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Systematic Review

Technologies to Optimize the Water Consumption in Agriculture: A Systematic Review

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Abstract: Agriculture is facing several very important challenges. Population growth means that more food must be produced to meet nutritional needs. However, this is putting excessive pressure on natural resources, such as water and land, which are heavily used for agricultural practices. For these reasons, we carried out a systematic review of existing studies in the scientific literature to better understand how innovative strategies can decrease water consumption in agriculture. It was performed following PRISMA guidelines, using the Scopus database to select papers that have investigated the link between water consumption and the main agriculture strategies, such as controlled-environment agriculture, hydroponics, and precision farming for field crops, in the last ten years. Data relating to the water requirements of the selected crops were estimated to provide a framework for evaluating possible solutions. The results showed that these innovative strategies have the potential to decrease water consumption, but more research is needed to fully understand their effectiveness and potential trade-offs. Therefore, both exogenous and endogenous crop factors should be considered to maximize water savings. The results will form the basis for a framework for assessing the sustainability of agricultural strategies and how they can be applied in a real-life case study.

Keywords: precision farming; Agriculture 4.0; water consumption; hydroponic systems; vertical farming; smart sensors

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1. Introduction

The future of food availability is very uncertain. In 2019, the land used for agricultural activities amounted to 4752 million ha, with one third being dedicated to temporary and permanent crops and the remaining portion to meadows and pastures. Between 2000 and 2019, the amount of arable land used mainly for irrigated crops doubled, while that for rainfed crops increased by only 2.6 percent. Over the same period, populations increased at higher rates, resulting in a 22% decrease in the land available per capita for crops and livestock farming activities. Indeed, according to the FAO, by 2050, agricultural activities will need to produce almost 50% more food than in 2012 [1]. This means that the exploitation of valuable resources, such as water and land, has never been so intense, pushing agricultural production to the limit.

Against this backdrop, several important global policy frameworks have been developed in recent years, including the 2030 Agenda for Sustainable Development, the Paris Agreement on climate change, the Addis Ababa Action on Financing for Development, the Sendai Framework for Disaster Risk Reduction 2015–2030, and the Small Island Developing States Accelerated Modalities. The 2030 Agenda for Sustainable Development is a plan of action for people, the planet, and prosperity that includes 17 Sustainable Development Goals with 169 associated targets that are integrated and indivisible. Among the various goals that need to be achieved are food security, improved nutrition, and the promotion of sustainable agriculture [2].

The context becomes more complex when the effects of climate change are considered. Extreme weather events are becoming more frequent and more severe. Human activities are estimated to have caused global warming of about 1.0 °C compared to pre-industrial levels, with a likely range of 0.8 °C to 1.2 °C. Available data on expected climate risks indicate that opportunities for adaptation to many climate hazards will be limited if global warming exceeds 1.5 °C [3]. Indeed, for this scenario, it is expected that the risks affecting agriculture, energy, food, and water will overlap spatially and temporally, affecting increasing numbers of people and regions.

For these reasons, it is essential to focus on minimizing water consumption, as the problem of drought is a growing problem in some geographical regions [3]. Predictions clearly show that, due to urbanization, there will be less land for agricultural practices, while population growth will lead to growth in the demand for food in order to meet the needs of the world's population. In the literature, there are multiple testimonies confirming that the future challenge will be to produce more while consuming less, i.e., limiting the exploitation of natural resources and limiting waste. For example, soil-less crops that can grow vertically indoors close to urban centers have been developed as an effective solution to this challenge. In hydroponic systems, plants are grown out of the soil with their roots in the air, placed inside an inert substrate, or perpetually immersed in a nutrient solution [4]

Several researchers have implemented systems with the aim of managing irrigation systems using IoT technologies and monitoring endogenous and exogenous crop factors, and machine learning algorithms were used to optimize the systems obtained [5–7].

Furthermore, with the aim of safeguarding water, innovative systems have been studied that are also able to recover water from the environment or from other sources [8].

Therefore, taking all this into consideration, it would be interesting to understand how the agriculture sector is preparing for future challenges. A review of existing studies in the scientific literature will be helpful to better understand how five different strategies applied to different crops might be evaluated in a global environment where resources will be increasingly scarce. This preliminary work will form the basis for a future proposal of a framework for assessing the sustainability of agriculture strategies in a real case study.

To prepare this article, a literature review was performed according to the PRISMA guidelines. The PRISMA statement was first designed for systematic reviews analyzing health interventions. However, the approach and the checklist items are applicable for different purposes in various contexts [9]. This review was carried out to draw together the information currently in the literature addressing this question: *in agriculture, can innovative strategies decrease water consumption compared to traditional agriculture?*

The Scopus database was used to identify papers that have investigated the link between water consumption and the main agriculture strategies, such as controlled-environment agriculture, hydroponic crops, and precision farming for field crops, in the last ten years. The methodology used for the systematic review is described in detail in Section 2. Then, Section 3 qualitatively describes the sources' characteristics, their geographical and temporal distribution, the main topics dealt with, and the results for water consumption and yield by crop category. The final section draws out the weaknesses of the literature and describes lines for future research based on the results obtained.

2. Literature Review Methodology

2.1. Literature Identification

For the literature analysis, we used the chosen methodology because it allows for clear and transparent systematic reviews. Using the PRISMA statement, we followed the checklist of 27 items and drew up a flow diagram in four steps. The checklist included the essential items required to analyze the literature clearly. Moreover, by following this procedure, it is much easier to evaluate missing results [10,11]. Using the Scopus database in December 2022, 71 papers published in English in the last ten years (2012–2022) were retrieved. Among them, articles, conference papers, short surveys, book chapters, reviews, conference reviews, and books were selected using a particular search strategy based on a PICO-style approach:

- P, problem: identifies the problem and its characteristics;
- I, intervention: identifies possible solutions;
- C, comparison: reports current practices;
- O, outcomes: shows the relevant outcomes of the study carried out, focusing on the solution that worked best.

This approach aimed to answer a precise question: *in agriculture, can innovative strategies decrease water consumption compared to traditional agriculture?*

The starting point of the search strategy was the analysis of data on water consumption in traditional agriculture and controlled-environment agriculture. A computerized search was undertaken to look for keywords using the "title, abstract and keywords" function, which we believed would be a better way to investigate the possible relationship between water consumption and agriculture technologies. In the early stage of the research, the first two criteria for the selection of studies from Scopus were:

- TITLE-ABS-KEY ("Water consumption" OR "water recovery" OR drought AND "traditional agriculture");
- TITLE-ABS-KEY ("Water consumption" OR "water recovery" OR drought AND "controlled environmental agriculture" OR "vertical farm*" OR "greenhouse").

Specific technologies were identified, and two different pillars were analyzed: soil-less cultivation and field cultivation. For soil-less cultivation, hydroponics, aeroponics, and aquaponics were analyzed. For field cultivation, we chose to further research topics related to precision agriculture. The Scopus search filters used in this second step were:

- TITLE-ABS-KEY ("Water consumption" OR "water recovery" OR drought AND hydroponic* OR aeroponic* OR aquaponic*);
- TITLE-ABS-KEY ("Water consumption" OR "water recovery" OR drought AND "precision agriculture" OR "precision farming" OR "smart agriculture" OR "Agriculture 4.0").

The strategy research adopted is represented in Figure 1.

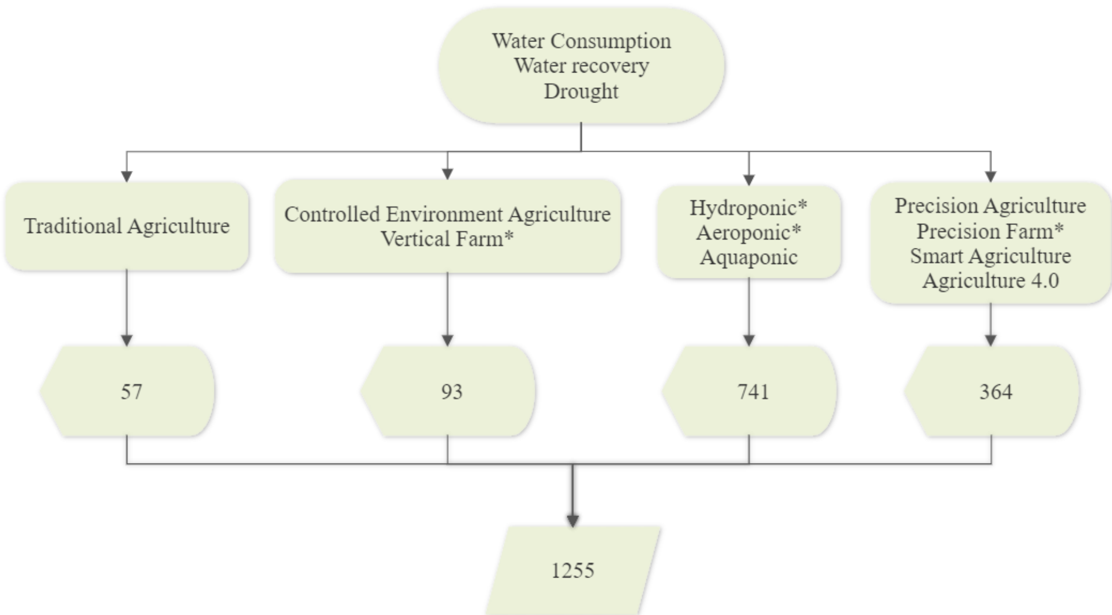

Figure 1. Flowchart for search strategy followed. We used the asterisk in the figure to indicate that Plurals and spelling variants are included in the search strategy.

