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29-Dec-2024

Dear Prof. MINAYA:

Your manuscript entitled "Smart control models used for nutrient management in hydroponic crops: a systematic review" has been accepted for publication in IEEE *Access*. The comments of the reviewers who evaluated your manuscript are included at the foot of this letter. We ask that you make minor changes to your manuscript based on those comments, before uploading final files.

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Thank you for your fine contribution. On behalf of the Editors of IEEE *Access*, we look forward to your continued contributions to IEEE *Access*.

Sincerely,

Dr. Wai-keung Fung
Associate Editor, IEEE *Access*
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Reviewer(s)' Comments to Author:

Reviewer: 1

Comments:
Dear Authors,
Thank you for considering my suggestions. I think the paper is far stronger with the changes made and I recommend it for publication.

Additional Questions:
Please confirm that you have reviewed all relevant files, including supplementary files and any author response files, which can be found in the "View Author's Response" link above (author responses will only appear for resubmissions): Yes, all files have been reviewed

1) Does the paper contribute to the body of knowledge?: Yes. The body of work groups information in a coherent manner and provides a reference source for information on the use of control systems in hydroponic growing.

2) Is the paper technically sound?: To my limited knowledge of how the authors have used AI and fuzzy logic to compile their data - it does seem sound. Moreover the results of their work do make coherent sense.

3) Is the subject matter presented in a comprehensive manner?: Yes. Especially with the changes made. The paper is far stronger and descriptive in a concisely informative manner.

4) Are the references provided applicable and sufficient?: Yes

5) Are there references that are not appropriate for the topic being discussed?: No

5a) If yes, then please indicate which references should be removed.:

Reviewer: 2

Comments:
1-Clarity of Key Concepts: The paper presents a solid review of intelligent control models in hydroponic systems. However, some key concepts, particularly those related to fuzzy logic, AI, and artificial vision, could benefit from clearer definitions or more in-depth explanations for readers unfamiliar with these techniques. A brief introduction or background to these concepts would make the paper more accessible to a broader audience.

2-Detailed Discussion on Practical Applications: While your paper does an excellent job of reviewing the theoretical aspects of control models, it would be beneficial to include more real-world examples of how these models are being applied in commercial or research settings. This could help illustrate the impact of these models and provide a clearer understanding of their practical implications.

3- Sensor Technology and Data Management: You mention the challenges related to sensor precision and managing large data volumes. It would be valuable to expand on the current advancements in sensor technology that could help overcome these challenges. Furthermore, a more detailed discussion on the integration of data management systems with these intelligent control models would be beneficial.

4- Model Adaptation: The section on adapting control models to different crops and conditions could be expanded. Given the diversity in plant types and environmental variables, how adaptable are these models across various scenarios? A discussion on the scalability and customization of these models would strengthen your review.

5- Future Research Directions: While the paper touches on future research, it would be helpful to provide more specific suggestions on areas that require further investigation. For example, exploring emerging trends in machine learning and AI that could complement intelligent control models might help guide future work in this area.

Additional Questions:
Please confirm that you have reviewed all relevant files, including supplementary files and any author response files, which can be found in the "View Author's Response" link above (author responses will only appear for resubmissions): Yes, all files have been reviewed

1) Does the paper contribute to the body of knowledge?: Yes, the paper makes a meaningful contribution to the body of knowledge. By conducting a systematic review of intelligent control models for nutrient management in hydroponic systems, it addresses a critical area of agricultural innovation. The integration of Fuzzy Logic, Artificial Intelligence, and Artificial Vision in hydroponics is a relatively nascent yet vital field, and the paper provides a clear synthesis of recent advancements and ongoing challenges in this domain.

The use of PRISMA guidelines ensures methodological rigor, enhancing the reliability of the findings. The paper not only identifies technological progress but also highlights pressing challenges, such as sensor precision, data management, and model adaptability, which are pivotal for guiding future research and practical applications.

2) Is the paper technically sound?: Yes, the paper appears to be technically sound. It demonstrates a structured and rigorous methodology by adhering to the PRISMA guidelines for conducting a systematic review. This ensures that the selection, evaluation, and analysis of the studies are transparent and replicable.

The focus on intelligent control models using Fuzzy Logic, Artificial Intelligence, and Artificial Vision is relevant and well-supported by the literature reviewed. The paper effectively outlines the techniques used for nutrient management in hydroponic systems, discussing their implementation, benefits, and limitations. The identification of challenges such as sensor precision, data management, and model adaptability shows a thorough understanding of the technical intricacies of the domain.

However, the technical soundness could be further evaluated by verifying the comprehensiveness of the dataset reviewed and assessing whether the comparisons and conclusions are based on a balanced and critical analysis of the studies included. Assuming these aspects are robust, the paper successfully meets the technical standards for research in this field.

3) Is the subject matter presented in a comprehensive manner?: After resubmitting, yes, the subject matter is presented in a comprehensive manner. The paper thoroughly covers the key aspects of intelligent control models for nutrient management in hydroponic systems, providing a clear and well-structured review of the field. It effectively addresses the use of Fuzzy Logic, Artificial Intelligence, and Artificial Vision, which are central to the subject, and offers an insightful analysis of their applications, benefits, and challenges in the context of hydroponics.

The review spans a five-year period, ensuring that the findings are current and relevant to the latest trends in the field. By incorporating a broad range of studies, the paper offers a holistic view of the advancements and remaining challenges in the field. The paper also identifies areas that need further development, such as the need for better sensors and more adaptable models, which enhances its comprehensiveness.

In terms of structure, the paper flows logically from the background and motivation for the study to a detailed discussion of methodologies and findings. This makes the subject matter accessible and well-rounded. However, the depth of the review could be enriched further by including a more detailed discussion on the practical applications and the scalability of these intelligent control models in real-world hydroponic systems.

4) Are the references provided applicable and sufficient?: The references provided applicable and sufficient

5) Are there references that are not appropriate for the topic being discussed?: No

5a) If yes, then please indicate which references should be removed.:

If you have any questions, please contact article administrator: Mr. Ankit Srivastava
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TOPICAL REVIEW

Smart Control Models Used for Nutrient Management in Hydroponic Crops: A Systematic Review

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ABSTRACT In recent years, agriculture has significantly evolved with the integration of technology, enabling the development of new cultivation techniques that respond to the growing demand for food and the need to conserve natural resources. In this context, we conducted a comprehensive review of models of intelligent control for managing nutrients in hydroponic systems by analyzing studies from the last five years. The selection of articles was based on the guidelines of PRISMA and research questions, focusing on control techniques based on fuzzy Logic, Artificial Intelligence and artificial Vision. These models are essential to automatically adjust the concentrations of nutrients, adapting to the needs of the plants at each stage of their growth. The review results highlight essential advances but also identify significant challenges, such as the need for precise sensors, the management of large volumes of data, and adapting the models to different crops and conditions. Despite these challenges, the benefits include a more efficient use of nutrients, a reduction in the consumption of water, and increased crop yields. Continuous research in this field is essential to improve the sustainability and productivity of hydroponic systems, offering new opportunities for agriculture in the future. The findings of this review provide a solid basis for evaluating the effectiveness of the control models and their application in real agricultural scenarios.

INDEX TERMS Hydroponic systems, intelligent control, artificial intelligence, fuzzy logic, control techniques.

I. INTRODUCTION

The increase in inhabitants at the global level has generated various problems regarding urbanization, health, transportation, and food. In this regard, technological progress has allowed us to solve such problems, mainly in the agriculture sector; through technology development, we have developed various ways of growing food, including hydroponics [1], [2]. This technique allows the growth of plants without the need to be in contact with the soil; these systems use a solution of water, nutrients, and fertilizers, which makes it possible to more efficiently the supply of nutrients to the plants for optimal development [3], [4]. The basic structure of a hydroponic system NFT is based on PVC tubing and a reservoir that contains a solution rich in nutrients for the crop. Its essential operation consists of recirculating the solution in the interior of the PVC pipe for set periods through manual or automatic control [5].

The demand generated in the food industry has encouraged the development of multiple investigations that have addressed hydroponic cultivation (CH) from various perspectives, which has allowed us to implement an alternative method of cultivation that develops in tight spaces, automated systems, PID control, fuzzy logic and artificial intelligence (AI) and with remote monitoring through the implementation of the Internet of Things (IoT) [6], [7], [8], [9]. This is to control the climatic variables, the supply of nutrients, pH, and water quality [10]. Controlling these factors has shown

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that it is possible to implement agricultural practices in places that only require a little space and mainly without covering large areas of land to grow food, as it is the traditional culture.

Fuzzy logic is a computational model that controls uncertainty and ambiguity in decision-making based on structured human knowledge, through binary values (true or false). Fuzzy logic works with degrees of truth for human interpretation modes that are inexact rather than precise [11]. On the other hand, AI comprises a series of algorithms and computational models, some of them inspired by the structure of the human brain, which have the ability to learn and reason from large volumes of data. These models use various techniques, such as neural networks, machine learning and artificial vision, to improve their performance autonomously, without the need to be explicitly programmed for each task [12].

In this scenario, technological innovation has allowed us to develop increasingly intelligent agriculture systems, supplying the necessary nutrients and controlling the climatic variables that directly impact the crop. The results of these intelligent systems have shown that they can have higher production and savings in the water resource, shortening production times and reducing losses [13], [14]. These factors have driven the implementation of hydroponics and research of other alternatives that allow you to control and monitor these systems. On the other hand, it is essential to look for alternatives that will satisfy the demand for food that is constantly growing to a possible crisis [15], [16].

There are currently different cultivation techniques that allow plants to grow without using soil, using a nutrient-rich solution instead. Several techniques have been developed in hydroponic crops to optimize performance and adapt to different types of plants and environmental conditions. Table 1 describes some of the most common techniques below:

TABLE 1. Techniques used in hydroponic crops [17].

