institutions and authors to work with and countries that might offer support for their research. Figure 5 shows the distribution map of the studies. Grouping by regions, we can notice that 32 studies were implemented in Asia (68%), 10 in the Americas (21%), 4 in Europe (8%), 1 in Africa (2%), and none in Oceania.

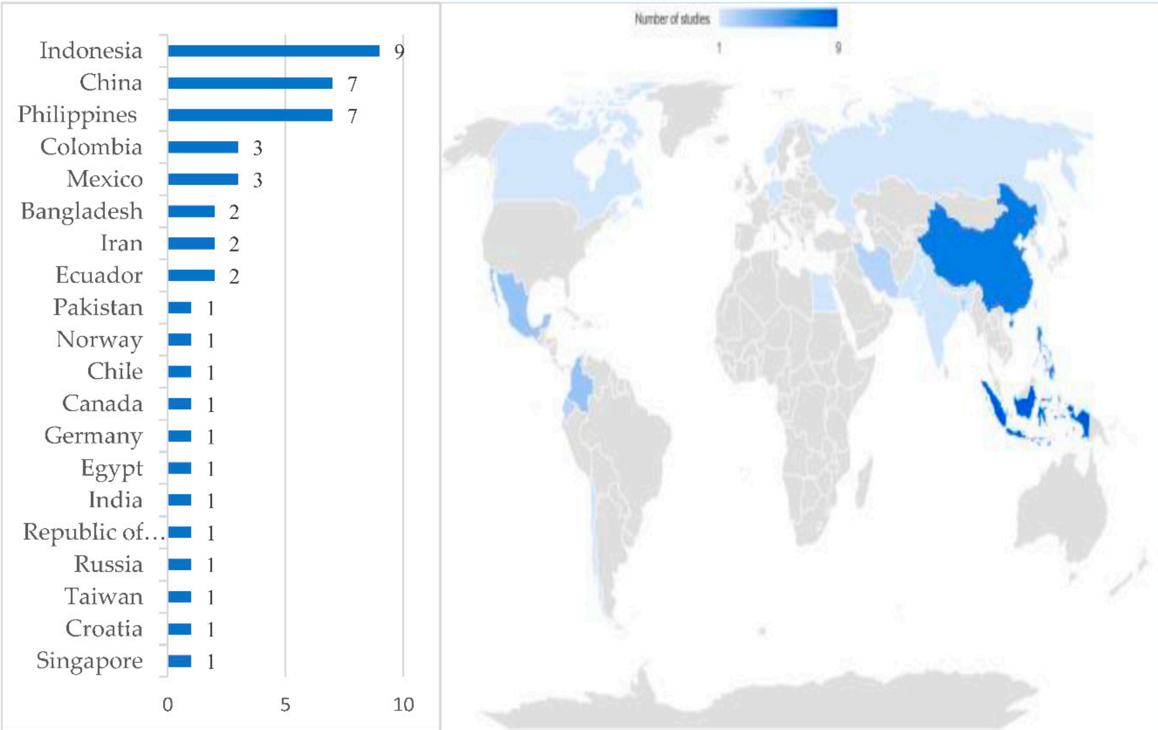

Figure 5. Distribution of the studies by country of the research.

Results in the left part of Figure 5 show Indonesia $(N = 9)$ as the country where most studies were carried out, followed by China $(N = 7)$ and Philippines $(N = 7)$ in the second place, and Colombia $(N = 3)$ and Mexico $(N = 3)$ in the third place. It is also important to note, that the studies were carried out in 20 different countries worldwide, reflecting the extended interest in aeroponics.

The practice of aeroponics aligns with the growing interest in sustainable and high-tech agriculture, as it addresses challenges related to limited arable land, water scarcity, and changing climatic conditions. Its global adoption reveals its potential to revolutionize modern agriculture and contribute to meeting the zero-hunger goal of the sustainable development goals (SDG2), especially in urban areas where traditional farming might be challenging. In this sense, it is important to note that the present study does not refer to the countries where aeroponics was implemented but to countries where aeroponic systems were enhanced by technology. This is why, while some studies place Africa as an important region for developing aeroponics [8,77], only one of the reviewed studies in this systematic review was implemented in that continent.