2.2. Inclusion Criteria for Literature Screening

At this stage, four selection criteria were applied as reported in Table 1. The first criterion was that papers were published between 2012 and 2022, as this was the period when interest in saving natural resources, such as water and land, began to grow. The second criterion limited the search to papers that were published in English only. Then, since the aim of this systematic review was to provide an accurate overview of engineering solutions, an inclusion criterion was applied though the filters of the Scopus database limiting the search to articles in the fields of engineering, chemical engineering, and energy. Finally, only publications in their final state were considered. Following this screening, it was possible to refine the search by selecting 161 papers. Described process and related results are represented in Figure 2.

Table 1. Inclusion criteria for screening using filters from Scopus and Excel.

	Traditional Agriculture	Controlled-Environment Agriculture	Hydroponics, Aeroponics, and Aquaponics	Precision Agriculture	Total Records	Excluded Records
Papers identified	57	93	741	364	1255	
Publication year (2012–2022)	45	71	548	338	1002	253
English language	43	59	523	323	948	54
Subject area: engineering, chemical engineering, and energy	8	21	60	82	171	777
Publication stage	8	21	60	81	170	1
Duplicate records	7	17	59	78	161	9

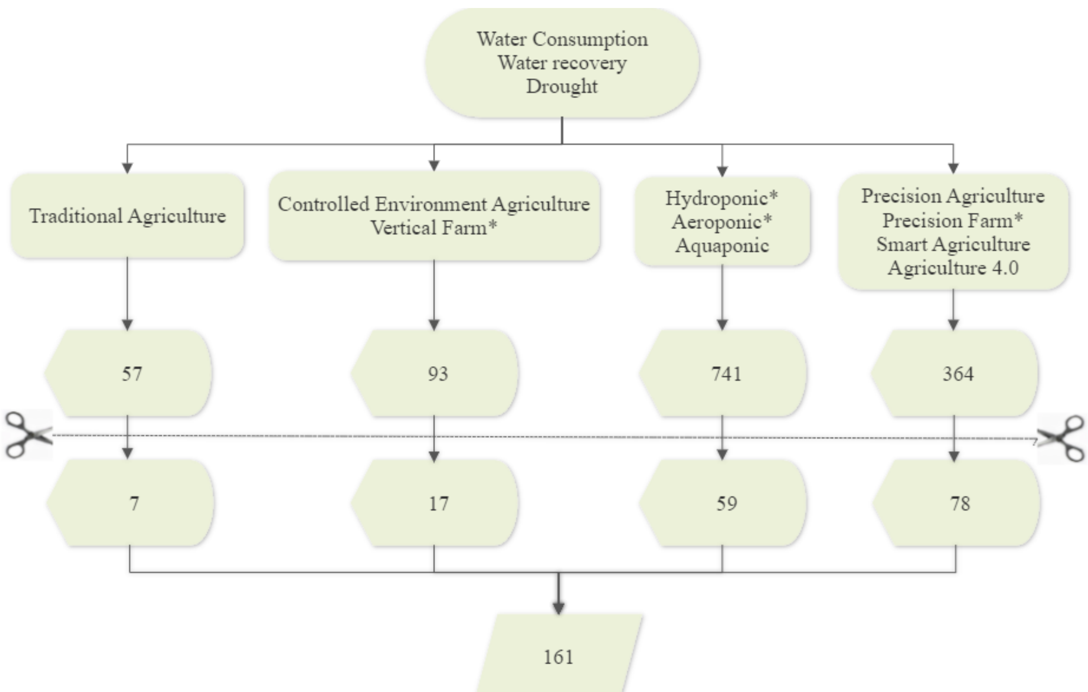

Figure 2. Flowchart for search strategy followed and screening stage. We used the asterisk in the figure to indicate that Plurals and spelling variants are included in the search strategy.

2.3. Eligibility and Inclusion Stage

The 161 articles selected through the previous screening phase were analyzed in detail by examining the abstracts, their main characteristics, and the journals in which they were published. This review focused on water consumption; therefore, studies that deviated from this topic were excluded. As a result, 97 articles were removed. This left a total of 71 articles that matched all the inclusion criteria and were, therefore, included in this analysis. Figure 3 shows the PRISMA flowchart used in this systematic review.

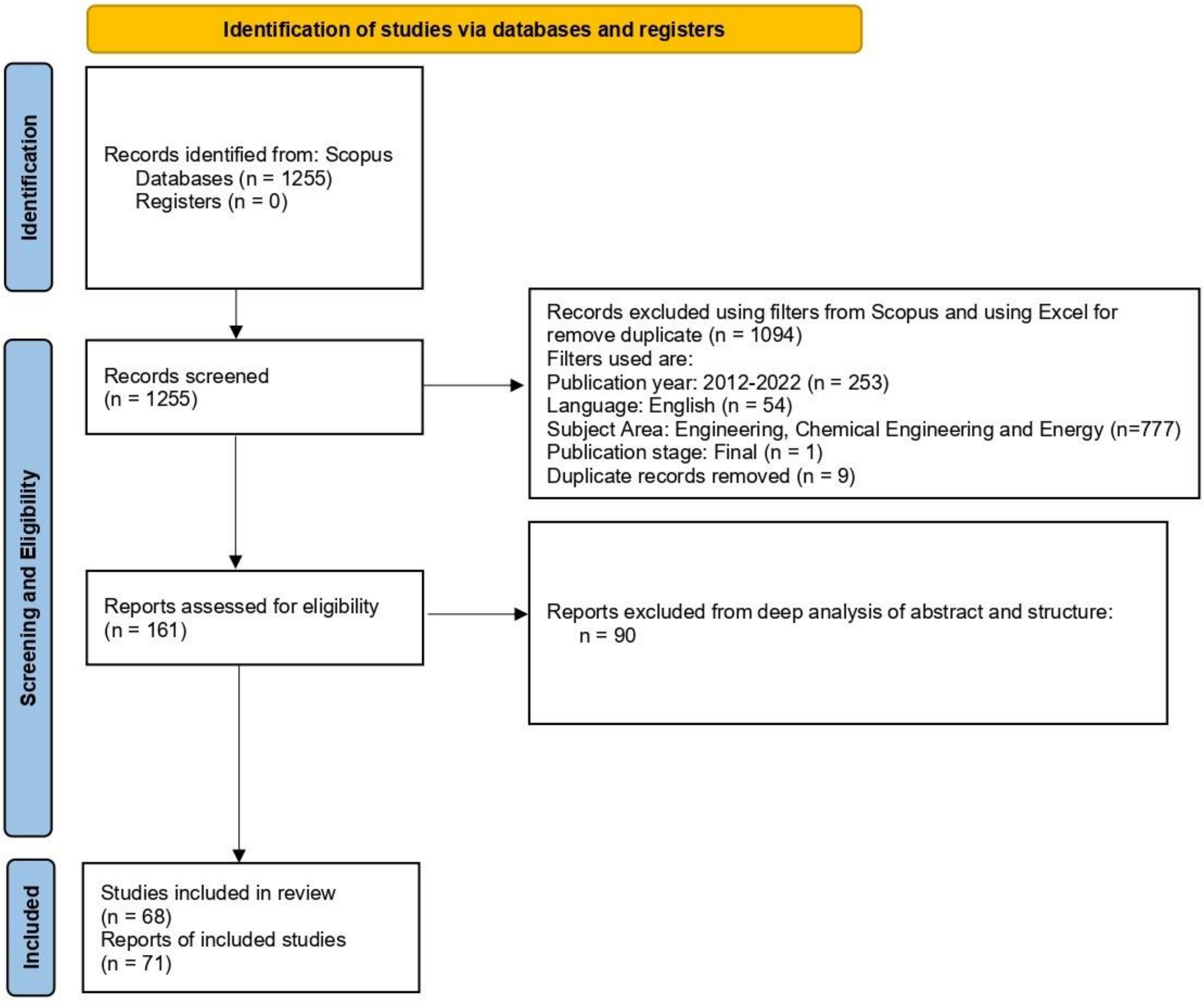

Figure 3. PRISMA flowchart for selection and data extraction.

3. Results and Discussions

The first article of relevant interest that addressed the issue of water consumption in agriculture was authored in 2012 [12]. It was then necessary to wait until 2017 for other studies with a focus closely related to the topic of interest in this review. As shown in Figure 4, starting from 2017, there was a major increase in terms of the number of published papers. This number maintained an approximately constant trend over the past three years (2020–2022). This shows that increasing attention is being paid to the global problems described earlier.