Technique	Description
Nutrient Film Technique (NFT)	This system uses an automated pump to circulate nutrients and water from a reservoir, and the nutrient solution circulates and enters the growing tray through a water pump.
Deep Water System (DWS)	In this system, the plant roots are directly submerged in the nutrient solution, and the air is delivered directly to them through diffuser stones or a pump.
Flood and Drain	This system works by periodically flooding the roots with the nutrient solution and then allowing it to drain so the solution returns to the reservoir.
Aeroponics	In this system, the roots are suspended in the air, surrounded by oxygen, and periodically moistened by a spray with a nutrient-rich solution distributed through an automated system.
Drip System	A pump helps the plants receive water or a nutrient-rich solution from the reservoir, allowing the efficient delivery of nutrients to the roots in an appropriate proportion.
Wick System	The system uses a wick of synthetic fibers, such as nylon, to transport the nutrient solution from the reservoir to the plant roots by capillary action, ensuring constant feeding.

Smart agriculture provides for the incorporation of new technology in food production; this allows the crop to perform the monitoring remotely, optimize the use of nutrients and automate the system almost in a simple way [18]. This concept is directly related to the automation of nutrients in hydroponic culture, a system related to this research work, which consists of the dosing of nutrients in hydroponic cultivation using techniques of intelligent control, focusing primarily on the control based on fuzzy Logic and Artificial Intelligence, to improve the precision of the control system incorporates significant amounts of data to the analysis in order to improve the modeling of the control system, using the techniques of deep learning (DL) [19], [20]. The automated systems in hydroponics seek to increase agricultural productivity [21], [22] by optimizing the use of water and nutrients in adequate amounts according to the need and stage of growth in which the plant [23], [24].

Although much of the research on technologies applied to intelligent farming is done to crops without soil, the use of control models in hydroponics is gaining relevance due to its benefits. These systems allow precise control overgrowth conditions, optimizing the efficiency of the use of resources and improving yields [25]. Unlike cultivation in soil, where the substrate acts as a shock absorber of nutrients, hydroponic growing requires detailed management of the nutrient solution to ensure that the plants receive the nutrients needed in a balanced way. This approach eliminates the barriers associated with using the soil, facilitating the implementation in urban spaces and promoting sustainability [26], [27].

The implementation of models of control in hydroponic culture includes advanced technologies such as fuzzy Logic, Artificial Intelligence (AI), and the Internet of Things (IoT). These technologies allow real-time monitoring of variables crucial to pH, electrical conductivity and nutrient levels, automatically adjusting to the system's conditions to optimize plant growth [27], [28]. AI, in particular, offers algorithms that can learn and adapt to different conditions, improving the efficiency of the distribution of nutrients in the crop. In addition, using these technologies in hydroponic culture increases productivity and contributes to the rational use of water [29], [30].

Integrating artificial Intelligence (AI) and fuzzy Logic in hydroponic farming has revolutionized how to supply nutrients and other critical parameters [31]. The AI controls the nutrient solution based on the information from the sensors installed during cultivation; these devices are responsible for generating a database for the analysis of the state in which the plant is located (shape, color, and size) based on these parameters, the system adjusts the number of nutrients needed, thus optimizing the distribution of nutrients and ensure healthy growth of the plants [21], [28], [32]. Systems based on AI used machine learning algorithms to maintain concentrations of nutrients at adequate levels, minimizing the use of resources and maximizing efficiency in agricultural production [33].

The application of fuzzy logic in hydroponic farming allows you to control the amount of nutrient solution supplied to the plants based on the information on the levels of pH, electrical conductivity, and ultrasound [34]. The rules diffuse determine when and how much fertilizer to add, automatically adjusting to the times and quantities according to the crop conditions and the environment, making the system's performance comparable to traditional methods, with faster growth of the plants. In addition, the fuzzy logic optimizes the control of nutrients in hydroponic systems to adjust the electrical conductivity (EC) and pH of the nutrient solution [29], [35]. Based on readings from sensors, the fuzzy logic controller regulates the time of operation of the pumps that contain nutrients. These automatic adjustments were made to ensure that the values of EC and pH were maintained within optimal ranges, creating an ideal environment for the healthy growth of the plants [36], [37], [38].

Automation reduces human intervention and allows for precise control and efficient use of critical parameters, improving the productivity and quality of crops [39]. The use of artificial intelligence and fuzzy logical control in modern agriculture has shown significant results in various studies. On the other hand, the combination of automation with a monitoring system, local or remote, allow early detection of diseases and pests, making the cultivation system even more precise, as it allows you to monitor constantly the levels of nutrients and weather conditions they are found in plants [40].

The artificial vision also plays a crucial role in intelligent agriculture through the use of predictive models built using regression of partial least squares (PLS) that have been applied to evaluate parameters such as TSS, pH, TA of plants, significantly improving the accuracy in comparison with the other models [38]. Another model used is Deep Kernel Learning, in combination with interconnected neural networks, which was used to verify the growth of plants using image analysis; the results showed improvement in the efficiency of the control and monitoring of hydroponic growth. These AI and logic control advances are transforming agriculture, making it more efficient and sustainable. For this reason, the article aims to analyze the results obtained in different investigations [41].

The contribution of this paper is to analyze the various components and technologies used in hydroponic growing and the nutrient supply. Also, we will discuss the automated systems used for the control of nutrients in crops hydroponically proposed in the literature, focusing primarily on controls based on AI and fuzzy logic to perform the comparison of the parameters used in the control of and results obtained in each technique. Will be discussed based on the results found in the literature of the essential attributes of a control system based on machine learning and fuzzy logic in order to assess the accuracy and efficiency of various predictions and decisions, such as the optimization of the dosing of nutrients, the pH control and the management of the temperature and humidity in real-time.

The remainder of this paper is organized as follows: Section II describes the methodology employed for the information search and formulating the research questions; Section III presents the results and discusses the findings; and Section IV sets out the review findings.

II. LITERATURE REVIEW METHODOLOGY

For the literature analysis, we used the methodology PRISMA [42] to make systematic reviews clear and transparent prior to the selection and analysis of the research. We considered the 27 items in the proposed methodology, which allowed us to analyze the information more easily from the literature obtained in the literature search, mainly in Scopus and other databases such as SpringerLink, Web of Sciences, MDPI (Institute for Multidisciplinary Digital Publication), IEEEXplore, and other journals indexed in Scopus.

The selection of articles through the research questions facilitated the search process: (i) How can fuzzy logic improve nutrient control in hydroponic crops? (ii) How effective are artificial intelligence algorithms for optimizing nutrients in hydroponic systems? (iii) What are the benefits and challenges of combining fuzzy logic and artificial intelligence in hydroponic nutrient management? These questions not only guided the selection of articles but also established an analytical framework for evaluating how each contribution addresses specific problems in hydroponic nutrient management.

The preliminary literature search, focused on relevant terms within the "title, abstract, and keywords," was aligned with the authors' research questions. This allowed identifying articles focused on the application of fuzzy logic and artificial intelligence for nutrient control and optimization in hydroponic crops and topics closely related to the study objective.

Three queries of search different were developed to identify the most relevant articles for analysis. The first equation focuses on algorithms and intelligent control inside hydroponic systems, along with the related fields of sustainable agriculture, to explore the breadth of adaptive algorithms applied in hydroponic culture (Table 2). The second equation incorporates artificial Intelligence and fuzzy Logic, and the terms related to the system's hydroponic automatic (Table 3). The third equation integrates the terms of the previous two equations, but within this context, it is added to the internet of things, pH, electrical conductivity, and nutrients (Table 4). Each search combined the terms using OR within each column and between columns AND to ensure the search results are comprehensive, covering relevant topics.

The organization and analysis of these data focus on profundity in understanding labor methods used to control nutrients, mainly in lettuce crops in hydroponic systems controlled by fuzzy Logic and AI. This synthesis pretends to report the results of the various investigations and indicates the difficulties presented during the development.

TABLE 2. The first search equation.

TERM 1 (TITLE-ABSTRACT-KEYWORDS) OR	AND	TERM 2 (TITLE-ABSTRACT-KEYWORDS) OR	AND	TERM 3 (TITLE-ABSTRACT-KEYWORDS) OR
Hydroponic Hydroponic Systems		Fuzzy Logic Artificial Intelligence		Nutrition control IoT Control System

TABLE 3. The second search equation.

TERM 1 (TITLE-ABSTRACT-KEYWORDS) OR	AND	TERM 2 (TITLE-ABSTRACT-KEYWORDS) OR	AND	TERM 3 (TITLE-ABSTRACT-KEYWORDS) OR
Hydroponic crop Hydroponic Systems Automatic Hydroponic System		Nutrients Fuzzy control Artificial Intelligence		Algorithms IoT Smart Control

TABLE 4. The third search equation.

TERM 1 (TITLE-ABSTRACT-KEYWORDS) OR	AND	TERM 2 (TITLE-ABSTRACT-KEYWORDS) OR
Hydroponic systems System Hydroponic crop Automatic Hydroponic System		Fuzzy Fuzzy Logic Fuzzy control Artificial Intelligence Neural networks Machine learning

Figure 1 shows the flow chart showing the result of applying the research strategy described in the search for literature related to the research topic; 654 articles were collected in total.

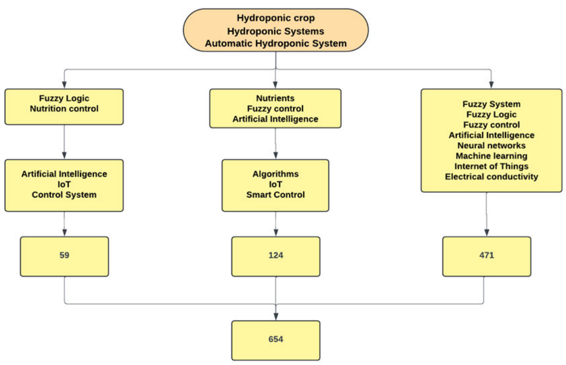

FIGURE 1. A flow chart describes the information search strategy, including the specific terms used.

