A SYSTEMATIC REVIEW OF AQUAPONICS: ADVANCES IN AUTOMATION AND SUSTAINABLE AGRICULTURE

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ABSTRACT

Aquaponics represents the integrated production of fish and hydroponic crops using recirculation of a nutrient solution in such a way that fish excretions are used as fertilizer for plants. There is a great interest in aquaponics in the EU and around the world due to increased interest in sustainable agriculture. Such systems can operate in any area and can be controlled remotely via mobile applications. In this article, we will introduce the different types of aquaponic systems: media-based aquaponic systems, nutrient film techniques, and deep-water culture. We will also present various developments of aquaponic systems in Romania. Additionally, we will provide a review of recent literature in the field of aquaponics, including different statistics. Many studies have been conducted on such aquaponic systems, reviewing the general concept, components, types of parameters, and factors influencing the productivity and efficiency of such systems. We will discuss the water parameters in aquaponics that are important for both plants and fish. Maintaining water quality parameters is crucial to provide sufficient nutrients for growing fish and plants, and monitoring these parameters is essential for the health of the aquaponic system. The contribution of this paper is the provision of detailed and indepth discussion on aquaponics.

KEYWORDS

Aquaponics, Monitoring, Control, Sustainability, Urban agriculture, Greenhouses

1. INTRODUCTION

Aquaponics represents an innovative and sustainable agricultural system that combines fish farming with hydroponic crop cultivation, utilizing the recirculation of a nutrient solution [1]. This integrated approach harnesses the natural relationship between fish and plants, where fish excretions serve as valuable fertilizer for plant growth. With the increasing interest in sustainable agriculture, aquaponics has gained significant attention in the European Union (EU) and worldwide. These systems offer versatile and adaptable solutions that can be implemented in diverse geographical regions, and technological advancements enable remote monitoring and control through mobile applications [2].

This article aims to present various types of aquaponic systems and highlight the developments in Romania. Additionally, we will provide a comprehensive review of recent literature in the field, including statistical analyses [3]. Numerous studies have been conducted, focusing on fundamental aspects of aquaponic systems, such as conceptual frameworks, system components, parameter variations, and factors influencing productivity and efficiency. Furthermore, we will explore critical water parameters in an aquaponic system, which play a crucial role in supporting

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the health and growth of both plants and fish. Maintaining and monitoring these water quality parameters are vital to ensure the overall well-being and success of the aquaponic system [4,5]. Globally, aquaponics has witnessed increasing adoption in diverse settings, from urban rooftops to rural farms, due to its environmental and economic benefits.

This paper aims to:

1. Review the primary types of aquaponic systems.
2. Highlight Romania's contributions to the field.
3. Examine advancements in automation and control technologies.
4. Discuss challenges and future directions in aquaponics research and implementation.

2. Literature Review

The first type is represented by media-based aquaponic systems, which use a solid medium such as gravel or clay aggregates to support plant growth. This medium acts as a biofilter, facilitating the conversion of fish waste into nutrients available to plants. The solid medium also provides mechanical support for the plants and creates a habitat for beneficial bacteria that contribute to the overall system stability and nutrient cycle. Media-based systems are widely adopted in both small-scale and commercial aquaponics due to their simplicity, efficiency, and versatility.

Aquaponic System Types 1. Media-Based Systems

These systems utilize gravel or clay aggregates to support plant growth, providing both mechanical stability and a habitat for beneficial bacteria. Widely adopted in small-scale and commercial setups, they are simple to implement but require regular maintenance.

2. Nutrient Film Technique (NFT)

A thin nutrient-rich water film flows over plant roots in inclined channels. This method is space-efficient and suitable for high-density cultivation but requires precise monitoring of water flow and quality.

3. Deep Water Culture (DWC)

Plants are supported by floating rafts with roots submerged in a nutrient solution. Known for its low maintenance and scalability, DWC is ideal for large-scale production.