There are two remarkable findings in this study regarding the country of the study. First, the significant number of studies conducted in Asia (68% of the studies) and second, the low number of studies conducted in Europe (8% of the studies). As for Asia, it is noteworthy how this region has opted to invest and develop technological solutions for enhancing aeroponics, especially in the western and southern-east regions of the continent. Stakeholders in these regions have interpreted integrating technology into aeroponics as a strategic approach to modernizing agriculture, increasing food production, and addressing various challenges that communities face in today's world. Conversely, although Europe is a leading continent in various technological-related aspects, there seems to be a lack of interest in developing technologies to be integrated into aeroponics. This region has all potential to lead the field, given the continuous interest shown in the planet's sustainability, their interest in healthy food, and their economic facilities. Therefore, the results of this study can serve as a call to European researchers and practitioners to analyze the multiple benefits of integrating technology into aeroponics and thus, promote such practices.

4.1.4. Publisher of the study

This variable corresponds to the publisher of the journal the study was published in (see Figure 6). We coded the publisher rather than the journal because most studies were published in different journals (or conference proceedings). No single journal or proceeding published more than three studies; therefore, coding the journals would produce a very long list. Information about the publisher is important because it informs stakeholders regarding the leading publishers in the field, allowing them to know where they can find relevant literature or where they can plan to publish their research.

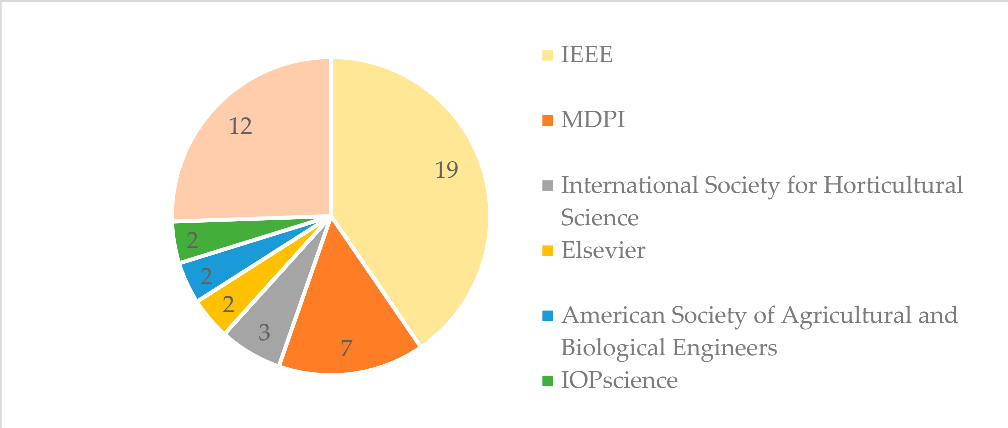

Figure 6. Distribution of the studies by publisher of the journal of publication.

Results in Figure 6 show that IEEE published the largest number of studies in the present systematic review (40% of the studies) followed by MDPI (15% of the studies). On the other hand, the number of studies published by Elsevier and Springer (two studies each) is strikingly low, as they are considered two of the most important academic publishing companies. Twelve studies were published by journals that do not belong to a specific publisher but are instead associated with universities or academic institutions. Additionally, it is important to mention that 24 studies (51%), were presented at scientific conferences and published as conference proceedings.