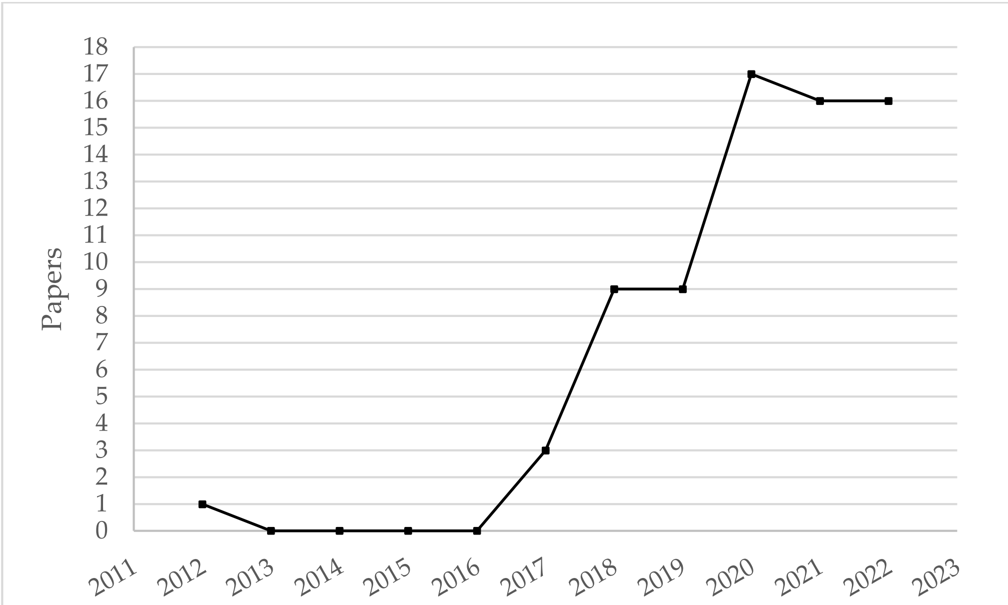

Figure 4. Trend in the number of papers on water consumption in agriculture for the last ten years.

We also analyzed the document types for the reviewed works. As shown in Table 2, of the 71 papers retrieved, 44 were articles, 24 were conference papers, and 3 were reviews. Furthermore, 36 were open access, indicating the relevance of the issue and a tendency to desire to share research results.

Table 2. Numbers of different document types for the retrieved papers.

Document Type	Papers
Article	44
Conference paper	24
Review	3

Since the issue dealt with in the present review is a global issue, the geographical distribution of the published papers was of great interest. The assessment was undertaken by considering the address of the corresponding author for each article, thus providing a clear idea of how different countries are tackling the current situation. As can be seen from the graph created using Excel shown in Figure 5, the issue is being dealt with worldwide, but Italy and the United States are the main countries where researchers have carried out work on water consumption in the agriculture sector.

Another very interesting analysis that was performed concerned the frequency with which the main keywords in these papers occurred. The most common keywords of the selected papers were reported in Table 3. The most popular were "irrigation", "agriculture", "crops", "hydroponics", and "Internet of Things".

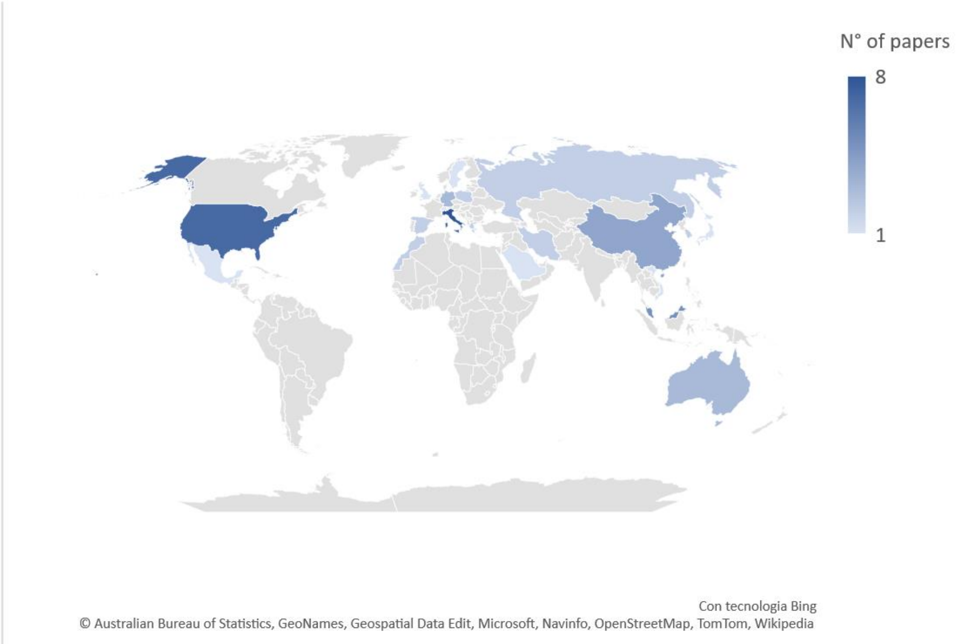

Figure 5. Global geographical distribution of published papers on water consumption in agriculture obtained by considering the addresses of corresponding authors.

Table 3. The frequency with which keywords occurred.

Keywords	Frequency
Irrigation	17
Agriculture	17
Crops	17
Hydroponics	16
Internet of Things	16
Precision agriculture	13
Water consumption	11
Soil moisture	10
Water supply	9
Water management	9
Agricultural robots	9
Cultivation	9
Greenhouses	9
Sustainable development	9

Using VOSviewer, it was possible to analyze the interconnections between the most prevalent keywords to obtain a clear understanding of the links between them and focus on the most relevant topics. The results of this analysis have shown in Figure 6.

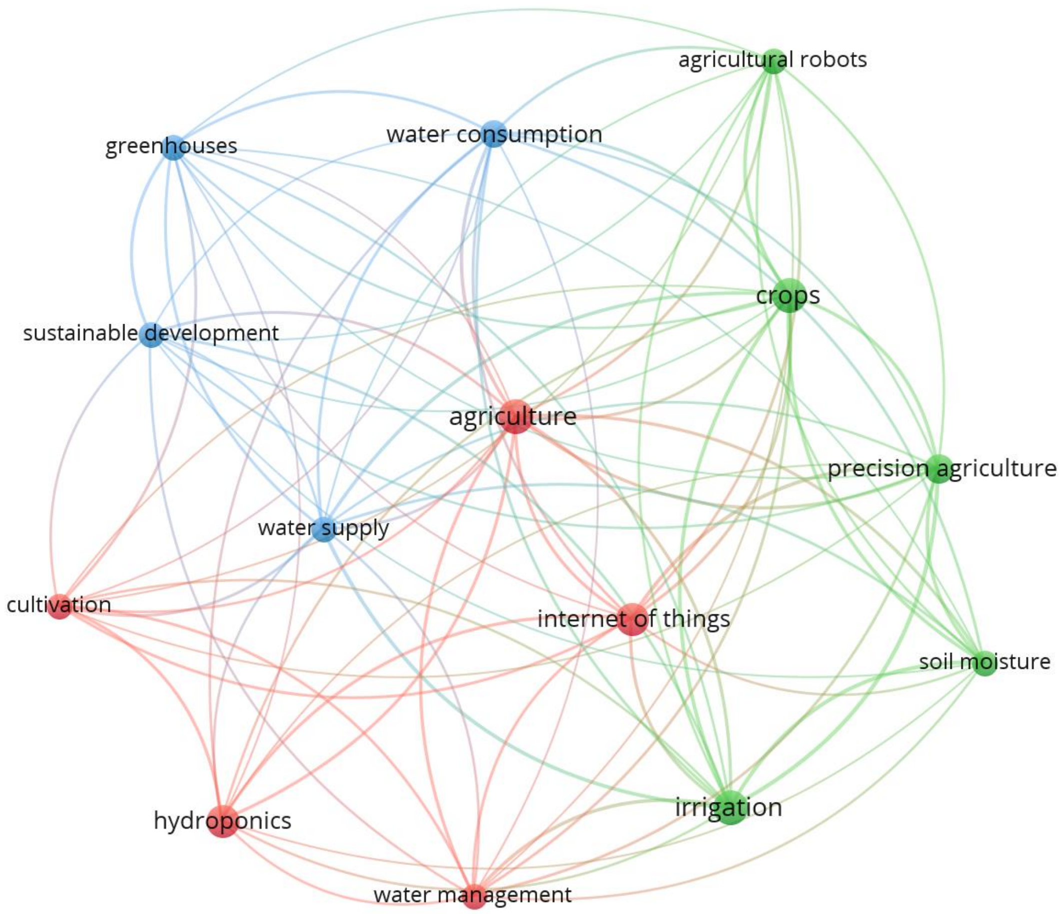

Figure 6. Relationships between the main keywords in the selected papers.

Based on this preliminary assessment, five main topics on which to focus our future attention were identified among the articles reviewed:

Topic one. Controlled-environment agriculture in greenhouses or vertical farming. In this topic, we also included solutions that used soil-less techniques, such as hydroponic systems, aeroponic systems, and aquaponic systems;

Topic two. Smart agriculture using sensors that monitor plant exogenous factors, such as soil moisture or environment condition;

Topic three. Smart agriculture using sensors that monitor plant endogenous factors, such as sap ion concentrations, to obtain a qualitative indication of water stress;

Topic four. Smart systems for the prediction of water stress and management of irrigation systems;

Topic five. Smart solutions for water-recycling systems.