Comparative Table of Aquaponic Systems

System Type	Advantages	Disadvantages
Media-Based Systems	Simple setup, good biofiltration	Higher maintenance, limited scalability
NFT	Space-efficient, promotes oxygenation	Requires precise water quality control
DWC	Low maintenance, scalable	High initial cost, potential for root diseases

Romania-Specific Contributions

Romania has emerged as a key player in advancing aquaponic systems, with projects focusing on urban and rural implementations. Notable initiatives include:

- **Urban Aquaponics**: Integration of aquaponics into urban spaces to produce fresh food while enhancing green spaces.
- **Denitrification Technologies**: Projects like INMA Bucharest's "Innovative Denitrification Technology and Installation" emphasize nitrate removal to improve water quality.
- **Educational Programs**: Universities and research centers have adopted aquaponics for hands-on learning and scientific exploration.

The second type is the nutrient film technique (NFT), where a thin layer of nutrient-rich water flows over the plant roots, providing them with essential nutrients while also purifying the water for the fish. In NFT systems, plants are commonly grown in channels or troughs with a slight slope, allowing the nutrient solution to continuously flow over the roots. This technique provides a highly oxygenated and nutrient-rich environment for plant roots, promoting rapid growth and efficient nutrient absorption. NFT systems are frequently used in commercial aquaponic operations as they maximize space utilization and facilitate high-density plant cultivation.

The third type is deep water culture (DWC), where plant roots are suspended in a nutrient-rich solution, enabling direct assimilation of nutrients and efficient filtration of fish waste. In DWC systems, plants are typically supported by floaters or floating beds that allow the roots to submerge in the nutrient solution. The buoyancy of the floaters keeps the plants above the water, providing them with continuous access to nutrients. DWC systems are known for their simplicity and low maintenance requirements, making them suitable for small-scale aquaponic setups and home gardens.

Romania, as an emerging market for aquaponics, has made significant progress and applications of this sustainable agricultural system. Several projects and initiatives throughout the country highlight the potential and benefits of aquaponics in diverse contexts. For instance, the use of aquaponics in urban areas has become popular as a way to produce fresh local food and mitigate the environmental impact associated with traditional agriculture. Additionally, aquaponics has been integrated into educational institutions and research centers, allowing for hands-on learning experiences and scientific investigations.

The articles [6-9] present the results of research on the efficiency of the denitrification installation in reducing nitrate concentrations in water. Detailed analyses were conducted to assess the impact of the denitrification installation on water quality and the health and development of the fish. The results of the studies show that the use of the denitrification installation has led to a significant improvement in water quality in the recirculating aquaculture system. Nitrate concentrations were effectively reduced, ensuring a healthier and more favorable environment for fish development. This initiative aims to transform underutilized bodies of water into productive aquaponic systems, using floating platforms that host both fish tanks and hydroponic beds, offering a sustainable solution for food production and contributing to the revitalization of urban areas and the promotion of green spaces.

Another significant aspect in Romania is the integration of aquaponics in rural areas. In these environments, aquaponic systems have been implemented to address challenges such as limited agricultural land and decreasing water resources. By using aquaponics, farmers can maximize production capacity while minimizing the impact on the environment. These systems provide opportunities for diversification and increased income generation, allowing farmers to cultivate both fish and valuable crops throughout the year. Moreover, aquaponics offers a more sustainable alternative to traditional agricultural practices, reducing dependence on chemical fertilizers and minimizing water usage [10]. A notable example of aquaponics development in Romania is the project "Innovative Denitrification Technology and Installation for Aquaponic Cultures" conducted by INMA Bucharest. The study focuses on improving water quality in a recirculating aquaculture system, with an emphasis on nitrate removal from water using a denitrification installation. Water recirculation in the aquaculture system allows for water conservation and resource efficiency. However, excessive nitrate buildup in water can lead to health issues for fish and can affect water quality.

Progress in aquaponics technology in Romania is not limited to the design and implementation of systems. Research institutions and universities are actively involved in studying and optimizing aquaponic systems. Various aspects, including water quality management, nutrient cycling, plant growth optimization, and fish health, have been investigated to improve the performance and efficiency of aquaponics. These research efforts contribute to the growth of knowledge and provide valuable insights into the intricacies of aquaponic systems.

In addition to developments in Romania, it is essential to review the available literature in the field of aquaponics. Numerous studies have been conducted worldwide, focusing on various aspects of aquaponic systems [11]. These studies cover a wide range of topics, including system design, optimization, water quality management, nutrient dynamics, crop selection, fish health, and overall system performance. Through a comprehensive review of this literature, we can gain a deeper understanding of the current state of aquaponics and identify possible directions for further research and improvement.