Identifying reputable publishers that cover studies integrating technology into aeroponics allows researchers, students, and professionals to access a wealth of information on the topic. Scientific articles provide insights, data, methodologies, and advancements in the field, helping individuals stay informed about the latest developments. Furthermore, being aware of publishers in the aeroponics domain can also help researchers connect with other professionals in the field. They can attend conferences, workshops, and seminars hosted by these publishers to network and collaborate with fellow researchers. Finally, the findings published in scientific articles about aeroponics can be applied in real-world applications, such as urban agriculture, vertical farming, and controlled environment agriculture. This information can be crucial for individuals and organizations looking to implement or improve aeroponic systems. Therefore, knowing which publishers publish scientific articles about aeroponics facilitates access to reliable, up-to-date, and credible information. This information is vital for advancing research, education, innovation, and practical applications in the field of aeroponics.

4.1.5. Publication date

We classified the studies by year of publication to identify the evolution over time concerning the integration of technology into aeroponic systems. This analysis is essential as it shows the tendency in the interest of the research community in the field. Figure 7 shows the distribution of the reviewed studies and the trend line over time.

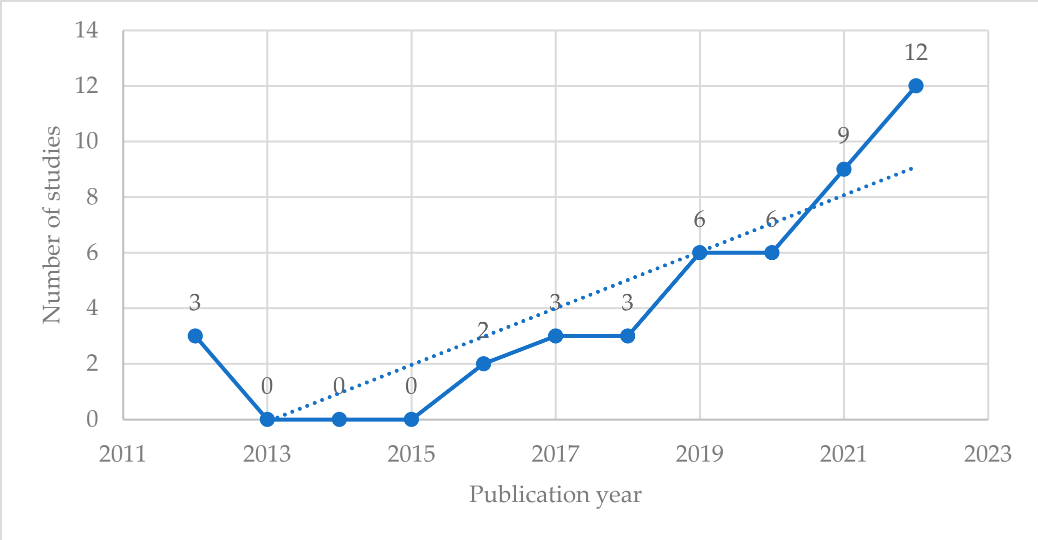

Figure 7. Distribution of the studies by year of publication.

Figure 7 indicates a steady increase from 2015 onwards. The results shown in Figure 7 do not include the number of studies published in 2023, as the search for studies was conducted in the middle of the year. However, the trend line indicates that the number of published documents tends to keep increasing, at least in the near future.

Monitoring the number of published studies per year helps gauge the growth of research interest in technology-driven aeroponics. A steady increase in the number of studies, as indicated in Figure 7, indicates a growing focus on the subject, reflecting its relevance and potential. This information is also important to funding organizations, both public and private, as they often rely on research trends to allocate resources. Knowledge of the number of studies can facilitate funding decisions related to technology development and research initiatives in aeroponics.

4.2. Advantages of the use of technology in aeroponic systems

We searched for the reported advantages of the use of technology in aeroponics in each study abstract, results, discussion, and conclusion sections. As expected, the integration of technology in aeroponics provides multiple advantages. All the studies reported at least one advantage, and most reported two or more. Hence, we organized the advantages into eight categories to produce a shorter list. Table 4 presents the description of the eight categories of advantages.

Table 4. Advantages of technology integration into aeroponics.