A. INCLUSION CRITERIA FOR THE SELECTION OF LITERATURE

To carry out this research, we established four selection criteria, detailed in Table 5. In the first place, we selected articles published between 2020 and 2024, a period in which the focus of interest of this review article is the increased interest in the development of control systems of nutrients in hydroponic culture. The second criterion limits the search and selection of articles published only in English, using the Scopus filter to include articles only in engineering, Mathematics and Energy. As a last selection criterion, only publications in their final version are considered. After applying these criteria, it was possible to reduce the number of items found to 127 articles that meet these criteria.

TABLE 5. The third search equation.

	Fuzzy Logic Nutrition control Artificial Intelligence IoT Control System	Nutrients Fuzzy control Artificial Intelligence Algorithms IoT Smart Control	Fuzzy System Fuzzy Logic Fuzzy control Artificial Intelligence Neural networks Machine learning Internet of Things Electrical conductivity	Total Records	Excluded Records
Paper identified	59	124	471	654	
Publication Year (2020-2024)	46	104	304	454	200
Language English	45	101	294	440	14
Engineering, Mathematics, and Energy	30	59	123	212	228
Duplicate records	13	55	59	217	85

An additional search was conducted in other databases following the same methodology to complement the information and expand the number of studies on the use of nutrient control techniques and methods in hydroponic crops. This search allowed us to identify 40 articles that enrich the research, considering that the equations used in Scopus did not allow an exhaustive exploration. As a result, combining both searches allowed us to generate a repository of 167 articles. Figure 2 outlines the process of inclusion and exclusion of articles according to the PRISMA methodology. The criteria used for the process of inclusion and exclusion of articles after the search are detailed below:

- Review articles were excluded, as this may lead to an incomplete view of the current knowledge on the topic.
- Articles with a focus solely on monitoring and control through IoT were excluded.
- We included all articles that focused on the use of intelligent control techniques and advanced AI-based control techniques for nutrient management in hydroponic crops.
- Articles that use control techniques related to the topic of interest were excluded, however, they are focused on other agricultural applications besides hydroponics.
- Articles focusing on nutrient control through artificial vision were included, but articles focusing on disease detection were excluded.
- Articles with a publication year of 2020 – 2024 were excluded.

The articles analyzed in this study aim to extract the most relevant information on the control methods employed for the control of nutrients in hydroponics, and they are also looking for in-depth information to set the variety of technologies used in systems hydroponics. What was made earlier in the process of inclusion and exclusion allowed us to deepen the analysis of the topics of most interest in this study: hydroponic systems, Artificial Intelligence, and Fuzzy Logic. In total, it read in detail 50 articles of the 167 that were initially published. The process of including articles for the review is outlined in the flow diagram PRISM of Figure 2.

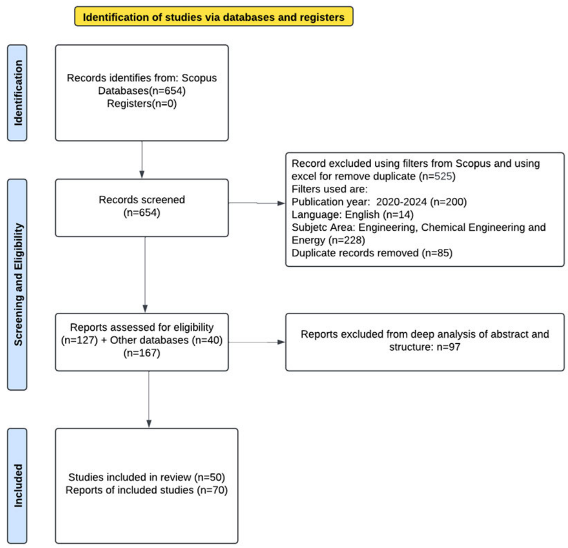

FIGURE 2. Example of the KNN algorithm applied to classify.

B. LIMITATIONS AND POTENTIAL FOR BIAS IN LITERATURE SELECTION

In this systematic review, it is also crucial to note that implementing the PRISMA methodology provides clarity and transparency to the data collection process. However, there are intrinsic restrictions that may negatively influence the results obtained. In this study, inclusion criteria, such as the choice of research in English and the criterion of publications between 2020 and 2024, could have ruled out significant research in other languages or previous periods that could provide valuable insights. Furthermore, the bias towards publications in fields such as engineering, mathematics, and energy limits the analysis to specific disciplines, which could restrict the variety of methodological and theoretical approaches. Although strict filters were used to preserve the impartiality and relevance of the selected articles, the objectivity and relevance of the selected articles was maintained. These potential biases underline the importance of considering findings in a wider range of contexts and disciplinary frameworks in future research.

C. RESEARCH CONTRIBUTION

The analysis of these articles allows for the collection of information. It makes it possible to recognize trends and challenges in incorporating Artificial Intelligence and fuzzy logic for regulating nutrients in hydroponic crops. In addition, the variables used in creating the control algorithms are detailed, with the results achieved and the restrictions detected for their application. In this context, the research contributes an analytical perspective of the current state of hydroponic nutrient regulation, highlighting possibilities for future development and sectors that require innovation. Likewise, a comparative analysis of the results obtained by other authors is carried out, which allows the impact and effectiveness of the different existing proposals to be evaluated.

III. RESULTS AND DISCUSSION

This section of results and discussion is divided into three parts. The first part focuses on analyzing the total set of 167 articles obtained from the literature search using the equations of search indicated in the section on methodology. The second part presents the results obtained and divides them into three main categories: artificial Intelligence, fuzzy logic, and artificial Vision. The results are presented in tables, figures, and images that will be used for the analysis. Finally, the last section describes the result of 50 articles that have greater relevance to the topic proposed in this paper according to the authors' criteria, considering main those that can generate greater interest in readers interested in conducting research related to hydroponics.

Figure 3 shows that publications on the control of nutrients in hydroponics have begun to emerge since 1996. However, between 1999 and 2018, interest in research in this area decreased. As of 2019, the number of publications experienced significant growth, reaching 35 in 2023. This increase reflects a growing interest in this area in recent years, which has led to the development of systems of hydroponic smart, thus addressing the global problem mentioned at the beginning of this study.

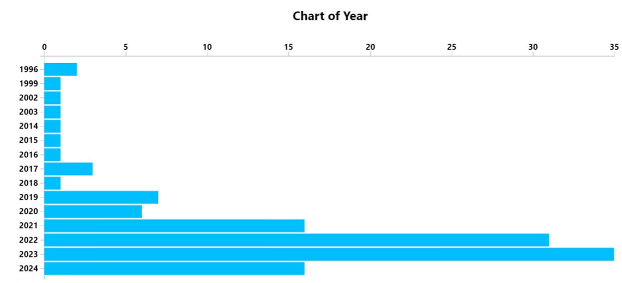

FIGURE 3. Number of publications per year related to controlling nutrients in hydroponic systems.

Another essential aspect that was carried out was the analysis of the types of research reviewed. As indicated in Table 5, of the 50 published papers, 33 correspond to journal articles, and 17 correspond to lectures or papers presented at conferences. With the use of VOSviewer, it was possible to analyze the interconnections between the most common keywords to understand the links between them and focus on the most relevant topics. The result of this analysis is shown in Figure 4, which shows the interconnection of the concurrent words repeated the most in the articles selected. The words displayed on the interconnect occur most frequently. For the analysis, we considered the words that are not within the equations of search but that are relevant in the control systems of nutrients in hydroponic systems as: "nutrient level," "machine learning," "monitoring system," "IoT technology," "nutrient film technique." These prayers allowed us to select items with a more extensive view for a more in-depth analysis.

Figure 5 illustrates that the interconnections between the keywords are more frequent, allowing a clear understanding

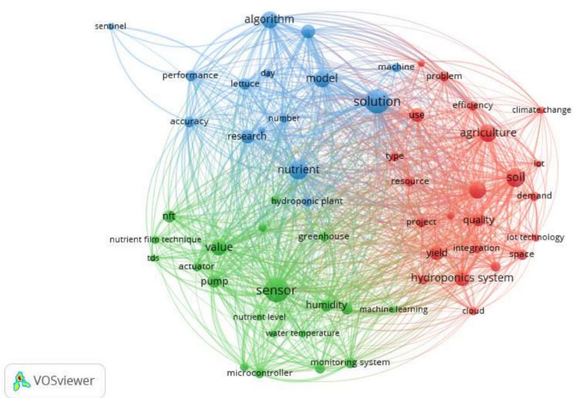

FIGURE 4. **Most common words in the abstract and title of the selected articles by year of publication.**

of their links and focusing on the most relevant topics. This analysis and a preliminary review allow you to set 3 approaches for the in-depth review of the 50 articles selected. These approaches are essential to identifying the most relevant results of the reviewed articles.

- The first approach is innovative hydroponic systems, which include artificial intelligence-based methods of controlling the supply of nutrients.
- The second approach is to supply nutrients in hydroponic systems using fuzzy Logic.
- Third approach: Artificial Vision is applied to hydroponic systems, and this approach is oriented mainly toward the supply of nutrients.

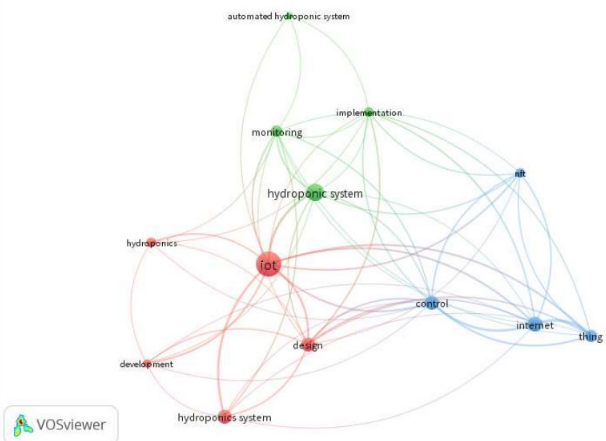

FIGURE 5. **Most common words in the title of the selected articles by year of publication.**

A. DETAILED ANALYSIS OF RESULTS

The content analysis of the 127 selected articles was carried out based on the results obtained in the inclusion process. A rigorous selection process finally filtered 50 investigations linked to hydroponic crop systems. This facilitated the recognition of relevant trends and provided a clear vision of the control techniques used in nutrient management. In this process, the characteristics of each technique were also carefully analyzed, establishing the variables required for its implementation, its precision and efficiency in the administration of the nutrient solution in crops. Focusing mainly on control systems based on artificial intelligence (AI) and fuzzy logic, given their ability to optimize resource management and improve results in agricultural production.