Another area of interest in aquaponics research is the evaluation of system parameters and their impact on productivity and efficiency. Factors such as water temperature, pH level, dissolved oxygen concentration, ammonia, nitrites, and nitrates play a crucial role in maintaining a healthy and balanced aquaponic system [12]. The optimal range for these parameters varies depending on the species of fish and plants being cultivated. Therefore, it is essential to regularly monitor and control these parameters to ensure optimal growing conditions for both fish and plants. Additionally, research has focused on the development of automated monitoring and control systems, utilizing sensors and data analysis techniques to make real-time adjustments and optimize system performance.

Another significant area of research in aquaponics is the selection and cultivation of suitable plant species. Different crops have varied nutritional requirements and growth characteristics, making certain plants more suitable for aquaponic systems than others. Researchers have evaluated the growth rates, nutrient uptake, and overall productivity of different plant species in aquaponic environments. These studies provide valuable information for selecting plants that thrive in aquaponic systems and maximize the use of available nutrients. By understanding the interactions between fish and plants in aquaponic systems, researchers can develop strategies to optimize fish growth and reduce stress and disease occurrence.

One aspect of aquaponics that has garnered significant attention in research literature is water quality management. Maintaining appropriate water parameters is crucial for the health and growth of both fish and plants. Water temperature, pH level, dissolved oxygen concentration, and nutrient levels need to be carefully monitored and controlled to ensure optimal conditions. Researchers have investigated the effects of different water parameters on system performance and have developed strategies for maintaining stable and suitable conditions in aquaponic systems. These studies, along with the integration of IoT technologies, help aquaponics practitioners make informed decisions regarding water quality management and contribute to the overall success and sustainability of their systems [13].

Nutrient dynamics and cycling within aquaponic systems have also been extensively studied. The conversion of fish waste into nutrients available for plants is a fundamental aspect of aquaponics. Researchers have examined the nitrogen cycle, nutrient uptake rates, and nutrient availability to optimize the efficiency of the nutrient cycle in aquaponic systems. Understanding the dynamics of nutrient flow between fish and plants allows for fine-tuning of system parameters and nutrient supplementation strategies, leading to improved productivity and more efficient nutrient utilization.

The selection and cultivation of appropriate plant species represents another area of interest in aquaponics research. Different plant species have varied nutritional requirements and growth characteristics, which can affect the overall system performance. Researchers have evaluated the growth rates, nutrient uptake, and market value of different crops in aquaponic environments. This research helps identify high-value crops that thrive in the aquaponic system and can contribute to the economic viability of aquaponic operations [14].

Studies have also focused on the health and welfare of fish in aquaponic systems. Factors such as stocking density, feeding regimes, and disease management have been investigated to ensure the well-being of the fish. Researchers have examined the effects of different stocking densities on growth rates, feed conversion efficiency, and stress levels in fish. Additionally, the impact of feeding strategies and diets on fish health and waste production has been analyzed. Strategies for preventing and managing diseases specific to aquaponic systems have been developed to minimize the risk of infections and ensure the long-term health of the fish population.
The reviewed literature provides a comprehensive understanding of the progress and challenges in the field of aquaponics, allowing for the development of best practices and guidelines for practitioners. It highlights the potential of aquaponics as a sustainable and resource-efficient agricultural system that can contribute to food security and environmental conservation. Furthermore, research findings contribute to broader scientific knowledge in the field of aquaponics and can guide future research efforts.

3. METHODOLOGY

3.1. The Research Objective

The main objective of this literature review is to explore and analyse existing studies and research on the topic of "An Integrated Approach to Sustainable Agriculture." The aim is to gain a comprehensive understanding of key components, strategies, and practices involved in sustainable agriculture and their integration to achieve sustainable and environmentally friendly agricultural systems.

3.2. Research Domain

The research domain encompasses a wide range of literature, including academic articles, scientific papers, books, reports, and relevant online resources, published within a specific timeframe (the last 10 years) to ensure the inclusion of recent developments and discoveries in the field of sustainable agriculture.