Advantage	Description
Time efficiency	Technology in aeroponics allows for precise control over various environmental factors, which helps plants grow faster, leading to shorter crop cycles and increased productivity compared to traditional farming methods.
Sustainability	Aeroponics is considered a sustainable farming method due to its efficient use of resources. Technology can further enhance sustainability by optimizing resource consumption, such as water and nutrients. Advanced monitoring systems can detect and address any inefficiencies, minimizing waste and maximizing resource utilization.
Cost-effective	Investment in technology for aeroponics results in long-term cost savings. By eliminating the need for soil and reducing water usage, aeroponics lower production costs over time. Additionally, the high yield potential and faster crop cycles lead to increased profitability.
Product size	

	Technology allows real-time monitoring of environmental factors such as temperature, humidity, CO2 levels, and light intensity. Automated control systems can adjust these parameters to create the ideal growing conditions, maximizing plant growth and yield.
Increased Production	Technology has a substantial impact on increasing production in aeroponics by optimizing various aspects of plant growth and resource management. For example, collecting and analyzing data on plant growth, nutrient levels, and environmental conditions can yield insights that facilitate the development of effective and sustainable growth strategies.
Space Efficiency	Technology allows for designing and constructing of modular growing structures tailored to the available space. These structures can be optimized for efficient space utilization while accommodating the specific needs of plants.
Clean production	The controlled environment of aeroponic systems can lead to fewer pest and disease problems. This can reduce the need for chemical pesticides and herbicides, leading to cleaner and healthier products.
Continuous production	Technology helps aeroponic systems operate continuously, allowing for year-round production. By providing a controlled environment, plants can be grown regardless of external seasonal variations, ensuring a steady and reliable supply of produce.

Results in Figure 8 show sustainability as the most reported advantage of using technology in aeroponics (53% of the studies). This is an encouraging result, as sustainability is one of the incentives for implementing this agricultural technique. A study by Sadek et al. [73] presented the design and implementation of a smart greenhouse using Industry 4.0-related technologies, such as IoT, AI, and machine learning. The authors claimed that by using these technologies, the aeroponic system maximized the use of water, energy, and agricultural fertilizers to achieve the highest productivity while supporting sustainable food production. The authors concluded that such a sustainability level was only possible using the implemented technologies.

Time efficiency was the second most reported advantage (45% of the studies). Technologies such as sensors and microcontrollers allow for precise control over environmental factors, helping reduce crop cycles, thus increasing efficiency. Using IoT, sensors, and microcontrollers, Dhanasekar et al. [72] implemented an efficient smart agriculture system. The authors concluded that the precision provided by using these technologies allows the creation of suitable environments for the plants, thus ensuring maximum crop efficiency.