The subdivision of the papers, following the topics introduced, is given in the Table 4.

Table 4. Topic-based classification of the papers.

Topic	Articles
1	[4,5,12–35]
2	[6,7,18,31–34,36–47]
3	[48–53]
4	[28,29,38,51,53–64]
5	[8,65–74]

3.1. Detailed Description of Each Topic

3.1.1. Topic One: Controlled-Environment Agriculture

Urbanization and increasing population growth are known to increase pressure on the exploitation of natural resources, especially those of interest to this study, land, and water. The projections are clear and state that, due to urbanization, there will be less land available for agricultural practices, while population increases will lead to growth in food demand to meet the needs of the world population. This means that the future challenge will be to produce more while consuming less; i.e., limiting the exploitation of natural resources and limiting waste. For these reasons, soil-less crops growing vertically indoors close to urban centers have proved to be a powerful solution to this challenge [4]. According to this study, it is very important that these urban greenhouses are integrated as much as possible within the urban network in order to optimize energy supply, water consumption, and wastewater reuse, as well as, above all, to meet the demand for horticultural products in the urban center. The authors describe the Agrotopia project, a rooftop research greenhouse in Belgium. Agrotopia was built on the top of an agricultural auction market in an area that was abandoned a few years previously. This new building is an example of urban transformation and sustainable use of land and resources that respects the surrounding environment. The project therefore has the ambitious goal of studying, demonstrating, and communicating how these techniques can lead towards sustainable agricultural development.

In terms of the research topic, this shows how important it is to thoroughly explore and optimize the process of growing crops in a controlled environment using soil-less techniques. In this regard, the authors of [13] deal with the issues related to the effect of climate change on agriculture by presenting specific solutions involving controlled-environment agriculture in greenhouses. Increasing water-use efficiency and protecting crops from adverse weather conditions, such as drought or extreme precipitation, are the most important priorities for adaptation. The authors of [15] predicted the performance of crops using an energy cascade model to optimize cultivation management in controlled-environment agriculture. The authors of [16], after assessing different solutions, including greenhouse cultivation, open-field cultivation, and vertical farming in buildings, stated that the most effective solution was represented by a plant factory design with no windows, completely artificial LED lighting, a photovoltaic system, and beer residue-derived fertilizer. The authors of [17] also analyzed different solutions involving indoor cultivation to assess how different resources can be used.

In hydroponic systems, the plants are grown out of the soil with their roots in the air, inside an inert substrate, or perpetually immersed in a nutrient solution (in the last case, adequate root oxygenation must be ensured). In this way, the crops receive the essential elements for development through a nutrient solution directly applied to the roots of the plants using different operating techniques. This provides the plants with everything they need for their stage of growth and environmental conditions. As a result, the crops grow more healthily, with higher yields and less environmental impact on land use and water than traditional crops. Other advantages can also be noted from the point of view of the exploitation of chemicals, such as herbicides and pesticides; this is because, as this method operates in a closed and controlled environment, there is no need to use such chemicals. However, there are several variables that need to be controlled, both environmentally and in terms of the nutrient solution and light needed for the photosynthesis process. In most cases, lighting is provided by special LED lamps, and environmental conditions are kept ideal with HVAC systems. Therefore, the energy demand must be thoroughly analyzed since it exceeds that required by traditional farming. The authors of [21] proposed the development of an artificial intelligence system for the management of a hydroponic system. The goal was not only to automate the entire process but, if used on a large scale, it was intended to provide a framework for the analysis of data on hydroponic cultivation in comparison to traditional agriculture techniques. The authors of [31] implemented a fully automated hydroponic solution using closed-loop control over variables endogenous to the plants, such as humidity, light intensity, turbidity, pH, and flow of nutrient solution. In this way, fully automated control was achieved. The system was advantageous in terms of cost, product quality, and work safety, as the principles of Industry 4.0 were integrated in these advanced agricultural practices. With the same aim, automated hydroponic systems have been set up. These used IoT technologies to ensure the conditions required for proper crop development [33,34].

An application of a hydroponic system is reported below in Figure 7.

Figure 7. Hydroponic system.

In addition to hydroponics, through which crops are grown using inert substrates, the authors of [20] studied an experimental aquaponic system in which the development of a soil-less crop was combined with fish farming. Leveraging such symbioses can minimize water consumption and reduce emissions. This experimental system was in an isolated room. The logical flow allowed the water from the fish-rearing area to pass through a mechanical filtration station that ensured the removal of most of the suspended solids discharged from the system. From here, the water passed to the plant-growing area. In this way, the crops received the elements they needed for growth and, at the same time, acted as a filter cleaning the water, which returned to the fish-rearing area through a closed system. To date, few studies have explored the advantages and disadvantages of such a solution; indeed, the results of [20] show how important it is to effectively evaluate the instrumentation and machinery that are used to achieve effective water and energy savings.

An example of the interaction between irrigation savings and cultivation is shown by an acquaponic system in Figure 8.

The authors of [30] carried out a lifecycle assessment (LCA) to evaluate the environmental impact caused by hydroponic and aquaponic crops in Europe. Fresh fruits and vegetables in European markets usually come from many sources, with a high proportion being exported products. The environmental impacts of these products typically result from the resources used for production and long-distance transportation in air-conditioned trucks. Considering Germany and the Netherlands as northern European countries and Italy and Spain as southern European countries, the authors suggested that, by effectively studying the setup for and the various sources of water and energy supply, local fruit and vegetables production in urban areas can be a sustainable solution. However, in the northern European region, there is higher energy demand related to maintaining environmental conditions inside greenhouses and supplying lighting, while in southern regions, the main issue is related to higher water consumption.

Figure 8. Aquaponic system.

3.1.2. Topic Two: Smart Sensors to Monitor Plant Exogenous Factors

Achieving sustainable agriculture means reducing not only the use of natural resources but also food waste from processing and transport. For waste originating from transport, the quantity can be reduced by concentrating vertical farming within urban centers, as this would lead to decreases in distance and transport time. To reduce waste from production, however, it is important to satisfy plants' needs in terms of nutrients, water supply, environmental parameters, the amount of light required for the photosynthesis process, etc. To achieve this, monitoring of the variables involved is essential. To maintain the nutrient solution elements at the optimal levels, it is often necessary to change the pH and electrical conductivity. However, as a result of this, there is a risk of losing sensitivity regarding the salts' level of absorption. To balance this, researchers have developed a model that aims to estimate the ion concentration within a solution using a machine learning approach, making it possible to correct ion interference effects that lead to the misreporting of results obtained from sensors. Thus, excessive absorption of salts into plants can be avoided [23].

A mini-hydroponic system was designed that can be used at the household level and can meet the household demand for fresh products. It relies on closed-loop control to monitor variables endogenous to the plants that are essential for their development and to minimize water consumption [32].

The need to automate agricultural operations is not only related to greenhouse crops but also field crops. Furthermore, in this case, the aim is to improve crop yields and reduce waste, water consumption, and the resulting environmental impacts overall, while, at the same time, improving food safety and the safety of operators. The authors of [36] set up an IoT-based system to manage an irrigation system and provide water to crops only when they needed it. The designed control was a closed-loop system and was based on data monitored by IoT sensors in the field that evaluated soil moisture and temperature. Furthermore, the authors of [5–7] evaluated systems that were aimed at managing irrigation systems by exploiting IoT technologies and machine learning algorithms.

In the case of crops that are spread over several hectares, such as orchards, it is very difficult to monitor the variables that would allow the water supply to be optimized to meet the needs of the crop. The challenge lies in the choice of both the type of sensor and the type of variable to monitor, but it is also important to assess the quality of the information obtained. In general, a widely used approach in the literature is to use soil moisture sensors. However, it has been shown that the control obtained with this method can be inaccurate because plant needs can vary with the same soil moisture content due to other factors, such as the evaporation rate and the water status of plants. This problem is particularly acute when the crop area is very large. Thus, the authors of [38], in order to optimize the water management for an orchard, proposed a system for estimating plant and soil water content using scattered soil moisture sensors, low-frequency remote sensing data, and meteorological information. The authors of [47], in their research, tested the effectiveness of a dielectric humidity sensor using infrared thermal imaging techniques. The authors explained that the use of such sensors could increase the sustainability of microgreen crops, and the increase in efficiency may be greater for crops with a longer growth cycle or higher water consumption.

An application of a smart irrigation system is presented below in Figure 9.

Figure 9. Smart controller monitoring plant exogenous factors.

3.1.3. Topic Three: Smart Sensors to Monitor Plant Endogenous Factors

In the literature, as can be seen from the number of papers dealing with the first two topics, much attention has been paid to the management of water systems by controlling factors intrinsic to the conditions surrounding the cultivation, such as environmental and soil conditions. If only extrinsic factors are monitored and controlled, there is a risk of the system responding too slowly to the needs of the crops or of inaccurate water management. This is because plants' water requirements also depend on intrinsic factors, such as a plant's stage of development, evapotranspiration rate, and water status. The authors of [51] proposed a system for assessing plant health by evaluating the impedance of the stem using special sensors. In their study, the authors were able to simultaneously measure the impedance of four tobacco plants and analyze the relationship between the measured impedance and the external environmental conditions obtained by measuring air humidity, soil moisture, temperature, and ambient light levels. The results are very interesting for future studies and indicate a link between the calculated impedance variation and the diurnal cycle.