3.3. Identification and Selection of Literature

A systematic approach will be followed to identify and select relevant literature. Multiple databases such as PubMed, Scopus, Web of Science, and Google Scholar will be used to search for articles using appropriate keywords and combinations (e.g., "aquaponics," "greenhouses," "sustainable agriculture," "integrated farming," "organic agriculture," "permaculture," etc.).

Inclusion and exclusion criteria will be established to filter and select the most relevant literature. These criteria may include content relevance to the research topic, source credibility and quality, and applicability in sustainable agriculture.

3.4. Data Extraction and Analysis

The selected literature will be examined and analysed in detail. Relevant information such as key concepts, definitions, theories, methodologies, and empirical findings will be extracted from each source.

The extracted data will be organized and categorized based on common themes, such as sustainable agricultural practices, integrated pest management, soil conservation, crop diversification, water management, agroforestry, use of renewable energy, and social aspects of sustainable agriculture.

A comparative analysis and synthesis of the literature will be conducted to identify patterns, trends, gaps, and areas of consensus or disagreement among different studies.

3.5. Evaluation of Methodological Approaches

The methodological approaches of the selected studies will be evaluated to assess the rigor and reliability of the research methods used.
The strengths and limitations of different methods, such as case studies, experiments, modeling approaches, and participatory research, will be considered to understand their implications for research in sustainable agriculture.

3.6. Synthesis and Discussion

The findings from the literature will be synthesized and organized to present a coherent and comprehensive overview of the integrated approach to sustainable agriculture.

Key themes, concepts, and practices resulting from the literature will be critically discussed, and their implications for sustainable agriculture, environmental conservation, and socio-economic factors will be explored.

Existing challenges, knowledge gaps, and future research directions will be identified to highlight areas that require further investigation and development in the field of sustainable agriculture.

3.7. Report Writing

The findings, analysis, and discussion will be compiled into a well-structured and coherent literature review report.

The report will include an introduction, methodology, findings of the literature review, analysis and discussion, conclusions, and recommendations for future research and practice.

3.8. Iterative Process

The literature review process will be iterative, allowing for continuous refinement and improvement based on feedback, ideas obtained during the analysis, and potential new directions discovered during the research.

4. ANALYSIS AND DISCUSSIONS

1. Technological Advances in Aquaponics 1. Internet of Things (IoT) Applications

IoT systems enhance monitoring and control through sensors and actuators, enabling real-time adjustments to water quality and system parameters.

- Example: IoT-based solutions for pH and dissolved oxygen monitoring.

2. Artificial Intelligence (AI) and Machine Learning

AI-powered tools predict nutrient levels, optimize feed rates, and identify system anomalies, reducing labor costs and improving efficiency.

3. Automation Systems

Automated control systems, integrated with predictive analytics and SCADA tools, streamline system management and improve resource utilization.

In [15] the authors emphasize the need for sustainable agricultural systems in the context of increasing global food demand. The authors highlight aquaponics as a method for increasing agricultural productivity using fewer resources by combining hydroponics and aquaculture. However, they draw attention to the fact that aquaponic systems require extensive automation, monitoring, and control. The authors suggest an Internet of Things (IoT)-based solution to this issue, using sensors and actuators to monitor environmental factors and water quality in aquaponic agriculture. They provide an innovative, interoperable, secure, scalable, selfpowered, and adaptable architecture that meets the needs of aquaponics [15]. Both articles [12] and [15] emphasize the crucial role of technology in contemporary agriculture. The first article focuses on creating embedded software and a control kit for soilless agriculture systems, while the second article suggests using the Internet of Things for monitoring and managing aquaponic systems. By addressing issues with traditional methods and promoting sustainable agricultural practices, both studies contribute to increasing the efficiency and productivity of agricultural practices.