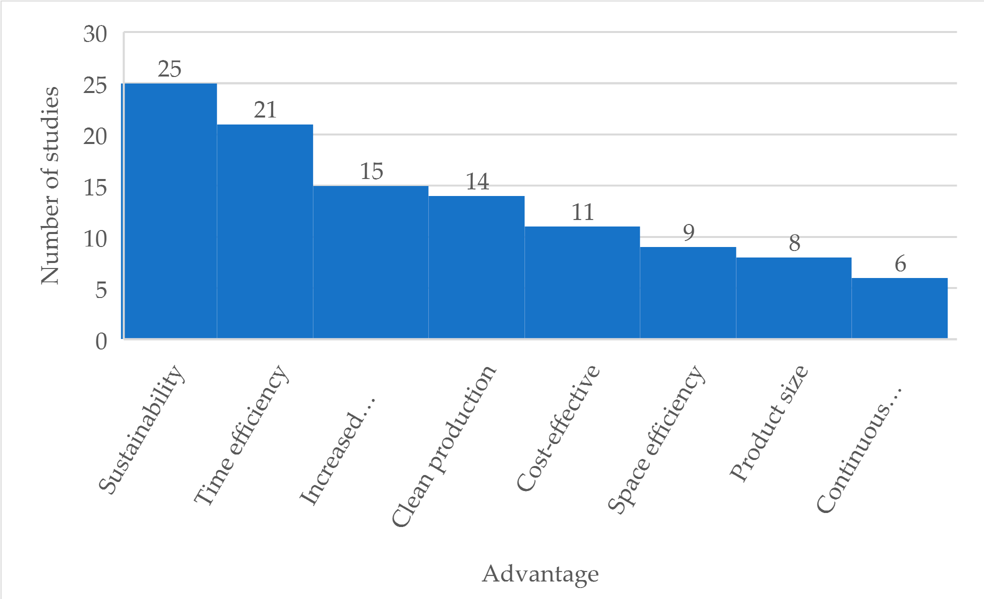

Figure 8. Advantages reported by the studies.

Technology has also been described to increase production in aeroponics (32% of the studies). For example, AI algorithms can optimize nutrient profiles and growing conditions for maximum production. Such is the case reported in the study by Riswandi et al. [63], who concluded that with technology controlling environmental factors such as temperature, humidity, and light, plants can experience accelerated growth rates, thus increasing overall productivity.

Thirty percent of the studies reported cleaner production as an advantage of using technology in aeroponics. Using specific technologies, such as automated monitoring and sterilization systems, ensures cleaner and healthier production through controlled environments that limit exposure to pests and diseases. For example, Guo et al. [76] implemented a back propagation neural network algorithm to identify mildew on the roots of mulberry branches in rapid propagation. The authors reported that the system accurately identified mulberry cuttings affected by mildew disease with an accuracy rate of 80%, which is described as excellent performance in ensuring clean and healthy production.

Cost-effectiveness is a contrasting finding in this study. While previous studies have identified high costs as one of the main challenges of integrating technology in aeroponics [12,78], 23% of the reviewed studies reported that using technology helps reduce costs associated with production. However, it is important to note that this benefit is not achieved in the short term. The study by Calzita et al. [74] highlighted the benefits of automation for cost savings. The authors reported a reduction in labor costs, use of resources such as nutrients, water, and pesticides, as well as increased productivity and decreased production cycles, which resulted in better profitability of the automated crop.

Space efficiency was reported as an advantage in 19% of the studies. For example, technology helps design and implement efficient vertical systems, making the most of available space. Such is the case reported in the study by Belista et al. [45], who used IoT, sensors, and different elements of dispenser technology to create a smart aeroponic vertical system. The authors highlighted that technology allowed them to maximize production while reducing crop spaces. Therefore, they propose this type of cultivation as essential to promote urban farming, where space is usually limited.

Product size was reported as an advantage in 17% of the studies. By controlling nutrient misting, humidity levels, and lighting through automation, plants receive optimal conditions for growth. This results in improved nutrient absorption, root development, and photosynthesis efficiency, all of which contribute to larger products. Yang et al. [9] implemented an ultrasonic aeroponic system to improve lettuce size. Using a smart dispenser system, the researchers managed to control the wind speed, the ambient temperature, and the atomization time, three determining factors for the product size. The authors claimed that the precise control of these variables, achieved thanks to technological tools, was key to obtaining better product size, thus improving the crop profitability.

Finally, 13% of the studies reported continuous production as an advantage of using technology in aeroponics. That is, controlled environments powered by technology enable year-round cultivation regardless of external weather conditions. This can lead to consistent crop production and a more predictable supply chain. By controlling root lighting of the roots of the artemisia plant, the study by Paponov et al. [75] achieved year-round production in an aeroponic system located in Norway. Additionally, the authors controlled the temperature and humidity of the roots, which translated into the precise control of the conditions for production. The authors highlighted the benefits of technology to ensure food production in places with extremely changeable climates, such as the northernmost countries.

4.3. Disadvantages of the use of technology in aeroponics

Reported disadvantages were also identified in each study's abstract, results, discussion, and conclusion sections. While the technology integration in aeroponics brings multiple benefits, some challenges remain to be addressed to obtain the best of this emerging production technique. Eight studies (17%) reported at least one challenge or disadvantage in Technology-based aeroponic systems. We organized the disadvantages into five categories to produce a shorter list. Table 5 presents the description of the five categories of advantages, and Figure 9 classifies the studies per reported disadvantages.