Tables 6, 7 and 8 list the publications selected for detailed analysis along with some highlights that allow identifying the most relevant elements of the publications according to the established approach, divided into three categories. Each table includes highlights that allow identifying the type of crop, the control algorithm developed, the variables employed, and the accuracy achieved during performance tests. This compilation not only facilitates a more comprehensive understanding of developments in hydroponics, but also serves as a valuable guide for future research in the area.

B. RESULT OF THE ANALYSIS BY TOPIC

1) HYDROPONIC SYSTEMS SMART

Hydroponic systems based on IoT, and machine learning have revolutionized modern agriculture, optimizing the growth and production of plants. These systems integrate advanced technologies such as neural networks and computer vision to manage and monitor critical parameters such as pH, temperature, humidity, and light intensity in real time. Various research studies have used neural networks to predict optimal cultivation conditions and apply regression algorithms and neural networks to adjust nutrients. This technological evolution improves efficiency and allows more precise control and automated crop environments, increasing productivity and reducing human intervention.

In [10] presents a hydroponic system-based intelligent artificial intelligence and IoT for tomato plants for the control applies networks neural deep that provide an action of appropriate control in real-time with greater precision; the network classifies the control actions according to the parameters of pH, the temperature, the humidity, the intensity of the light and the water level in the tank, picked up the hydroponic system. The proposed model was trained in the cloud with 5,000 data collected in real time and adjusted 10,000 times to reduce the error in the prediction. The model trained is implemented on a Raspberry Pi3, which sends the input data to an Arduino to run the control action, which is appropriate. As a result, the precision of the system achieved 88,50%.

In [44], authors explore a hydroponic system based on the technique NFT plants with Bok Choy, using IoT and multiple linear regression. The system adjusts the timing of the pump activation according to the threshold values established by farmers to keep nutrient concentrations between 1,000 ppm. The multiple linear regression showed effectiveness with an accuracy of 92.42%, facilitating precise control of nutrient solutions in different volumes of deposit and threshold values

TABLE 6. The highlight for systems is hydroponic smart based on artificial intelligence.

Category	Ref.	Description
Artificial Intelligence	[10]- [43]	Present an innovative hydroponic tomato system based on deep neural networks and IoT, which was implemented on Raspberry Pi3 and Arduino. This system achieves 88.5% accuracy in parameter control and 83.67% accuracy in nutrient prediction and management by SVM.
	[44]- [45]	Propose a hydroponic system using the techniques NFT and DWC with control based on IoT and multiple linear regression to adjust the pump's time of activation according to threshold values set, achieving an accuracy of 92.42% in the pump setting.
	[46]- [47]	Implement neural networks in a microcontroller to predict levels of pH and EC, achieving a value of linear regression R of 99% and an approximate error of 5% in the control of the pH. Include computer vision and predictive models to verify the growth of plants.
	[12]	Develop an automated agriculture system without soil using artificial intelligence to control nutrients in systems, NFT, and a Hydroponic Control Smart (HCS) based on AI for correcting faults in greenhouses, with storage in the cloud of Microsoft Azure.
	[48]	Implements AI-SHES, a mobile app with artificial intelligence, to control hydroponics. It uses a Raspberry Pi, sensors, and an algorithm called DLCNN to detect diseases accurately.
	[49]	Develops the System of Maturation Artificial Sensor-Based (S-BAR), controlled by sensors and microcontrollers. Through an on/off control system, it optimizes maturation time and energy consumption.
	[50]- [51]	Use Artificial Vision and predictive models, such as regression of partial least squares (PLS) and Deep Kernel Learning, to verify the growth and analysis of nutrients in lettuce. However, it makes errors in predicting calcium and magnesium.
	[52]- [53]	Combine a neural network, sequential (RNN) with temperature, light, and TDS sensors to control a hydroponic system and uses logistic regression and decision trees for the growth of plants, Rama Tulsi, achieving an accuracy of 95%.
	[54]	Applied neural networks convolutional (CNN) to identify nutrient deficiencies in basil, highlighting VGG16, with an accuracy of 93.82% after the fine adjustment.
	[55]	Uses machine learning algorithms such as Lasso Regression and KNN to predict nutritional values in hydroponic systems, showing reduced water use compared to traditional methods.
	[22]	Explores spectroscopic techniques and machine learning models to predict phosphorus concentrations in hydroponic solutions, showing efficacy in the prediction with hybrid models.
	[23]	Combines fuzzy logic and neural networks to predict growth parameters in lettuce, achieving a high accuracy (0.82-0.96) in net photosynthesis and transpiration predictions in systems NFT.
	[33]	Develop a system to detect NPK nutrients in hydroponics using spectroscopy and artificial intelligence techniques. The detection accuracy is 98%, and the margin of error is low.
	[56]	Proposes a DWC system for basil and lemon, using AI to optimize the critical parameters. The system showed results in plant height and EC and pH levels compared with OpenAg predictions.
	[57]	Studies the impact of parameters on spinach growth in hydroponic systems, using AI to predict the development. RFR showed the highest accuracy (98.3%).

without exceeding the values of TDS optimal required in the culture. In [46], a neural network is implemented on a microcontroller to predict pH and electrical conductivity (EC) levels in hydroponic systems. The model, trained in MATLAB, achieved a linear regression R value of 99% and a low Mean Squared Error (MSE). The predictions were accurate for EC values, while deviations for pH were minor. The study highlights the importance of maintaining appropriate nutrient levels for optimal plant growth and production efficiency.

In [12], authors present an automated agriculture system without soil based on artificial intelligence to improve the production of vegetables. We use an NFT system that automatically controls pumps and valves, programmed in C++ on an ATMEGA328P microcontroller. The system maximizes the use of land to allow cultivation in layers, reduces human intervention, provides balanced nutrients for rapid growth and healthy plants, and allows for continuous production throughout the year. Artificial intelligence ensures an accurate and efficient process in the blend and the supply of nutrients to the plants, thus improving conventional agriculture.

In [60], a Hydroponic Smart Control scheme is proposed to monitor and control failures in hydroponics and greenhouses. It uses a driver that uses artificial intelligence that continuously monitors the data sent from the sensors installed in the greenhouse environment and the microenvironment of the root zone. The data are stored in the cloud of Microsoft Azure to perform the analysis; in case deviations are detected, the controller based on AI compares the deviation and performs the task required, allowing the action for adaptive and efficient implementation. We also describe an algorithm of differential equations for the differential protection in greenhouses, allowing the detection of faults and the real-time verification of operating signals.

In [43], the design and development of a hydroponic smartphone system using IoT, which uses deep learning and reinforcement learning, are proposed techniques. With models DRL, the system is applied to various classifiers, including logistic regression, decision tree, and machines support vector (SVM); for the analysis, we used a database of 8,858 samples of performance, damage, and nutrient supply. The results showed that the classifier machine support vector obtained the highest accuracy, 83.67%, followed by the logistic regression, 83.61%, which allowed us to predict and effectively manage the supply of nutrients, control crop damage, and the production yield of crops in hydroponic systems. Reference [48] deals with implementing AI-SHES, a mobile app with artificial intelligence that controls hydroponics. This application uses a Raspberry Pi, sensors of temperature, humidity, pH, turbidity of the water, and a camera to assess the state of the leaves of the plants

TABLE 7. The highlights on controlling nutrients in hydroponic systems based on fuzzy Logic.

Category	Ref.	Description
Fuzzy Logic	[37]- [58]	Explore an automated system based on fuzzy logic for managing nutrients in aquaponics and controlling fans and pumps of water in hydroponics. It uses microcontrollers such as Arduino and structures IoT, with methods such as Min-Max, Mamdani, and the centroid for dosing.
	[59]	Analyzes hydroponic systems in vertical agriculture using the Fuzzy EDAS method to select the best alternative in terms of production, stock depletion costs, and flexibility.
	[45]	Evaluate three levels of automation (manual, semi-automation, and full automation) in hydroponic farming using TODIM with numbers diffuse, concluding that semi-automation is the best option.
	[36]- [60]	Propose a fully automated watering system in an urban area and a hydroponic system based on flow deep water (DFT) using fuzzy logic and microcontrollers such as Raspberry Pi and ESP32. These systems demonstrate an increase in crop yield by 40%.
	[30]- [61]	Control temperature, humidity, CO2, and the concentration of nutrients in a greenhouse and hydroponic system, using fuzzy logic to maintain optimal cultivation conditions by adjusting the pH and EC, with an error of ± 0.0035.
	[62]	Implements control diffuse in a hydroponic NFT to adjust the electrical conductivity in three stages according to the plant's growth, with an error rate of 8.9%.
	[63]- [64]	Develop a system of diffuse control to manage the temperature in a greenhouse and the energy consumption of the actuators in hydroponics, achieving an 18% reduction in energy consumption.
	[65]	Propose a system of diffuse control to calibrate sensors and correct measurement errors. The shipping and receiving data was 75% efficient, and pH adjustment was completed in 30 iterations.
	[66]	Develop a greenhouse smartphone using fuzzy logic and IoT to control temperature and humidity with high efficiency, leading to a reduction of energy consumption of 15%.
	[3]- [29]- [54]- [67]	Use fuzzy logic and IoT to monitor and adjust pH and EC in hydroponic crops, maintaining EC at 1.4-2 µS/cm and pH between 5.5-6.5, with a margin of error of 0.999. LSTM is used for sequential data analysis.
	[68]	Controls the concentration of nutrients in a hydroponic system with a fuzzy logic controller using the Sugeno method, achieving stabilization in 76 to 138 seconds.
	[69]	Provides a hydroponic system with adaptive neurofuzzy inference (ANFIS) to automatically adjust the concentration of nutrients, improving accuracy by 67% compared to traditional methods.
	[70]	Presents a hydroponic system with a fuzzy logic controller based on Mamdani, reaching an accuracy of 94.24% in the setting of nutrients and an average time of 13 minutes and 49 seconds to achieve desired conditions.
	[71]	Designs a system aquaponic using fuzzy logic to optimize the control of the pH and turbidity of the water, with a reduction of 7.65% in turbidity and an average error of 8.78% in the control of the pH.