Advanced management systems are crucial in aquaponics, according to [16] and [14]. The first article highlights the importance of proper design, monitoring, and corrective actions, focusing on the MES function in controlling and regulating integrated aquaponic production systems. Managing aquaponics with IoT technologies, predictive analysis, SCADA, ERP, and MES is examined in the second article. It presents a case study illustrating the advantages of IoT-based models and emphasizes how IoT and MES work together to maximize the potential and benefits of aquaponic systems [14, 16]. Authors in [17] and [18] contribute to the development of aquaponic systems. In [17], authors use an improved fuzzy neural network with a genetic method to forecast dissolved oxygen, a crucial component in aquaculture water. In [18] the authors discuss how to incorporate Industry 4.0 technology into aquaponic systems, presenting the AquaONT ontology model as a means of encoding and representing knowledge in these systems. These research efforts highlight the importance of efficient forecasting techniques and semantic interoperability for maintaining system stability and increasing production potential in aquaponics.

Technology and advanced control systems used in aquaponics are briefly described by the authors in [19], who also highlight the potential for future systems to become smarter, more intensive, precise, and efficient. In [19] the authors analyze the effectiveness of nanofiltration as a method for tertiary treatment, with a focus on treating wastewater for reuse in aquaponics. The paper highlights the advantages of establishing a hybrid nanofiltration-reverse osmosis system, as well as the removal of various pollutants. Together, these articles provide insight into the essential hardware, software, and wastewater treatment factors for creating and improving aquaponic systems.

The development of sustainable food production systems is supported by [21] and [22] focusing on aquaponic systems in northern latitudes, the first article provides suggestions for maximizing resource utilization and energy efficiency. It emphasizes the importance of greenhouse configurations and energy-saving techniques for maximizing water and nutrient usage. Integrating smart technology to maximize productivity per unit area is highlighted in the second article, which offers a broader perspective on agriculture techniques in controlled environments. The article discusses the use of precision agriculture technologies and the benefits of soilless agriculture. Both works underline the importance of efficiently managing resources and incorporating smart systems in contemporary agricultural operations.

The works [24] an [25] provide perspectives on several aspects of innovative agricultural methods. In [23] the authors explore different growth conditions compared to spinach cultivation in soil and floating hydroponics. The article [24] provides an overview of smart hydroponic systems and how they can address food production issues and [25] discuss the use of IoT technology in aquaculture, particularly for monitoring and managing water quality. Together, these articles contribute to the development of efficient and sustainable agricultural practices.

In [27] the authors focus on the use of PID controllers and fuzzy logic in a smart greenhouse, while in [26] the authors describe the creation of an adaptive algae disinfection system for closed water supply facilities. Both research efforts contribute to the evolution of efficient and sustainable techniques in their respective fields. The article [28] examines methods for automatic CO2 enrichment in greenhouses, highlighting the challenges and possibilities of maintaining ideal CO2 levels. The authors of [29] Part 1 provides an overview of the numerous tasks and strategies used throughout by presenting a taxonomy of functions in aquaculture production systems. These research efforts work together to create efficient and sustainable methods for agriculture and aquaculture.

In articles [30]-[32], the authors provide a systematic and detailed understanding of technological solutions and treatment functions involved in aquaculture production systems, which helps in creating an engineering design methodology for aquaculture. For the development, optimization, and management of sustainable and efficient aquaculture systems, researchers, engineers, and practitioners in the field can significantly benefit from the taxonomy provided in these articles. The three articles included in this synthesis are concerned with the creation and application of monitoring and control systems in agricultural and environmental settings.

The publications [33]-[35] emphasize the importance of advanced monitoring, management, and production technologies for improving water quality, environmental conditions, and agricultural output. The use of IoT technology, microcontrollers, and data analysis tools allows better crop growth, reduced energy consumption, and more efficient water management. These research efforts contribute to the creation of new and eco-friendly methods for monitoring the environment and agricultural production, aiming to increase productivity and resource efficiency.

The articles [36], [37] highlight the importance of intelligent systems, state-of-the-art control methods, and monitoring technologies in various agricultural and industrial contexts. Optimized production in controlled environments, improved monitoring of agricultural systems, and more efficient quality categorization are all made possible by combining data-driven techniques, artificial intelligence algorithms, and IoT technology. Ultimately, these studies enhance productivity, resource efficiency, and sustainability in these domains by promoting the creation of creative and long-lasting solutions for quality control, greenhouse agriculture, and controlled environment agriculture.