Table 5. Disadvantages of technology integration into aeroponics.

Advantage	Description
Technical Complexity	High-tech systems require a certain level of technical expertise to set up, operate, and troubleshoot. Growers need to understand the technology involved to ensure proper functioning and prevent potential issues.
Setup Cost	Implementing and maintaining advanced technology in aeroponic systems can be expensive. The initial investment for high-tech equipment, sensors, automation systems, and energy sources can be a significant barrier, especially for small-scale growers.
Power dependency	Advanced technology relies heavily on a stable and reliable power supply. If there are power outages or disruptions, it could impact the functioning of automated systems and disrupt plant growth.
Maintenance and Monitoring	High-tech systems require regular maintenance to ensure they function optimally. Downtime for maintenance and repairs could interrupt production schedules and lead to decreased yields.
Learning Curve	Introducing technology into an aeroponic setup requires a learning curve. Transitioning to technology-driven systems involves a learning curve for growers. Adapting to new methods, understanding software interfaces, and troubleshooting technical issues can take time and effort.

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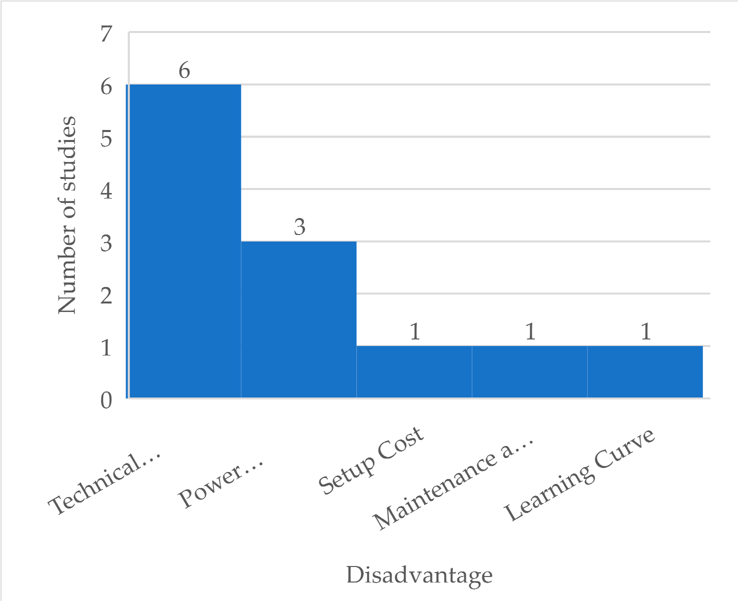

Figure 9. Challenges reported by the studies.

Technical Complexity was the most reported challenge of using technology in aeroponics (13% of the studies). That is, the more technological elements a system has, the more complex the system will be [79]. This challenge was pointed out by Setiowati et al. [71], who reported that aeroponic systems with advanced technology can become complex, with multiple components working together. The authors concluded that ensuring compatibility and reliability among various components, such as pumps, misting systems, nutrient delivery mechanisms, and sensors, can be the main challenges to succeed in modern aeroponics.

Power dependency was reported as a challenge in 6% of the studies. Integrating technology often increases energy consumption, especially if advanced lighting and environmental control systems are used. More importantly, power failures can translate into crop loss. In their study, Sani et al. [10] claimed that balancing the benefits of technology with energy efficiency is crucial for sustainable operations. In this sense, the authors highlighted the importance of using renewable energy sources to mitigate the negative effects of power consumption in aeroponics.

Finally, setup cost, maintenance and monitoring, and learning curve were associated as an advantage of integrating technology into aeroponics in the study by [73]. While it is well known that aeroponics technology is a long-term inversion, it is also true that initial costs are only affordable by some stakeholders. Similarly, integrating technology into aeroponics implies maintaining and monitoring those technologies. Therefore, downtime for maintenance and repairs could interrupt production schedules and lead to decreased yields. Finally, technology integration involves adequate technical expertise to ensure the system's proper functioning. Therefore, this situation may require additional training or hiring specialized personnel.