TABLE 8. The highlights of the use of vision artificial in hydroponic systems.

Category	Ref.	Description
Artificial Vision	[72]	Proposes a hydroponic system that intelligently uses vision multi-layer and IoT to identify deficiencies in macronutrients through the analysis of texture, color, and shape of the leaves, together with environmental data such as humidity, light, temperature, and water levels. Employs an architecture MLP with NN Backpropagation and ReLU, obtaining a MAPE lower than 10%.
	[73]	Presents a hydroponic system for lettuce that uses deep learning to detect diseases early. It uses Faster R-CNN with Inception V2 and YOLO, achieving accuracy of 70% and 97%, sensitivity of 68% and an F1 Score of 80%.
	[74]	Evaluates the growth of lettuce using machine vision and machine learning with logistic regression (LR), K near neighborhood (KNN), and machine support vector linear (LSVM). KNN achieved an accuracy of 91.67% and an average accuracy crusade of 87.06%.
	[41]	Provides a decision support system based on ANN to classify the stages of lettuce's growth, using features of artificial vision such as morphology, color, and texture. The system showed promising results in the classification.
	[75]	Investigates identifying diseases in lettuce roots in hydroponic systems using a camera and temperature sensors controlled by Arduino and Raspberry Pi. Achieved an accuracy of 91% using a Tree model to analyze the roots.
	[76]	Studies the presence of chlorosis on lettuce leaves using artificial vision, collecting 533 images. The SVM and KNN models achieved 100% performance, while Naive Bayes achieved 92.93%. The pH is maintained between 5.5 and 7 and the electrical conductivity (EC) between 1.2 and 1.8 mS/cm.

by an algorithm DLCNN that evaluates the state of the plant in order to detect diseases. The results show the ability of AI-SHES to classify diseases and manage growth effectively.

The sensor-based artificial ripening system (S-BARS) proposed in [49] is controlled by sensors and a plate of microcontrollers, with data collected in real-time via excel. Authors use a control system on/off and optimized parameters, such as the maturation time and the consumption of electrical energy, by adjusting the operating conditions to improve the effectiveness of the maturation system. In [50], it employs machine vision to check the growth of the plants using predictive models built with regression of partial least squares (PLS). Models for TSS and titratable acidity showed superior performance with coefficients of determination (R 2) of 0.88 and 0.83, for the cross-validation (R2CV) and the prediction (R2Pred), respectively, in comparison with the model of pH showed a lower performance.

In [47], authors investigate a system embedded with pH and electrical conductivity sensors controlled by a system PID and neural networks. An increase was observed daily in the relationship light time/dark time (TLL-SD) and a mean pH of 5.65 with a minimum standard deviation, achieving an approximate error of 5% in the pH control. In [51], authors use vision and a model for Deep Kernel Learning with neural networks interconnected. Authors used LabVIEW to create the control, and MSAM was used to analyze lettuce's calcium and magnesium levels. The errors found for calcium and magnesium were approximately 27.02 $mg\,L^{-1}$ and between 10.5 $mg\,L^{-1}$ and 17.2 $mg\,L^{-1}$, respectively.

The sequential neural network model (RNN) in [52] combines temperature sensors, light, and TDS to control a cultivation system. The test of 9 days with lettuce demonstrated the effectiveness of the algorithms pre-trained in managing the ecosystem of culture. In [53], authors develop a monitoring system enabled by IA for the growth of the medicinal plant Rama Tulsi. Using logistic regression and decision trees, the system automates the monitoring and adjustment of growth parameters, achieving an accuracy of 95% compared to similar jobs. The data are compared in the cloud with the ideal conditions for real-time adjustments.

In [54], authors apply neural networks convolutional (CNN) to identify nutrient deficiencies in basil plants in hydroponics. Models DenseNet201, ResNet101V2, MobileNet, and VGG16 were evaluated, highlighting VGG16 with an accuracy of 93.82% after the fine adjustment, focusing on the relevant symptoms of the plants. In [55], authors propose using machine learning algorithms such as Lasso Regression and KNN hosted on a server in Flask. These models predict nutritional values from variables such as EC, pH, and water temperature, showing reduced water use compared to traditional crops.

In [77], VH400 sensors were used to measure soil moisture in an irrigation experiment. The model LSTM employee, with an input layer, two hidden layers, and an output layer, showed an increase of 9.375 in the relationship TLL-SD by day and a mean pH of 5.65 with a standard deviation of 0.058, reaching an error of 5% in the control of the pH. In [22], authors explore spectroscopic techniques and machine learning models to predict phosphorus concentrations in hydroponic solutions. Models SVM, KNN, Random Forest, and assembly techniques effectively predict phosphorus, with hybrid models showing a robustness top. In [23], parameters such as temperature, humidity, CO2, and light are used in an NFT system controlled by an Arduino microcontroller and a ZigBee device. The combination of fuzzy logic and neural networks has allowed us to predict the growth parameters of lettuce with a high degree of accuracy, between 0.82 and 0.96, in the predictions of net photosynthesis and transpiration.

In [33], authors develop an intelligent system for detecting nutrients NPK in hydroponics using spectroscopy for the real-time measurement of nitrogen, phosphorus, and potassium. The system implements techniques of artificial intelligence like artificial neural networks (ANN), convolutional (CNN), and recurrent (RNN) to optimize the management of nutrients and environmental factors. The data are collected using a light sensor TCS3200 and an Arduino microcontroller, with programming done in Python for processing and analyzing, which allows the adjustment of the variables of culture. The monitoring and control system achieves an accuracy of 98% in the detection of nutrients, with an average loss of 0.4145 in the tests, which indicates a margin of error under predictions.

In [78], authors develop a hydroponic system that combines techniques of film nutrients (NFT) and deep water culture (DWC) to optimize the growth of plants. The system monitors critical parameters such as electrical conductivity (EC) and water pH using three machine learning methods: linear regression, regression, decision tree regression, and random forest. The results show that the regression random forest is the most accurate to optimize the addition of nutrients and water, according to the formula that relates the EC planned and the EC current. If the result is less than 85%, nutrients are added; if you exceed 115%, water is added; and if you are between 85% and 115%, no addition is performed. This approach improves the system's efficiency and ensures optimum plant growth.

The hydroponic system of cultivation in deep water for the growth of basil and lemon proposed in [56] used a control system based on artificial intelligence (AI) to optimize the critical parameters such as the concentration of nutrients, pH and temperature of the water. The results showed that the basil plants reached an average height of 14 cm, with EC levels between 1400 and 1600 μS/cm and a pH of 5.8 to 6.3, while the nutrient temperature was maintained between 28 and 30 °C. These measurements were compared with predictions made by an algorithm based on the data set of OpenAg, which estimated an average height of 16 cm; the height difference is attributed to environmental conditions that are not ideal in the experiment.

In [57], authors study the impact of various parameters on the growth of spinach in hydroponic systems using artificial intelligence to predict its development. For 75 days, the pH was kept between 5.5 and 6.5, and the electrical conductivity (EC) was between 1000 and 1500. Data collection was used on sensors DHT22 and DSB18B20. To calculate the correlation between the parameters collected are used for the correlation of Pearson, Spearman, and Kendall were employed for the analysis. The prediction models applied included RFR, GBR, KNR, and BRR, with RFR being the most accurate with 98.3%, followed by GBR (97.0%), KNR (95.6%), and BRR (85.8%). In [3], authors present a comparative analysis of machine learning algorithms to predict the diameter of bulbs of onion in four hydroponic systems: a Technique of Film Nutritious (NFT), floating (FL), aggregate (AG), and aeroponics (AER). The system NFT was noted for its precision in the predictions, while the system AG obtained the highest value of R-squared (0.996%). The AER system was the most efficient in computational time (481 ms with XGBoost), and the floating system was optimal for prediction with deep neural networks (DNN), especially with learning federated, achieving a faster convergence.

In [79], authors develop a hydroponic system for tomatoes that combines artificial neural networks and digital image processing to automate production tracking. The study introduces an index of productivity based on the pixel area of the tomatoes in the captured images, achieving accurate identification with an error rate of 1.07%. In addition, the system optimizes the application of nutrients and climate monitoring, ensuring a controlled environment. It is concluded that the use of nutrient-diluted to 50% does not significantly affect the production, which allows the optimization of the dosage without compromising the performance.

2) SUPPLY OF NUTRIENTS IN HYDROPONIC SYSTEMS USING FUZZY LOGIC

In recent years, fuzzy logic has been used in various investigations because it has become the empirical knowledge in control systems using rules of fuzzy linguistic variables. This approach is used in hydroponics to identify critical variables, such as irrigation, the ideal temperature for cultivation, the distribution of nutrients, and other climatic variables that directly impact the crop. These variables can be integrated into a decision-making system within an intelligent controller.

Fuzzy logic is being widely used in agriculture, in aquaponic systems it has proven to be a valuable tool that allows the control of variables such as: pH, EC and water quality. In the case of [58] a combined system based on fuzzy logic and inference methods such as Min-Max and Mamdani is explored for nutrient management with the help of an Arduino microcontroller. The system design is divided into two main parts: the nutrient solution control system and fuzzy logic to control the solenoid valves that regulate the pH and EC levels, for this they use the integrated fuzzy logic library (eFLL) in the microcontroller, the results showed that the control takes 1.5 min to stabilize the mixture for pH values between 6 - 7 and 0.8 to 1.2 EC.