The authors off [38], [39] show how artificial intelligence approaches can be used to predict complicated phenomena. Liu's study demonstrates how fuzzy neural networks can be used to anticipate exports for international trade, considering a variety of parameters. Dullah et al.'s study demonstrates the use of NAR models for river flow prediction, along with the incorporation of exponential smoothing techniques to increase accuracy. These AI-based prediction techniques have applications in water resource management, economic planning, and decision-making. These research efforts enable more precise and informed predictions, using state-of-the-art computational tools, allowing better resource allocation and improved management tactics. The three studies included in this synthesis focus on different aspects of using cutting-edge methods in aquaculture, precision agriculture, and water reuse.

The publications [40] and [41] demonstrate how cutting-edge methods, including hybrid algorithms, machine learning, and novel systems, can be used in various aspects of agriculture and water management. The research aims to improve productivity, sustainability, and resource efficiency in aquaculture, precision agriculture, and water reuse. The different investigations contribute to the creation of more practical and successful procedures in various fields, through the use of AI-based algorithms, intelligent data analysis, and innovative methods.

In [42], authors provide a detailed analysis of how artificial intelligence (AI) has changed the way water treatment and desalination of saline water are performed. The study highlights how artificial neural networks (ANN), genetic algorithms, and other machine learning (ML) and deep learning approaches can be used to optimize intelligent water services. The review compares AI-based modeling approaches with traditional modeling techniques, examines challenges and deficiencies, and highlights the potential uses of AI in data processing, modeling, prediction, and decision-making in the desalination and water treatment industries.

The efficiency of a pilot-scale wastewater treatment system in a commercial aquaculture operation is the subject of a study [43]. Sedimentation, denitrification, ozonation, trickle filter treatment, and chemical flocculation are part of the treatment train. The study evaluates how well chemical and carbonaceous solids are removed during the treatment process. The results show that over 70% of particles are removed through sedimentation, while COD and total suspended solids (TSS) are also removed through ozonation and chemical flocculation. The study supports the recovery and reuse of effluent, demonstrating the efficiency of the treatment train in reducing contaminants in aquaculture wastewater.

According to [44], in Malaysia, vertical farming is becoming increasingly important due to the anticipated growth of the urban population and the need for food security. However, vertical farming systems face challenges regarding energy consumption. To evaluate the possibility of integrating green energy in urban agriculture, the research proposes a tool for modeling optimal building geometries, integrated with an energy yield estimation tool. The research analyzes the load requirement, designs solar photovoltaic systems for vertical farms, and evaluates the financial and environmental implications. The results demonstrate that integrating solar photovoltaic systems reduces the levelized cost of energy (LCOE), decreases CO2 emissions, and reduces dependence on the utility grid.

Overall, these studies demonstrate how artificial intelligence, state-of-the-art treatment methods, and the use of renewable energy can improve water treatment, desalination procedures, and sustainable agricultural operations.

The papers [45] and [46] provide insights into methods and innovations for increasing freshwater fish production, improving energy efficiency in agricultural greenhouses, and exploring the possibilities of offshore floating bioreactors for microalgae cultivation. These developments address issues related to energy consumption, environmental impact, and economic viability in these industries, promoting sustainable and efficient agricultural techniques.

Articles [47] and [48] emphasize the importance of state-of-the-art technology, automation, and optimization in water treatment, aquaponics, and integrated aquaculture-agriculture systems. They demonstrate how machine learning, artificial intelligence, and smart technology have the potential to enhance productivity, reduce water consumption, and increase environmental sustainability in various fields. However, to ensure successful implementation of these technologies, issues related to data management, explainability, reproducibility, and standardization need to be addressed. The three articles comprising the discussion in this synthesis focus on how aquaponic systems can utilize automation, computational thinking, and the Internet of Things (IoT). These innovations aim to increase productivity, sustainability, and monitoring capabilities in aquaponic projects. In their work, [48] the authors investigate how aquaponic projects can help undergraduate students develop computational and systemic thinking. Students used IoT to design and build an automated aquaponic system for real-time monitoring and control. Integrating aquaculture and hydroponic subsystems, hardware and software components, communication networks, and data collection and analysis allowed for high yields and high-quality fish and vegetable produce. The transdisciplinary and technological features of the aquaponic system provided students with both hands-on experience and theoretical understanding of computational and systemic thinking.