For the same reason, in [48–50], an organic electrochemical transistor inserted into the stems of the plants themselves was introduced for the continuous monitoring of changes in the ionic composition of plant sap in real time. Plant sap is a liquid transported in plants' vasculature, the content of which is highly variable depending on the environmental conditions, which strongly influence plants' physiological state. The transistor was applied to study abiotic stresses in a controlled environment on several species, including tomato, kiwi, and soybean. In tomato crops, it was able to detect water stress within the first 30 h of its onset. In the field, it was connected to a Wi-Fi network capable of transmitting the signal to an app. Therefore, this sensor was able to detect the onset of water stress and could potentially send a signal to either the farmer or to the operating machines indicating that it is time to irrigate, thus significantly reducing the wastewater and increasing sustainability. Specifically, the ionic sap measurement took place every 10 to 15 min and, based on the data measured, it was possible to determine if the plant was suffering from water stress and what the plant needed, whether it was water, calcium, potassium, or any other nutrient, providing clear advantages not only economically but also environmentally. Such information cannot be obtained from soil testing because probes inserted in fields only reveal water shortages that affect soil and not plants, risking irrigation being undertaken at inappropriate times. Experiments carried out first in a protected environment (in a greenhouse) and then later in an open field during the summer months showed that, on average, savings of 36% for water and 20% for fertilizer were obtained during the campaign. This system can be applied in any type of cultivation and does not require any specific preparation for its use.

3.1.4. Topic Four: Smart Systems to Predict Drought Stress

Considering that the aim is to make agriculture practices as sustainable as possible, it is very important to consider model systems or instrumentation that would allow us to understand how plants behave vis-à-vis water stress and how much it affects yield and product quality. Therefore, being able to model such behavior means being able to predict plant conditions under water stress, which in turn provides an intelligent framework with which to efficiently manage irrigation systems. The authors of [53] investigated which state-of-the-art methodologies are aimed at predicting water stress for different crops. In this study, models were classified according to their basic setup, i.e., soil-based drought models, drought models based on hydroponic aqueous culture, and agar-based drought models. The authors of [29] studied the effects of seawater on the wellbeing of crops and whether they were salt-sensitive or salt-tolerant. These effects were compared with those from a common NaCl solution, and it was found that the seawater resulted in lower stress, especially for salt-sensitive species.

The authors of [56] addressed the issue of drought in the Mediterranean region. They demonstrated the effectiveness of a scheme for predicting drought stress and managing irrigation systems with several cotton crops in a central region of Greece. The scheme combined data from different sources, such as historical rainfall, data from sensors that measure soil water content, data extrapolated from very-high-resolution satellite images, and data on intrinsic plant variables, such as the evapotranspiration rate and normalized difference vegetation index. Another promising system for assessing drought stress in crops was proposed in [57]. The authors tested a system that uses IoT sensors and a machine learning algorithm to assess drought stress through pictures obtained with a camera. The results of these tests showed that the system achieved 74% accuracy in assessing drought stress for soybean and corn crops. Furthermore, the authors of [41] developed an efficient solution that combines information from the environment, crops, and soil with a machine learning algorithm that allows control to be increasingly refined.

In hydroponics, the supply of elements such as nitrogen, potassium, and phosphorus is essential for proper plant development. In field crops, these elements occur naturally in the soil, but the often-aggressive farming practices used mean that soils are becoming increasingly deficient in these elements. However, incorrectly managed fertigation processes can lead to various problems for the environment and crops, such as eutrophication and groundwater contamination. To avoid such problems, it is advisable to use automatic fertigation systems, such as control-based and time-based systems. Considering this, the authors of [59] stated that control-based systems are preferable, as they allow for lower environmental impact and water consumption.

3.1.5. Topic Five: Smart Solutions for Water-Recycling Systems

With the aim of safeguarding water, innovative systems have been studied that are also able to recover water from the environment or from other sources. According to [8], it is possible to recover water using innovative dehumidification technologies, such as liquid desiccants. In controlled-environment agriculture, the energy used for cooling, heating, and dehumidification can lead to both higher costs for electricity and a significant carbon footprint if the grid energy comes from fossil fuels. Experimental results confirmed that vacuum membrane distillation using PVDF hollow fibers was effective in desalting calcium chloride and magnesium chloride to obtain concentrated solute and fresh water that could be used in controlled-environment agriculture. Therefore, employing this water-recycling system, the water footprint for the same vegetables can be reduced by 98–99%. The authors of [65] carried out a demonstration of the feasibility of the fertilizer-drawn forward-osmosis process at the laboratory and pilot scales, showing that it was possible to ensure a nutrient solution suitable for hydroponics systems via osmotic dilution of synthetic wastewater effluent using a commercial hydroponic nutrient solution and draw solution. Therefore, with this system, it is possible to valorize wastewater as a sustainable water resource. The authors of [66] assessed the application of biogas slurry as an energy-efficient withdrawal solution for an osmotic dilution forward process, making it possible to extract water from wastewater with traces of metal pollutants for later use as a solution for hydroponic crops. Considering that the issue of water reuse is becoming increasingly important, it is necessary to not only intensify existing methods for surface and groundwater treatment but also to develop freshwater desalination technologies. The authors of [67] developed an energy-efficient technology for desalinating seawater and obtaining clean, fresh water through its forced evaporation with subsequent moisture condensation, thus providing an efficient operating unit that can be used independently, for example, for water supply for hydroponic crops.

As is well-known, in hydroponic greenhouses, it is very important to maintain suitable indoor environmental conditions to maximize the development of crops. The authors of [74], in a greenhouse in Poland for lettuce crops, designed a system to recover water from exhaust air. This water-recovery system exploits condensation in a crossflow heat exchanger operating within an air-conditioning system that maintains the required air parameters. Experimentally, it was found that the effectiveness of the system was very high due to the specific parameters of the indoor air with which the lettuce was grown and the need for constant air exchange inside the greenhouse. The efficiency rose to 100% during the winter months, while it was very low during the summer months. In each case, it succeeded in satisfying 67.1% of the crop water requirements. Since the availability of water is very low in Poland, to cover the entirety of the crop water requirements, another solution has been developed with the same hydroponic greenhouse as the previous work that allows for the collection of rainwater from the roof surface, thus combining two solutions [69]. In the latter study, the authors carried out an analysis using the recorded rainfall in Poland from the last 20 years and hourly meteorological data recorded between 2012 and 2019. Based on the analysis of long-term water-recovery systems, rainwater was presented as a less stable source of water than water recovered from exhausted air. Despite this, the rainwater-recovery system achieved an interesting efficiency level during the summer months of 38.94%. After proper sizing of the tanks and a careful economic analysis, a solution was proposed that could cover 90.4% of the water demand.

Considering the same topic, the authors of [70] investigated the potential of concentrated fertilizers for water recovery through forward osmosis. In their study, they determined the thermodynamic limits of fertilizer osmosis resulting from osmotic equilibrium, the operational limits resulting from the need to maintain proper flux levels, and the limits resulting from non-ideal transport dynamics with the aim of determining the amount of water that can be recovered for hydroponic crops. The authors showed how important elements for the development of crops, including nitrogen, potassium, and phosphorus, could be recovered with this process from a municipal wastewater feed source. The results of these experiments showed that it was possible to cover 32% to 99% of the water demand for the reported hydroponic crops.

Water sanitization processes may be chemical or physical, such as filtration, the application of radiation, or heat exchange processes. In heat exchange processes, in order to obtain an adequate level of sanitization, the required temperature is sometimes high and the timelines difficult to meet. For this reason, the authors of [71], in the context of water source recovery, developed a system for the sanitization of water that can be used with hydroponic crops at lower temperatures and with shorter times than traditional sanitation treatment. This was achieved through the simultaneous application of heat and solar UV radiation. The system studied involved the combination of an evacuated-tube solar collector and a flat-plate solar collector. This made it possible to eliminate the pathogens that may develop during agricultural practices and can be a problem for both food safety and water consumption.

The authors of [73] aimed to combine the benefits of hydroponics with the benefits of the circular economy in water management in a pilot plant. In this experiment carried out in Germany, municipal water was recovered and used as a source to supply lettuce growing in a hydroponic greenhouse. The water collected in this district came from domestic sources and was, therefore, suitable for use in hydroponic systems. First, in this pilot plant, the municipal water was treated at a basic level to discharge the organic compounds using aerobic (activated sludge process) and anaerobic (expanded granular sludge bed reactor) processes. At this point, the water still contained contaminants and pathogens that posed food safety problems. Ozone was used to eliminate pathogens because it is a molecule with high oxidizing power, while an oxidative process was used to eliminate micro-contaminants (biologically activated carbon filtration). Once sanitized through these treatments, the water was ready to be used.