4.4. Level of technology integration in aeroponics

We evaluated the level of technology integration based on the TAISA model (see Figure 1). This analysis aims to identify the purpose of technology integration in each specific aeroponic system. Accordingly, we assigned each case a level of "limited," "basic," "moderate," or "advanced." This evaluation was performed by two researchers with degrees in electronics who are experts in aeroponic systems. Figure 10 depicts the number of studies in each category.

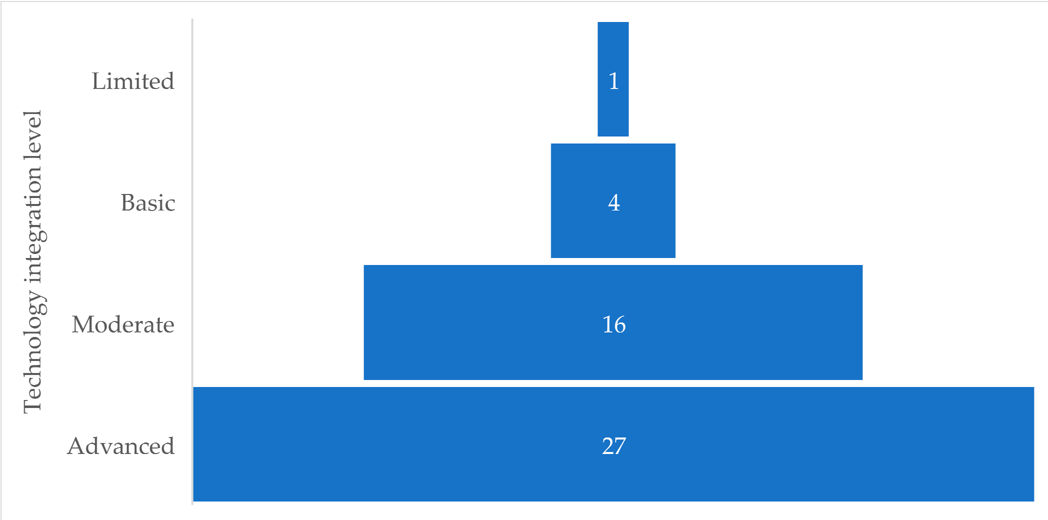

Figure 10. Level of technology integration in aeroponics.

As indicated in Figure 10, 2% of the studies presented a limited level of integration ($N = 1$), indicating that the purpose was not to improve the system functions but to replace some traditional tools. Nine percent of the studies presented a basic level of integration ($N = 4$), which indicates that producers partially implemented technological-based solutions with some improvements in the process. Similarly, 34% of the studies used technology at a moderate level ($N = 16$), indicating that some processes were intervened with technology, and the production was notoriously improved. Finally, 57% of the studies presented an advanced level of technology ($N = 27$), indicating that all the processes were intervened with technology, and technology was implemented to create new processes. Next, we describe some studies and the motivation behind being coded in the assigned category.

4.4.1. Limited integration of technology in an aeroponic system

As indicated in Figure 1, a study was coded as "Limited" when technology was used to substitute specific activities or tools without functional changes or improvements. In the present review, only the study by Dannehl et al. [43] was assigned to this category. The study proposed a hybrid aeroponic/nutrient film technique system for the cultivation of greenhouse tomatoes. The system was installed using conventional materials and equipment available on the market. Despite using multiple elements related to dispenser technology, their study did not report functional changes in the process. That is, the implemented technology did not enhance the process; it only replaced manual irrigation.