This shows its speed and precision in managing nutrient solutions in hydroponics. However, pH and EC values change according to the crop, so they are not uniform in all investigations, as demonstrated in [67], where the factors considered include temperature, EC and pH, with ideal values set at: 1.4-2 μS/cm for EC and a pH of 5.5 to 6.5 to perform the control. On the other hand, integrating IoT technology in aquaponic crops with fuzzy control showed better results. The tests carried out for 38 days, with sensor readings every minute, showed a performance with an approximate error margin of 0.999. This was achieved thanks to integrating the Long Short-Term Memory (LSTM) model for handling sequential data, combined with fuzzy logic unlike [58].

On the other hand, it is important to consider that the model proposed in [67] is complex to implement despite having promising results. In [71], an aquaponic system was developed using fuzzy logic to optimize the control of water pH and turbidity. The proposed system includes an Arduino Mega 2560 microcontroller and an ESP8266 module for IoT connectivity. Tests show that the pH level of the water is maintained in an optimal range of 6.3 to 7.3 and the turbidity is reduced from 8.11% to 0.46% after the filtration and recirculation process. However, this data processing takes 5.04 seconds, and the pH control presented an average error of 8.78%. This contrast shows that error can be a limiting factor in crops requiring greater precision. This further sharpens the dependence on the combination of complementary models and technologies as demonstrated in [67], to maximize efficiency and reduce the error percentage.

The study of hydroponic systems that employ fuzzy logic-based control techniques has proven to have wide application in improving crop yield. These systems stand out for their ability to regulate critical parameters such as pH, EC, nutrient management, and climatic parameters. In [59], the Fuzzy EDAS method is used in vertical crops to identify key criteria such as crop types and production volume. The results showed that the industrial warehouse is more favorable in production and costs, although with less flexibility than other systems. On the other hand, in [45], the importance of integrating emerging technologies such as robotics, artificial intelligence, and the Internet of Things in agriculture through automation is addressed to sustainably meet the global demand for food. Three levels of automation (manual, semi-automation, and full automation) were evaluated for hydroponic agriculture in controlled environments, using the TODIM method with fuzzy numbers to incorporate risk factors into the decision-making process, where semi-automation through 15 evaluated criteria showed better performance. These tools allow for more informed decision-making, although their implementation is complex.

Other experimental research such as that of [36], experimented with 28 chili plants in an urban greenhouse, where they implemented fuzzy logic rules in a Raspberry PI to control the nutrient solution in the plants is provided by drip irrigation from a mixing tank. The amount of fertilizers A and B is adjusted according to the phenological stage of the plant and the variables of pH, EC and temperature of the mixture. The system shows that the plants grow faster compared to the traditional method. On the other hand, in [30], a study of the growth of cucumbers was carried out in a greenhouse at the Tarbiat Modares University in Tehran, Iran. For the implementation of diffuse color, variables such as temperature, humidity, solar radiation, CO2 and ppm were considered. The results show that control regulates the environmental parameters to obtain the ideal conditions for the growth of cucumbers. Similarly, the fuzzy controller made by [80] adjusts the electrical conductivity (EC) and pH in a hydroponic system using specific sensors to determine the operating time of the acid and alkaline solution pumps. The results showed an error rate of $\pm$0.0035 over 19 days in lettuce plants. Not having precise results limits the analysis of its performance; however, it is important to highlight the performance generated in hydroponic crops.

In [62], a fuzzy control is implemented that adjusts the electrical conductivity in an NFT type hydroponic system, the control of the nutrients is carried out in three phases according to the growth of the plant in an NFT type hydroponic crop. The results show a precision of 91.1% in the measurements thanks to images, EC and water volume. In [63], a fuzzy control system with 3 rules is developed for an NFT hydroponic system, to control the water temperature using fans to maintain optimal lettuce crop conditions, the results show an accuracy of 91%, however, it is not guaranteed that the adequate level of nutrients is supplied to the plants.

In [61], a double control is developed using fuzzy logic to control pH, EC, humidity and ambient temperature in a strawberry hydroponic system, the control takes the input variables so that the system can supply the necessary amount of nutrients to the crop according to the growth stage of the plant. The first control system regulates the irrigation time of the nutrient-rich solution, based on information from the substrate humidity, substrate temperature and ambient temperature sensors. The second system is responsible for determining the irrigation time of the water without nutrients. The input variables for this controller are EC and pH. The results indicate that crop growth is optimized, but not having precision data limits the analysis of the achieved performance. In [37] a fuzzy logic system is implemented to control a fan and a water pump. To develop the control, pH, water level, temperature and humidity variables are used. The system acts when the control detects that the pH is outside the ranges of 5.5 to 6.5. The system also has an IoT interface that allows the user to monitor the operation of the crop, this helps to create an optimal production environment for the plants. However, not indicating the achieved performance limits its understanding in terms of operation.

Energy efficiency and sustainability is another point that must be addressed in hydroponic systems. In [66] a small-scale smart greenhouse is developed using fuzzy logic and the Internet of Things (IoT). The system integrates a fuzzy PI controller with temperature and humidity sensors, actuators such as fans, and irrigation systems. The results showed that temperature control reduced the standard deviation by 20% and maintained an accuracy of ±0.5°C, while humidity control had an average error of only 2%. In addition, a 15% reduction in energy consumption was achieved during system operation. On the other hand, in [64], a fuzzy control system with 5 rules is implemented to balance the actuators' operation and the crop's needs. The results of this project showed that energy consumption was reduced by 18% compared to a traditional scheme. This consideration is important for increasing food productivity and saving resources.

In [81] an automated hydroponic system based on the Deep Flow Hydroponic (DFT) technique is developed for spinach cultivation. The system maintains the pH of the nutrient solution at an optimal point of 5.5 using a fuzzy logic controller with 25 rules, an ESP32 microcontroller and a pH sensor. The algorithm adjusts a valve to add phosphoric acid or potassium hydroxide to maintain the set value. The system proved effective, with pH response times ranging from 336.07 to 966.15 seconds and a maximum overshoot between 0.54 and 0.72. Achieving a 97.4% accuracy in control contributed to an increase in crop yield by 40% compared to conventional methods. In [65], a fuzzy logic control is developed that creates a rule to calibrate the sensors and correct possible measurement failures to supply the necessary amount of nutrients in the solution before it recirculates through the hydroponic cultivation system. The efficiency of the calibration system showed that the optimal pH values vary between 5.5-6.5 and the PPM values vary between 1050-1400. To verify these results, 30 iterations were carried out to reach the optimal crop conditions. The pH variable used for control could cause a slight deviation in assigning the correct amount of nutrients according to the crop type.

It is important to consider the use of combined control systems that use Fuzzy Logic, such as the research carried out in [29] and [30] that highlight the use of ANFIS-based systems for control in hydroponic systems, in bok choy and Chinese lettuce crops. In [23], the ANFIS controller regulates critical parameters such as pH, keeping it between 5.5 and 6.5, and EC between 600 and 900 μS/cm, ensuring optimal conditions for crop growth. On the other hand, [69] extends the system functionality by integrating IoT, allowing automatic adjustments and remote control to manage nutrient concentration. The proposed system maintains the nutrient concentration between 600-900 ppm, if the level is higher than normal, a pump is turned on to discard water from the tank and another pump to fill the tank until the nutrient level returns to normal. ANFIS uses the data from TDS and pH sensors to control solenoid valves, achieving a 67% improvement in pH and nutrient adjustment accuracy compared to a Sugeno-based fuzzy controller. Both studies demonstrate the effectiveness of ANFIS in optimizing critical parameters in cultivation. However [69], stands out for its ability to overcome limitations of previous fuzzy methods and its focus on automation combined with IoT.

Hydroponic systems based on fuzzy control present significant differences in architecture and performance depending on the method and technology used. In [68], a fuzzy controller that includes 9 rules based on the Sugeno method regulates the nutrient concentration. The controller input variables are the error and the error variation in the concentration, while the outputs control the angle of the servomotor that adjusts the water and nutrient valves. The results show that, with an initial concentration of 400 ppm, the stabilization time was 138 seconds, while for 700 ppm it was 76 seconds, achieving an accuracy of 95%. On the other hand, in [70], the Mamdani method, the input variables are the TDS data and the volume of water in the dosing tank, and the output is the activation of the solenoid valves. The system achieves 94.24% accuracy in nutrient adjustment, albeit with a longer average time (13 minutes and 49 seconds), reflecting a more comprehensive approach by including variables such as water volume and temperature.

In [15], a smart hydroponic system focused on lettuce cultivation was developed, using artificial intelligence (AI) and fuzzy control to optimize nutrient management and environmental conditions such as temperature and humidity. The system uses sensors to monitor critical parameters (pH, electrical conductivity, temperature) and actuators that adjust the growing environment automatically. Machine learning algorithms integrated into the software enable real-time decision making. The results show a 30% increase in lettuce production (12 kg/m^2) and a 25% reduction in water consumption compared to traditional systems. These investigations highlight the importance of the choice of control method and the integration of advanced technologies, and their influence on the accuracy, response time and sustainability of hydroponic systems during their operation.

3) ARTIFICIAL VISION APPLIED TO HYDROPONIC SYSTEMS

Machine vision has gained prominence in several investigations in recent years because it can convert visual analysis into automated control systems using advanced algorithms. In hydroponic culture, this approach is crucial to identify and monitor critical variables such as the state of health of the plants, the early detection of pest control, the monitoring of growth, and the optimal distribution of nutrients. Integrating these variables in an intelligent controller's decision-making system allows constant real-time monitoring and adjustments. The importance of the vision in the hydroponic culture lies in its ability to improve the efficiency and productivity of the crop significantly, reducing the need for manual intervention and optimizing the use of resources, which is vital for the sustainability and profitability of farming modern.