As can be seen, most water-recovery systems feed hydroponic systems that are well-suited for this operation. Indeed, in wastewater, the elements that would normally be added if drinking water were to be used are already present. Therefore, the quantities of these elements are adjusted, pathogens and heavy metals are removed, and a sustainable source of water is obtained. Another concept that is very interesting for agriculture applications is that of recovering the water from HVAC systems employed to maintain the proper conditions.

3.2. Detailed Results for Each Crop

To further investigate the issue of water consumption and to study the link between the technologies developed to date and the reference crops, two benchmarks were set: crop yield and water consumption. These benchmarks were calculated in terms of the area used (expressed in hectares) and the time (using daily and annual data). This was because the data from the papers pertaining to the water consumption and yield of the corresponding crops were not all the same dimensions; thus, the aim of this analysis was to standardize them so that an initial qualitative comparison could be undertaken.

As Figure 10 shows, the greatest numbers of articles focused on crops such as lettuce and tomatoes, which accounted for 30% and 16% of the total, respectively. Another 7% of articles focused on fruits, such as apple, cherry, strawberry, and pomegranate. The remainder analyzed different types of crops, as can be seen in Table 5. This is why detailed data on the water consumption and yields for lettuce, tomato, fruits, and other crops are given below.

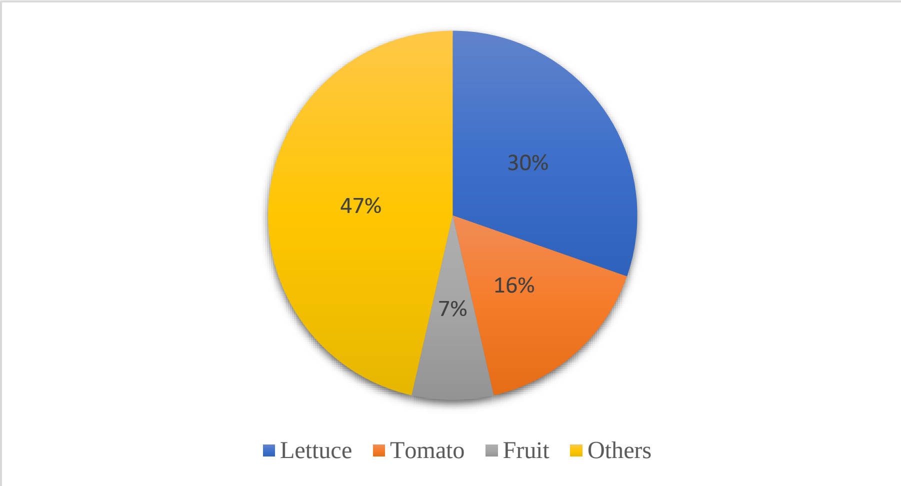

Figure 10. Distribution of papers in relation to the different crops treated.

Table 5. Numbers of articles dealing with specific crops.

Crops	Number of Papers	Crops	Number of Papers
Lettuce	17	Xian cai	1
Tomato	9	Cai xin	1
Wheat	4	Bell pepper	1
Soybean	2	Gynura procubens	1
Spinach	2	Apple	1
Potato	2	Cherry	1
Hazelnut	1	Strawberry	1
Cotton	1	Pomegranate	1
Alfalfa	1	Chili	1
Rice	1	Pasture grasses	1
Tobacco	1	Sugarcane	1
Pecan	1	Microgreens	1
Almond	1	Saffron	1

To assess the amount of water required to meet the needs of a given crop, it is necessary to consider the entire process. Therefore, it is necessary to assess the water requirements for irrigation before planting in drylands; the water requirements for flooding irrigation, such as rice cultivation; the water requirements for the crop grown when considering evapotranspiration; and the water requirements for special aims, such as cooling, heating, dehumidification, or preventing frost [36].

3.2.1. Results for Water Consumption and Yield for Lettuce

According to the FAO, lettuce is one of the most widely cultivated crops in the world. As Figure 11 shows, its overall production has increased over the years to close to 28 million tons [1]. It is an annual plant that is native to the Mediterranean region and grown in temperate and subtropical areas. It belongs to the daisy family Asteraceae and is most often grown as a leaf vegetable. This crop is suitable for both open-field and greenhouse cultivation. It can grow in late autumn and early spring because it is very resistant to extremely hot and cold conditions. The harvest period under optimal conditions is after about 70–80 days [75]. Several morphotypes of lettuce are grown in production operations, but the most common are the romaine lettuce, leafy lettuce, headed crispy lettuce, and oily lettuce morphotypes. The morphotypes and varieties of lettuce grown depend on both market strategies and commercial requirements [76].

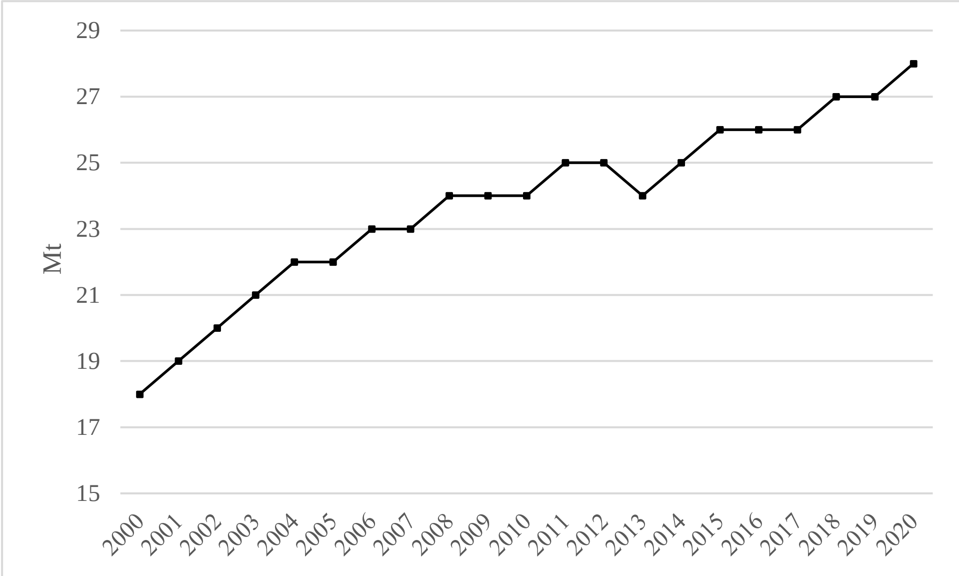

Figure 11. Global production of lettuce in the last 20 years expressed in megatons. Source: FAO. 2022. FAOSTAT.

Several experiments have been conducted on lettuce crops. Table 6 shows the results of the research that led to the quantification of the impact of the technologies used. Crop water requirements were estimated using remote sensors and fuzzy logic with the aim of optimizing the efficiency of the irrigation system to save water [36]. The variables input into the control were related to the environment in which the crop was grown. They were soil moisture, air humidity, air temperature, wind speed, soil permeability, rainfall, vegetation, and air pollution. For the fuzzy logic, the control outputs were the reference and water-stress evapotranspiration, the water pump conditions, the duration of water pump operation, the volume of water required for agricultural land, the irrigation efficiency, and the water losses. Three different modes of operation were assessed: in the first and second modes, the average daily and hourly data were considered. In the third case, the effects of air pollution, soil moisture, vegetation, and the rate of water infiltration were not assessed. The result, in this case, was that the second method was most accurate for determining water consumption and provided water savings of 70%. With the model, assuming irrigation once a day, the average water was calculated, and it was equal to 48,960 L/day. Considering that the farm area was 15 ha, the water requirement per ha was equal to 3264 L/ha. According to the authors, this fuzzy system can be used for any crop type [36].

An aquaponic system was designed for growing a particular fish species and lettuce; employing a useful area for crop growth of 50 m, the expected yearly production of lettuce was four tons. Regarding water consumption, the annual water consumption was 1070 m^3, including that necessary for the proper operation of the machinery within the system and for the healthy and adequate growth of both the animal and plant species treated. Carrying forward our analysis comparing various solutions using one hectare of area as a reference, once the useful surface area of action is known, the specific water consumption and specific yield can be calculated to be equal to 586.4 L/ha day and 11 kg/year ha, respectively [20].

Table 6. Detailed description of lettuce yield and water requirements.

Technologies	Topic	Lettuce						
		Farm Area (ha)	Daily Water Requirements (L/day)	Water Requirements per ha (m^3/ha)	Water Requirements per kg (L/kg)	Yearly Crop Yield (kg/year)	Crop Yield per ha (kg/ha)	Harvests per Year
Remote sensing and fuzzy logic control [36]	2	15	48,960	1191.36	-	-	-	-
Aquaponics system [20]	1	0.005	2932	214.036	-	4000	219	-
Hydroponic greenhouse [69,74]	5	0.0522	1030	19.16	-	-	-	-
Hydroponic greenbox [27]	1	0.000225	138.8	225.160	276.95	183	2227	12
Hydroponic greenhouse [27]	1	0.006967	4026	210.940	279.575	5256.6	2227	12

Researchers have demonstrated the effectiveness of cultivation inside a 1.5 × 1.5 × 2.1 m greenbox. This system was assembled using commercial grow tents, lighting elements, environmental monitoring and control modules, a ventilation system, and a nutrient solution delivery system. The crops inside this greenbox were compared with crops inside an experimental greenhouse. The water consumption and yield data for 12 annual harvests are outlined in Table 7. It was found that both the greenbox and the greenhouse offered the desired environmental conditions for growing lettuce, but the greenbox may have had some advantages in operational terms since greenhouses are often situated in urban areas and require high investments due to the more expensive land and procedures for planning and setting them up. Indeed, it is possible to adapt greenboxes to any vacant urban space with a minimum of adjustment [27].