4.4.2. Basic integration of technology in an aeroponic system

A study was coded as "Basic" when a few fundamental technological components were incorporated to improve functionality and efficiency. For example, the study by Mazhar et al. [61] developed an automated atomization and spraying system to grow lettuce in an aeroponic system. Specifically, the system aimed to impact the chemical properties of the nutrient solution, biomass yield, root-to-shoot ratio, and nutrients uptake. The system allowed a high dosage accuracy of plant root coverage, thus saving energy, resources, and contributing to sustainability. In this case, the implemented technology improved the process but did not fundamentally change it.

4.4.3. Moderate integration of technology in an aeroponic system

A study was coded as "Moderate" when technology was consistently integrated into an aeroponic system to significantly improve the product quality and sustainability efforts. For example, the study by Mehmood et al. [69] designed a prototype aeroponic system for indoor vegetable plant growth using the AutoCAD design software. The system included a timer to control the irrigation interval, a submergible pump, a plastic pipe for the flow of water, and LED lights to control the requirement of sunlight. The authors claimed having reduced the number of hours dedicated by the growers and the number of resources utilized throughout the process, thus contributing to efficiency and sustainability. In this case, the implemented technology modified the process and enhanced efficiency and sustainability.

4.4.4. Advanced integration of technology in an aeroponic system

A study was coded as "Advanced" when technology was fully integrated into the system to create new processes, not otherwise possible without the use of technology. The fertigation control system presented by Setiowati et al. [71] is a clear example of an advanced integration of technology. The system managed to control the temperature of the roots at an ideal temperature for growing lettuce. This precise control would not be possible without using technology; therefore, in this case, the technology redefined the process. The system used multiple technologies, such as IoT, sensors, and microprocessors, which altogether enhanced the system's efficiency, rentability, and sustainability.

4.5. Limitations of the study and future research

The results of this study are promising and show how integrating technology into aeroponics can provide multiple benefits for growers, consumers, and nature alike. However, some limitations must be considered when interpreting our results. First, we included journal articles and conference articles published in four bibliometric databases. Therefore, considering other types of studies, such as dissertations, books, and unpublished studies, could have enriched the scope of our results. Additionally, including different databases and conference proceedings could enhance the sample, providing a more accurate panorama.

On the other hand, this study uses the TAISA model to identify the technology integration level in aeroponics and how this integration benefits the production process. Therefore, we encourage stakeholders to embrace similar research projects to identify how technology can be integrated into similar sustainable agricultural techniques, such as hydroponics and aquaponics.

5. Conclusions

This systematic review identified the status and tendencies in the usage of technology in aeroponics as well as the main opportunities and challenges. Furthermore, the study introduced TAISA model to identify the level of technology integration in sustainable agriculture. To the best of our knowledge, this is the first study of its type. Therefore, the results of this review can serve as a reference for policymakers, researchers, and producers.

As for the trends regarding the use of technology in aeroponics, the results indicate that most implemented technologies are related to industry 4.0 and sensors. Furthermore, the most cultivated products are vegetables, particularly lettuce. Indonesia is the country where most studies were developed, and Asia the leading continent regarding the publication of studies related to technology integration into aeroponics. IEEE published the largest number of studies, and finally, the classification by year of publication indicates an increasing number of studies from 2015.

As for the advantages of integrating technology into aeroponics, sustainability was the most reported advantage. This result is positive, as sustainability is a key incentive for implementing this aeroponics. On the other hand, technical complexity was described as the main challenge of integrating technology into aeroponics. The integration of advanced technology requires technical and expert knowledge, which increases the system's complexity.

Finally, the results indicate that the most common level of technology integration is "Advanced," which supposes that technology has been implemented with the purpose of redefining and creating new processes. It is important to note, that the level of technology integration depends on factors

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such as budget, system scale, and the goals of the aquaponics project. In summary, the integration of technology into aeroponics has the potential to reshape modern agriculture by fostering sustainable practices, increasing yields, mitigating resource constraints, and assist in achieving the zero-hunger sustainable goal. As technological advancements continue to evolve, careful consideration of both the benefits and limitations will pave the way for a more efficient, productive, and resilient aeroponic cultivation system.

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