The analyzed research demonstrates its importance in monitoring and control in hydroponic systems. In [72], a system is implemented that allows identifying deficiencies in macronutrients in the crop, using multilayer neural networks (MLP) with Backpropagation and ReLU by analyzing three characteristics: texture, color and leaf shape. The intelligent hydroponic system is divided into two parts, the first for data acquisition in the morning and afternoon hours, the second to identify and estimate the deficiency of macronutrients in plants. The results show that the mean absolute percentage error (MAPE) is less than 10%. This error indicates that the proposed system is ideal in identifying nutritional deficiencies.

In [73], an intelligent hydroponic system for lettuce cultivation is presented, where it uses deep learning algorithms such as Faster R-CNN and Inception V2, together with YOLO, for early detection of diseases to improve crop production. The analysis of 53 images out of 412 using TensorFlow showed that the proposed model achieved a precision of 70% and an accuracy of 97%. However, the precision is relatively low, although the model is effective in terms of accuracy, it could improve its precision in identifying diseases by expanding the database. It is also essential to indicate that the difference between precision and accuracy has a relatively low rate of false positives, helping to improve agricultural production.

In [74], the analysis to evaluate the growth is performed using three machine learning estimators: logistic regression (LR), K-nearest neighbor (KNN), and linear support vector machine (LSVM). For this, lettuce images were generated by computer vision for 10 weeks, gathering 300 images processed in Matlab to extract the attributes and collect data for the analysis of the health status of the plants. To evaluate the performance of the models, the data was divided into 80% for training and 20% for test data. The results showed that KNN achieved an accuracy of 91.67% and a cross-mean accuracy of 87.06%. These results demonstrate the effectiveness of disease detection. However, since the study focused mainly on growth analysis and not on specific diseases, the results could vary if a more complex classification of diseases were addressed.

In [75], the authors focused on the state of lettuce roots in a hydroponic system to identify diseases related to temperature and water status. They use a camera to visually observe the roots and temperature sensors to monitor the water. Root images were captured twice daily (morning and evening), collecting 1200 images. To determine the state of the plant roots, the Decision Tree model was used, using 80% of the data for training and 20% for testing. The system achieved an accuracy of 91%. This approach is essential since it considers another methodology for disease detection. However, it is crucial to consider that erroneous data could be generated due to water contamination and other factors, which could limit the interpretation of results.

In [76], using artificial vision, a study was developed to evaluate the presence of chlorosis in the leaves of lettuce plants grown in a hydroponic system. A total of 533 images were collected, of which 273 corresponded to healthy leaves, and 260 showed signs of chlorosis. Support Vector Machine (SVM), Nearest Neighbor (KNN), and Naive Bayes (NB) models were used to classify the leaf status. The results showed a 100% performance for SVM and KNN and 92.93% for NB. In addition, the nutrient solution was maintained at a pH between 5.5 and 7 and an electrical conductivity (EC) of 1.2 to 1.8 mS/cm. Their high performance in terms of accuracy reflects the models' ability to correctly classify leaf images, which can directly influence production improvement.

On the other hand, in [41], an ANN-based decision support system is proposed to classify the growth stage of lettuce using features such as area, perimeter, color, and texture. For training, 90 images were used, divided into 70%, 15% for validation, and 15% for testing. This image processing technique allowed the extraction of crop characteristics in order to determine which growth stage the crop is in. The system's performance showed 92.9%, indicating high accuracy in classifying lettuce growth stages. However, several aspects do not allow a deeper analysis of how the performance metric was evaluated. In addition, although practical, the image processing technique uses a small database. It depends heavily on the quality of the images and the capture conditions, which could affect the system's accuracy in natural environments.

C. DISCUSSION

The comparison between the various approaches and algorithms used in hydroponic systems reveals significant differences in accuracy, amount of data used, efficiency, and applicability. The absence of information on the accuracy percentage in some studies limits the analysis of the results obtained, makes it difficult to identify possible problems presented, and restricts the evaluation of improvements in crop performance. Similarly, in other studies analyzed, the lack of detail on the data and types of variables used to implement the algorithm makes it even more challenging to understand its development and applicability. Table 9 presents a general summary of the percentages of accuracy obtained in the different studies analyzed.

The algorithms used in hydroponic systems to control nutrients, environmental parameters, disease detection, and growth evaluation reveal notable differences in performance, amount of data used, and diversity in the controlled variables. Algorithms such as Fuzzy Control stand out for their ability to quickly adapt to crops such as lettuce, strawberry, cabbage, and spinach. Most of these studies were carried out in hydroponic systems where a precision between 90.1% and 100% was achieved through the use of 3 to 25 rules to control critical variables such as pH, ppm, temperature, and water level [62], [63], [65], [68], [70], [81]. On the other hand, studies such as [36], [37], [45], [59], [61], [64], [66], and [80] need to indicate the results obtained, which limits the understanding of the performance achieved in the proposed control system. Therefore, based on the findings, it is essential to consider that the number of rules does not define the accuracy of fuzzy control; this parameter is affected by the number of controlled variables and the number of controlled outputs. Consequently, it is suggested that for future implementation of fuzzy logic-based control systems, variables that directly influence the level of nutrients, such as pH, ppm, and EC, should be used, and several rules between 10 and 16 should be established based on the results obtained with 15 rules in [71].

In studies that use deep neural networks, such as the work presented in [10], an accuracy of 88.50% was achieved by analyzing 5000 data and 10,000 training epochs, controlling variables that regulate the supply of nutrients such as pH and water level. The results demonstrated the ability to control multiple variables effectively in real-time. However, other approaches, such as Machine Learning proposed in [22], achieved higher accuracy in algorithms used, such as SVM: 96%, KNN: 92%, and RF 98.53%, in managing phosphorus concentration in hydroponic systems. Unlike the previous proposal in this research, 2500 data were used, of which 1750 were used for training and the rest for testing. However, this suggests that, although neural networks are robust, regression models may be more effective in applications where specific parameters, such as nutrient concentration, need to be adjusted.

On the other hand, approaches based on artificial intelligence, such as RNN, ANN, and CNN, have proven to be highly effective in controlling nutrient levels in hydroponic systems. For example, in [33], using these algorithms, an accuracy of 88.5% was achieved in controlling nutrient concentration (NPK) with 5000 data and 10,000 training epochs. Despite their complexity, these methods allow a more efficient optimization of the hydroponic system compared to more straightforward techniques, such as regression algorithms that achieved an accuracy of 90% in controlling variables such as temperature and humidity [60]. However, studies such as [37] apply only ANN and obtain better results in controlling variables that directly affect nutrient concentration in the crop, such as pH, EC, water level, temperature, and humidity. For the algorithm training, 3950 data were used and distributed in 70% training, 15% validation, and 15% testing, achieving an accuracy of 99%. On the other hand, in [54], the use of artificial vision in the research carried out on spinach crops presents promising results in the monitoring of plant development; the use of CNN allowed the analysis of 10,000 images related to the growth and number of spinach leaves, the results demonstrated an accuracy of 89.54%. Integrating multiple machine learning techniques provides a more robust and adaptable approach. However, it comes at the cost of increased complexity and the need for more advanced computational resources to obtain better performance.

More recent research, such as that in [58] and [71], explores combining fuzzy logic with artificial intelligence systems such as ANFIS, overcoming the limitations of traditional fuzzy controllers. These advanced approaches allow for greater accuracy and efficiency in nutrient regulation, better adapting to environmental fluctuations. However, implementing these more advanced systems can be more expensive and complicated than traditional methods, posing a dilemma between simplicity and sophistication. In contrast, the studies in [74] and [76] focus on the use of more traditional machine learning models, such as KNN, SVM, and Naive Bayes, to assess plant growth and health. In [74], the use of KNN showed a high accuracy of 86.69% in estimating the growth percentage, standing out for its simplicity and effectiveness in a limited image context (300 images). Likewise, [76] showed outstanding results with 100% performance in classifying chlorosis in 533 images using SVM and KNN, suggesting that these methods can be as effective as deep learning models in certain applications. However, the implementation of advanced IoT and computer vision techniques demonstrates that the integration of environmental and visual data can offer a more holistic solution, allowing for a more precise adjustment in disease detection. Although more complex, this approach can be crucial to maximize sustainability and efficiency in hydroponic production.

The use of ANN in hydroponic systems has proven to be an effective tool, especially when analyzing visual variables such as area, perimeter, color, and texture in lettuce crops in a relatively small set of 90 images for training and validation, an accuracy of 92.9% was obtained [41]. On the other hand, integrating Faster R-CNN, with a set of 2 million records, allowed precise control of nutrient supply in tomato crops, reaching an accuracy of 98.93% [79]. This result emphasizes the positive impact of the dataset size on the

TABLE 9. Algorithms used for nutrient supply in hydroponic cultures.