Table 7. Detailed description of tomato yield and water requirements.

	Topic	Parameters Monitored	Tomato				
			Farm Area (ha)	Daily Water Requirements (L/day)	Water Requirements per ha (m^3/ha)	Yearly Crop Yield (kg/year)	Crop Yield per ha (kg/ha)
Hydroponic greenhouses [26]	1	Nine exogenous factors	2.8 40 1.65 6.58	25.7 per kg 367 per kg 15.2 per kg 47.4 per kg	3.35 per kg 3.35 per kg 3.35 per kg 2.63 per kg	-	-

As a result of this analysis, the hydroponic solution was found to be the most sustainable solution in terms of water consumption for lettuce cultivation, resulting in consumption of 19.16 m^3/ha. Remote sensing with fuzzy logic control was also a potentially suitable solution with 1191.36 m^3/ha. A very interesting data point came from the comparison of the hydroponic greenhouse and hydroponic greenbox. In this case, the hydroponic greenhouse was more sustainable under the same operating conditions.

3.2.2. Results for Water Consumption and Yield for Tomato

As shown by FAO data, tomato is one of the most important crops, with world production close to 190 megatons and a harvest area of 5.3 million hectares [1]. Data about tomato production, depending on the annual tons produced and the extension of cultivated land, were reported, respectively, in Figures 12 and 13. Tomatoes are a fast-growing crop with a vegetation period of between 90 and 150 days. Temperature and humidity play key roles in optimizing yields. In fact, tomato is a very frost-sensitive crop, but it grows well in mild, dry climates [1]. These data, combined with the characteristics of the crop, are the basis for the great attention paid to it; indeed, as can be seen from Table 5, several studies in the literature focus on tomatoes.

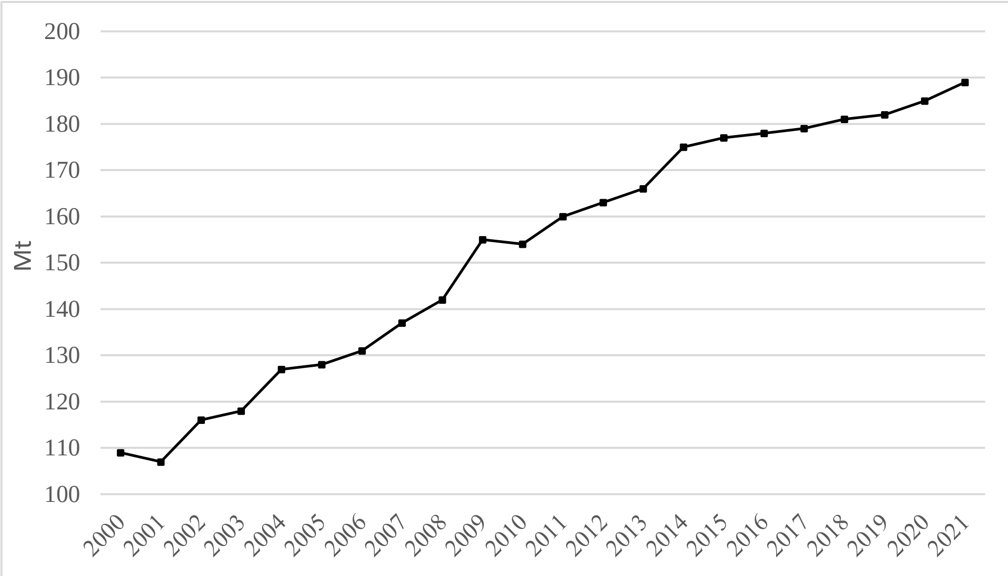

Figure 12. Global production of tomato in the last 20 years expressed in megatons. Source: FAO. 2022. FAOSTAT.

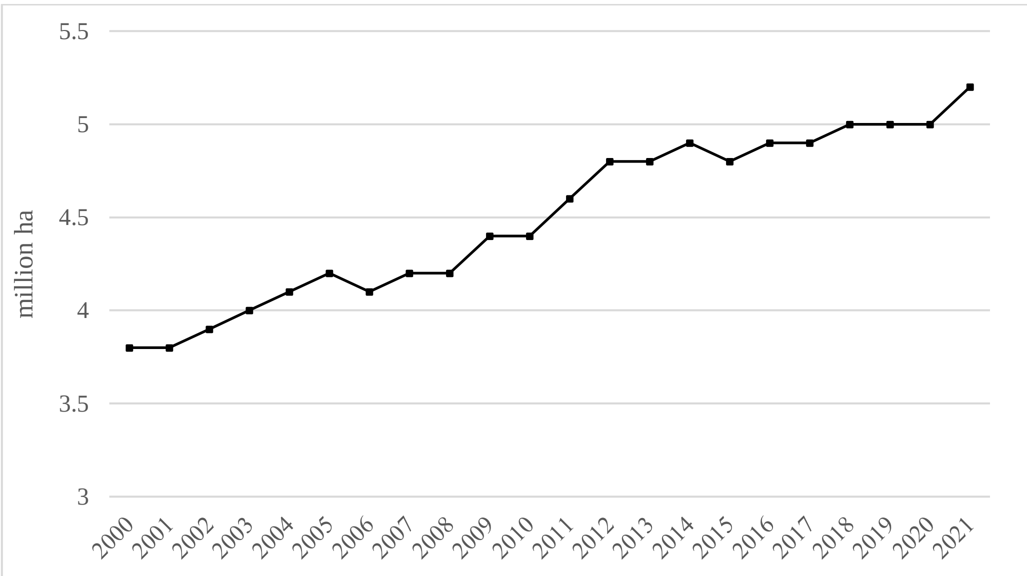

Figure 13. Area harvested for tomato in the last 20 years expressed in million ha. Source: FAO. 2022. FAOSTAT.

Following this trend, several studies in the literature focus on tomatoes as a crop. One study investigated a hydroponic system for growing tomatoes—in particular, the F1 hybrid tomato Suhyana—but did not provide accurate data regarding water consumption and yield [21]. Several other researchers [24,30,47–49,70] have performed tomato studies but did not quantify their results in terms of water consumption and yield.

The authors of [26] carried out a scenario analysis utilizing a geographical information system to assess the effects of seasonality, growth method, and production area size on the overall quality of the energy–water–food node. In this study, four companies operating in the territory of Qatar were considered. These companies differed in their technologies and extension areas, but all grew tomatoes in hydroponic greenhouses. It was found that taking advantage of hydroponic greenhouses results in water savings and higher yields compared to field crops but also higher energy consumption, as it is necessary to power the various systems needed to operate the greenhouse, such as HVAC systems and a reverse osmosis plant if it used to obtain fresh water from wastewater. As can be seen from the table, this analysis highlighted how the size of the farm area also has an impact on the overall energy and water consumption, which was evident when comparing 40 ha with 1.65 ha.

The values that emerge from this analysis show that hydroponics is a sustainable solution for growing tomatoes in both small and medium/large greenhouses. For this case, the water requirements per hectare were quantified and amounted to 3.35 m^3/ha.

3.2.3. Results for Water Consumption and Yield for Fruits

Table 8 shows the water consumption and yield data for various orchards. For example, the authors of [36] implemented a control system based on fuzzy logic in the field, providing interesting data on apples and cherries.

Table 8. Detailed description of fruit yields and water requirements.

Technologies	Topic	Fruits						
		Farm Area (ha)	Daily Water Requirements (L/day)	Water Requirements per ha (m^3/ha)	Water Requirements per kg (L/kg)	Yearly Crop Yield (kg/year)	Crop Yield per ha (kg/ha)	Harvesting per Year
Remote sensing and fuzzy logic control, apples [36]	2	7	60,000	3128	-	-	-	-
Remote sensing and fuzzy logic control, cherries [36]	2	3	24,000	2920	-	-	-	-

3.2.4. Results for Water Consumption and Yield for Other Crops

In this section, we report the most significant results for crops other than those mentioned above. The authors of [45] reported results in terms of water consumption for a solution based on the use of sensors for data acquisition, a platform for analyzing the big data acquired, a wireless actuator system, renewable energy sources to meet the energy needs of the various components used, a storage unit, a control unit, and a cluster controller. As can be seen from Table 9, using this system, considering 5 days of sampling and an area of 25 square meters, water savings of 71% were achieved.

Table 9. Detailed description of yields and water consumption for other crops.