Algorithm	Conditions / Data	Variables Controlled	Type of Crop	Plant	% Precision	Ref
Control Fuzzy	25 rules	pH (level of nutrients)	Hydroponic	Spinach	97.4%	[81]
Control Fuzzy	16 rules	Level of nutrients and amount of water	Hydroponic NFT	Mustard greens	94.24%	[70]
Control Fuzzy	3 rules	Temperature	Hydroponic NFT	Lettuce	91%	[63]
Control Fuzzy	9 rules	TDS (ppm)	Hydroponic	Lettuce	95%	[68]
Control Fuzzy	3 rules	EC, volume of water	Hydroponic	Pakcoy	90.1%	[62]
Control Fuzzy	5 rules	pH, EC, water-level	Water	-	100%	[65]
Control Fuzzy	15 rules	pH, turbidity of the water	Acuapónico	-	99.2%	[71]
Deep Neural Networks (DNN)	5000 data, 10000 iterations	pH, moisture, light intensity, temperature, water level	Hydroponic NFT	Tomato	88.5%	[10]
Machine Learning (SVM, KNN, RF)	2500 data (1750 training)	Concentration of phosphorus	Hydroponic	-	SVM: 9.60%, KNN: 9.20%, RF: 98.53%	[22]
RNN, ANN, CNN	45045 samples	Levels of nutrients (NPK)	Hydroponic	-	98%	[33]
Neural Networks (ANN)	90 pictures	Vision variables: area, perimeter, color, texture	Hydroponic	Lettuce	92.9%	[41]
Machine Learning (Logistic Regression)	88858 samples	Doses of nutrients, damage control, and performance	Hydroponic	-	83.61%	[43]
ANN	3950 data (70% training, 15% validation, 15% testing)	pH, EC, water level, temperature, humidity	Hydroponic NFT	-	99%	[46]
KNN, Regression Lasso	-	Temperature, humidity, air quality	Hydroponic	-	90%	[60]
CNN	-	Nutrient levels and disease detection	Hydroponic	Tomato	99.29%, 99.23%	[48]
CNN	10000 photographs	Growth, number of sheets	Hydroponic	Spinach	89.54%	[54]
Deep Kernel Learning	100 training data	17 variables: pH, EC, temperature, nitrate, potassium, calcium, sodium, etc.	Hydroponic	Lettuce, Tomato, Eggplant	85%	[56]
Decision Tree	1200 pictures of healthy roots, 1452 of rotten roots	State of health of the roots	Hydroponic DWC	Lettuce	91%	[75]
Faster R-CNN	2 million records (70% training, 30% testing)	Supply of nutrients	Hydroponic	Tomato	98.93%	[79]
ANN	90 images (70% training, 15% validation, 15% test)	Percentage of growth	Hydroponic	Lettuce	92.9%	[41]
KNN, SVM, L-SVM	300 images (80% training, 20% testing)	Percentage of growth	Acuapónico	Lettuce	KNN: 86.69%, L-SVM: 80.79%, LR: 79.60%	[74]

model accuracy. Similarly, the Deep Kernel Learning method, despite considering a wide range of 17 variables such as pH, EC, and temperature, presented a more limited accuracy of 85% due to its reduced set of 100 samples used for training, which highlights the importance of having a more extensive database for robust models, since not using sufficient data can lead to overfitting, which could cause the model not to work correctly [56].

In terms of detection and evaluation of specific parameters, Decision Trees proved to be the most effective in identifying the health status of roots in DWC hydroponic cultivation systems, achieving an accuracy of 91% when using a dataset composed of 1200 images of healthy roots and 1452 images of rotten roots [75]. However, this percentage could be improved using hybrid models or neural networks, especially by expanding the number of images in the training and testing stages. On the other hand, logistic regression, applied to the control of nutrient doses and yield in hydroponic systems, showed a more modest performance with an accuracy of 83.61% despite using a large volume of 88,858 samples [43]. On the other hand, the combination of models such as KNN and Lasso regression stood out for their 90% accuracy when monitoring environmental variables such as temperature, humidity, and air quality in hydroponic systems, demonstrating that combined approaches can offer practical solutions for specific problems [60].

Analysis of the studies shows that a larger volume of data contributes significantly to the accuracy of the models. For example, [33], with 50,688 initial samples, reports an accuracy of 98%, in contrast to [56], which uses only 100 data and achieves an accuracy of 85%, highlighting the importance of the dataset size to develop robust and generalizable models. Some hybrid approaches, such as the Machine Learning approach in [22], achieve outstanding accuracies of 99.73%, evidencing that the combination of algorithms can outperform individual approaches. Controlled variables are also determinants for the performance of the models; factors such as nutrient levels (NPK, pH, EC) [32], [46] and environmental parameters (temperature, light, humidity) [10], [56] are recurrent due to their direct impact on crop quality, underlining the need for comprehensive monitoring. As for algorithms, neural networks (ANN, RNN, CNN) dominate complex tasks such as nutrient status prediction and disease detection [48]. However, classical methods such as

SVM, Random Forest, and decision trees are still relevant, especially in contexts with smaller data sets [22], [75].

Finally, the research analysis allowed us to determine that the algorithms used in hydroponic systems significantly impact the efficient use of water and plant growth. Fuzzy Control, for example, allowed an increase in the height of controlled plants of 13.84 cm compared to 12.94 cm in uncontrolled plants on day 19 in lettuce, strawberry, and broccoli crops [80]. Likewise, in [45], using Fuzzy Control, 60-70% water savings were achieved. On the other hand, random forest regression showed 80-90% water savings in hybrid NFT and DWC systems, making it a highly effective option for various crops [78]. At the same time, using KNN achieved 90% savings by controlling key variables such as pH, EC, temperature, and humidity [55]. The Faster R-CNN algorithm revealed that optimizing the nutrient supply at 50% resulted in higher tomato productivity, demonstrating the importance of balancing water and nutrients [79].

These results highlight the need to use various models in natural resource management; however, with limited information provided by the authors on the results obtained related to water savings and improved growth, it is difficult to perform a more in-depth analysis to identify the factors that contributed to the improvement. Likewise, it is not easy to establish a better model for future implementation without accurate data. For this reason, it is suggested that information be expanded to other types of soilless cultivation where nutrient management or Control of variables such as pH or EC that directly influence nutrient concentration is carried out. It is also essential to consider that the need for more information related to water resource-saving percentages also makes it difficult to evaluate the impact of hydroponic systems compared to traditional cultivation.

IV. CONCLUSION

Algorithms used in hydroponic systems, such as Fuzzy Control, Neural Networks (ANN, CNN, RNN), and traditional models (KNN, SVM, Random Forest), have been shown to have a significant impact on the efficient management of nutrients in these systems. These methods allow for the optimization of water use and the control of critical parameters such as pH, EC, and temperature, which directly influence plant growth. For example, Fuzzy Control has been used in various crops such as lettuce, strawberry, and broccoli; the results showed an increase in the height of the controlled plants and a water saving of up to 70 %. Likewise, the random forest regression stood out for its ability to save between 80% and 90% of water in hybrid NFT and DWC systems. At the same time, the Faster R-CNN algorithm managed to optimize the supply of nutrients in tomato crops, resulting in higher productivity. The ability of these systems to monitor and adjust critical parameters in real-time allows for precise control of the crop environment, which reduces human intervention and increases productivity.

The reviewed research highlights the effectiveness of automated, artificial intelligence (AI)-based hydroponic systems in optimizing crop growth and production. In real-time, these systems employ neural networks, computer vision, and machine learning to manage critical parameters such as pH, electrical conductivity, temperature, and nutrient concentration. Integrating these technologies into microcontrollers and IoT devices enables precise and adaptive control of growing environments, achieving high accuracy in predicting and adjusting conditions, thereby improving efficiency and reducing human intervention. Furthermore, applying algorithms such as deep neural networks and multiple linear regression have shown high levels of accuracy in predicting parameters and necessary adjustments, contributing to healthy plant growth and more sustainable production.

On the other hand, combining AI with advanced control and monitoring techniques, such as spectroscopy and digital image analysis, has enabled the development of more sophisticated and autonomous systems that optimize the growing environment, nutrient management, and plant growth monitoring. This not only improves crop yield and quality but also contributes to greater sustainability by optimizing resource use and minimizing natural resource waste. The reviewed systems show clear potential to transform conventional agriculture into a more efficient and technologically advanced model.

Fuzzy logic has proven to be effective in automating and controlling agricultural systems, especially in hydroponic and aquaponic crops. It has been possible to manage critical variables such as irrigation, temperature, and nutrient distribution by converting empirical knowledge into fuzzy rules and linguistic variables, thereby improving efficiency in agricultural production. The reviewed studies show that fuzzy logic has been successfully applied in automated systems to regulate parameters such as pH, electrical conductivity, and nutrient concentration. These systems have proven effective in reducing errors and optimizing plant growth, integrating with emerging technologies such as the Internet of Things (IoT), artificial vision, and neural networks, which have significantly increased precision and efficiency in crop management. Projects that integrate fuzzy logic with controllers based on methods such as Mamdani, Sugeno, and ANFIS have shown substantial improvements in the accuracy of control of critical variables, resulting in increased crop yield and reduced operating costs. In particular, the use of advanced sensors and microcontrollers such as Arduino and Raspberry Pi has facilitated the implementation of intelligent systems that automatically monitor and adjust growing conditions, ensuring an ideal environment for plant development. These advances highlight the potential of fuzzy logic in modern agriculture, offering practical solutions to the current challenges of sustainable food production.

Research in hydroponic crops demonstrates the increasing importance of machine vision to optimize the detection and monitoring of critical variables such as plant health and nutrient use efficiency. Studies highlight how advanced machine learning algorithms such as neural networks, logistic regression, and support vector machines (SVM) have effectively classified health states, identified nutrient deficiencies, and predicted growth in plants like lettuce. Furthermore, integrating machine vision with IoT technologies has enabled more precise and automated control of growing conditions. This includes monitoring root status and water temperature and identifying nutrient deficiencies by analyzing leaf morphological, color, and texture features. AI-based decision support systems have proven to be a powerful tool to classify growth stages and adjust nutrient supply in real-time, as research shows 91.67% accuracy in assessing plant growth using KNN. These advances highlight the potential of artificial vision to improve sustainability and productivity.

Considering the relevant literature, using different intelligent control models in hydroponic crops for nutrient monitoring stands out. Each of these studies stands out for employing techniques focused on viability and automation in different products, both large-scale systems and customized solutions. The continuous monitoring of parameters such as temperature, pH, and electrical conductivity plays a vital role in the results of each investigation because they highlight the positive potential of the systems proposed by each author for the improvement and performance as well as the quality of the crops. These investigations significantly advance toward implementing more precise and autonomous hydroponic systems.

This review shows the most significant findings related to nutrient control in hydroponic crops. pH and electrical conductivity are fundamental parameters that allow for significant improvements in soilless cultivation systems. Nutrient dosing is an aspect that can prevent the eradication of plant diseases and optimize both resources and efficiency in agricultural production. Managing uncertainty and variability in agricultural environments are topics of ongoing development and research for sustainability in the context of increasing food demand.

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