Technologies	Topic	Other crops						
		Farm Area (ha)	Daily Water Requirements (L/day)	Water Requirements per ha (m^3/ha)	Water Requirements per kg (L/kg)	Yearly Crop Yield (kg/year)	Crop Yield per ha (kg/ha)	Harvesting per Year
Traditional farming [42]	2	0.0025	480	70,080	-	-	-	-
Remote sensing and fuzzy irrigation control unit [42]	2	0.0025	135.2	19,739	-	-	-	-
Irrigation + rainfall + fertilization system, wheat [45]	2	10	-	1660	-	-	-	-

Table 9. *Cont.*

Technologies	Topic	Other crops						
		Farm Area (ha)	Daily Water Requirements (L/day)	Water Requirements per ha (m^3/ha)	Water Requirements per kg (L/kg)	Yearly Crop Yield (kg/year)	Crop Yield per ha (kg/ha)	Harvesting per Year
Remote sensing and fuzzy logic control, wheat [36]	2	10	428,400	15,636	-	-	-	-
Remote sensing and fuzzy logic control, almond [36]	2	1	25,200	9198	-	-	-	-
Remote sensing and fuzzy logic control, alfalfa [36]	2	8	364,500	16,630	-	-	-	-
Conventional farming, gynura procubens [18]	2	-	-	561	-	-	-	-
Fuzzy logic control, gynura procubens [18]	2	-	-	466	-	-	-	-
Gravimetric control, microgreens [47]	2	-	-	272	16	-	17,000	-
Control-based system and dielectric moisture sensor, microgreens [47]	2	-	-	233.7	12.3	-	19,000	-
Hydroponics in plant factory, cai xin/xian cai [16]	1	0.05	116	848	16	31,800	53,000	12
Greenhouse, cai xin/xian cai [17]	1	0.05	160	1166	22	31,800	53,000	12
Open field, cai xin/xian cai [16]	1	0.025	47	689	13	15,900	53,000	12
Hydroponics in plant factory using renewable energy, cai xin/xian cai [16]	1	0.05	94	689	13	31,800	53,000	12
Hydroponics in plant factory using waste valorization, cai xin/xian cai [16]	1	0.05	116	848	16	31,800	53,000	12

Table 9. *Cont.*

Technologies	Topic	Other crops						
		Farm Area (ha)	Daily Water Requirements (L/day)	Water Requirements per ha (m^3/ha)	Water Requirements per kg (L/kg)	Yearly Crop Yield (kg/year)	Crop Yield per ha (kg/ha)	Harvesting per Year
Hydroponics in plant factory using renewable energy and waste valorization, cai xin/xian cai [16]	1	0.05	94	689	13	31,800	53,000	12
Model to monitor drought stress using satellite data, potato [55]	4	-	-	2000	57	-	35,000	-

The authors of [45] studied the impacts of different irrigation and fertilization strategies applied to a wheat crop in an LCA study. This study provided data on the extent of the land used for production and on water consumption, which are summarized in Table 9. The different strategies analyzed involved the combination of irrigation and rainfall and different concentrations of fertilizing elements. The values given in the table relate to 100% irrigation, regardless of fertilization process.

The effectiveness of an irrigation control system for gynura procubens in an urban area in Malaysia was investigated in another studied. It was compared to traditional agricultural practices. Using IoT sensors to monitor soil moisture, environment temperature, and humidity, along with a fuzzy control system, water consumption decreased by 16.93%, while the growth rate increased by a maximum of 76.64% [18].

In the previous section, the findings from [47] were reported. Here, we can mention that the control-based system using a dielectric humidity sensor achieved a 30% reduction in water consumption and an 11.5% increase in yield compared to the gravimetric method. The authors of [16] compared different solutions involving plant-factory, greenhouse, and open-field cultivation for cai xin and xian cai.

Finally, further interesting data in terms of yield and water consumption were found in a study on potato cultivation [55], which is the most commonly irrigated crop in Sweden.

The crops involved in this last analysis differed from case to case. It is interesting to note that hydroponics again proved to be the solution with high water-saving potential. Fuzzy logic is widely used for remote sensing and water resource management and shows promising results. However, it was not possible to undertake a quantitative comparison as these data refer to different crops.

4. Conclusions and Future Research

Agriculture is a key sector of national and global economy and, therefore, it is essential to adopt innovative solutions that maximize its profitability. Furthermore, climate change and population growth are forcing us to try to take measures to mitigate their negative effects in order to be able to feed the whole population. In this paper, we discussed technological developments that aim to optimize water consumption or water-use efficiency. However, farmers' perceptions of these new technologies need to be analyzed and studied. One of the main problems is that farmers find it difficult to implement precision farming technologies. The main reasons for this are often related to farmers' lack of awareness of the issues within the sector, such as financial limitations, technological difficulties, and communication difficulties, since Wi-Fi-type networks are often not available in the field. This is why it is important for governments to promote information campaigns so that farmers are made aware of the issues and are informed about the benefits they can gain from the application of Agriculture 4.0 technologies [77]. In the future, therefore, such solutions must be more user-friendly, cheaper, and more robust. In addition, the energy aspect must be considered and optimized to ensure that the devices used consume less energy, thus increasing their life expectancy and reducing faults [78].

The adoption of Agriculture 4.0 techniques in developing countries is more complex as there are several issues that must be considered:

- The availability of an adequate data transmission network that would allow the various devices to communicate with each other via the Internet;
- The availability of sensors;
- The availability of equipment and devices that can operate in the Agriculture 4.0 environment;
- The availability of experts in innovative technologies.

However, farmers in developing countries face several challenges, such as a weak socioeconomic environment and rising cultivation costs. Thus, to address these issues and encourage the spread of advanced agricultural practices, it is important to adopt several strategies at the local, national, and global levels [79]. Indeed, there will have to be a great deal of support from the governments of developing countries at the small-farm level to ensure increased production and improved efficiency in the use of land and water resources. It is, therefore, clear that the dissemination of these solutions in developing countries will be more complex, but there is evidence in the literature that small steps are beginning to be taken [80–85].

The review provided some interesting insights into what the next challenges in agriculture will be and how the research community is preparing to meet them. The different technologies implemented were clarified, giving a quick idea of how broad the field of agricultural research is today. The trend that emerged was that of producing more while consuming less and, above all, limiting any kind of waste as resources become increasingly scarce. Increasing emphasis is being placed on precision agriculture, both in the field and in the greenhouse, using a combination of different technological solutions, such as advanced controls based on information from different sources. Each resource that is used, such as sensors, satellites, weather stations, time series, etc., corresponds to a different type of information. The review showed that the most frequently used sources of information are the monitoring conditions outside the plant, which are mostly based on the assessment of soil conditions and the environment in which the plant grows. In contrast, the use of dedicated instruments to measure the health status of crops by monitoring intrinsic parameters, such as a sap analysis, is less common. Studies based on the control of exogenous factors showed that it is certainly important to monitor and control environment conditions. However, those that also studied endogenous factors emphasized that the needs of the crop can be more accurately identified and assessed in this way. A tip for future studies is to integrate these sources as much as possible. By combining these resources, it is possible to implement control systems that consider different types of information and allow irrigation systems to be managed based on the evaluation of their different aspects.

In addition, it was found that hydroponic vertical farming has a lower impact on water and soil consumption, but the energy aspect must be evaluated, as it plays a predominant role in the operation of all the systems involved.

There are several shortcomings in the current literature. In fact, studies have focused on a small scale and not on a large scale. The studies also lack useful data that could be used to quantify the positive effects of the technology and, at the same time, facilitate the comparison of existing technologies. In this review, results in terms of water consumption per hectare and yield per hectare for different technologies were quantified. Consequently, a suggestion that may help future research is to quantify these data to obtain quantitative feedback on the technologies used. The link between agricultural practices and wastewater treatment must also be improved. Research must improve these technologies and ensure a circular economy for water utilization, as the literature review showed that this is a potential aspect of achieving water savings.

All the technologies analyzed have the potential to improve the sustainability of the agriculture sector by optimizing the use of the resources used while also increasing their profitability. Saving water is an issue that must be addressed worldwide since the exploitation of this resource has reached worrying highs. The positive effects of the technologies summarized in this paper are clear on a global scale. However, it is necessary to assess the long-term effects of water management systems on regional hydrological cycles. Indeed, there are not enough detailed analyses in the literature to assess whether, at a regional level, the water savings achieved at the level of one crop translate into real savings when considering the whole groundwater or river basin [86]. It is certainly clear that everything depends on the source of the water supply used to support the growing crops. A technology that aims to optimize the use of water resources can have an impact on the balance of the water cycle either by reducing water abstraction through better management or by increasing abstraction by maximizing the efficiency of the irrigation system. In this regard, there are important gaps in the literature that need to be filled. Future research should explore the link between the hydrological cycle and crop management in order to obtain a framework for assessing the water balance on a broad time scale and maximize the sustainability of agricultural practices not only locally but also regionally and nationally [87,88].

From the technologies analyzed, the low prevalence of digital twins for farms emerged. Therefore, a suggestion for future research is to implement digital twins for the modeling of water collection and distribution networks for irrigation purposes. This would help to ensure the correct supply of water and nutrients to crops, minimizing the consumption of resources and increasing the efficiency and sustainability of water use. The models developed can be tested and validated in the field to establish the link between the simulation models and intelligent IoT systems in the field. Digital twins, information sources, and machine learning algorithms may be the key to the development of autonomous robotic solutions enabling advanced mechanization and management of water resources based on the models developed both in the field and in greenhouses or vertical agriculture.

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