According to the study [49], an automated solar-powered aquaponics system can be used to sustainably produce food in arid environments, particularly in Oman. The system integrates multiple modules, including a cooling and heating system, an aquaponics management and monitoring system using an Arduino microcontroller, and a solar energy conversion system. Experimental data collected during summer and winter showed that the designed aquaponics system can be sustained, highlighting its economic viability and ecological sustainability.

The research [50] focuses on an IoT mobile application for monitoring an automated aquaponics system. The main components of the system are romaine lettuce and Nile tilapia, combining hydroponics and aquaculture. The pH and temperature of the system are continuously monitored and adjusted by the Intel Edison processor. The automated aquaponics system shows significantly higher growth compared to traditional fish farming and hydroponics methods, as evidenced by a study analyzing plant and fish development in these systems.

5. RESULTS

In this paper, the diversity of aquaponic system constructions was examined, conducting a detailed analysis of 50 published works. The main purpose was to highlight the results and methodology used in identifying and synthesizing these studies, thus providing a comprehensive perspective on the evolution of the aquaponics concept.

In the first part of the paper, various types of aquaponic system constructions were explored, emphasizing researchers' adaptations and innovations based on the specific requirements of different environments and contexts. The analysis underscored the diversity and complexity in the construction of aquaponic systems.

In the second part, emphasis was placed on the results of the 50 analyzed works, synthesizing the main findings and highlighting significant contributions to the field of aquaponics. The methodology used in identifying and analyzing these works was detailed, including the process of source selection and evaluation, emphasizing specific criteria that ensured a comprehensive and objective analysis.

Within the paper, an analysis of the advantages and disadvantages of the aquaponics concept was also addressed, highlighting the positive impact of these systems on environmental sustainability, resource efficiency, and food security. Challenges and limitations were also recognized, providing a balanced perspective on the subject.

The last aspect addressed, in addition to technological progress contributing to the development and facilitation of aquaponic systems, was the sustainability of these systems. Key innovations contributing to sustainability were highlighted, as well as aspects related to the efficiency of natural resource use, management, and system performance, emphasizing the crucial role of technology in advancing the aquaponics concept.

In conclusion, the paper provides a comprehensive analysis of aquaponic system constructions, the results from 50 identified works, the methodology used in their identification, the advantages and disadvantages of the concept, and the associated technological progress. Through this, it is hoped to contribute to the promotion of sustainable development in aquaponic systems.
This study analyzed 50 published works on aquaponics to synthesize key insights. Key findings include:

1. **Efficiency Gains**: Automation technologies significantly enhance system productivity and reduce manual intervention.
2. **Water Quality**: Maintaining optimal parameters (e.g., pH, ammonia, nitrates) is crucial for system health and productivity.
3. **Crop and Fish Selection**: Research highlights the importance of species compatibility to maximize yields and maintain ecological balance.

Challenges

- **Scalability**: Transitioning from small-scale to commercial systems requires significant investments and infrastructure.
- **Crop Diversity**: Limited plant species thrive in aquaponic environments, necessitating further research on nutrient requirements.
- **Knowledge Gaps**: Lack of standardized protocols hinders widespread adoption.

Future Directions

1. **Low-Cost Automation**: Developing affordable control systems for small-scale farmers.
2. **Broadening Species Research**: Investigating underutilized crops and fish species to expand system diversity.
3. **Policy Integration**: Encouraging government support through subsidies and publicprivate partnerships.

6. Implications of Aquaponics from a Sustainable Agriculture Perspective

Aquaponics, as an integrated and sustainable agricultural system, has significant implications for the future of agriculture and food production. The unique combination of fish farming and hydroponic crop production, coupled with nutrient-rich water recirculation, offers numerous benefits and potential contributions to sustainable agriculture. In this section, we will discuss the implications of aquaponics in terms of environmental sustainability, resource efficiency, food security, and economic viability.

Compared to conventional agriculture, aquaponics has a reduced ecological footprint. The naturalness of aquaponic systems minimizes water consumption as water is continuously recycled, leading to significant water savings compared to traditional soil-based farming. Additionally, aquaponics eliminates the need for synthetic fertilizers as fish waste serves as a natural and organic nutrient source for plant growth. This reduces the risks of pollution associated with fertilizer runoff, which can lead to water contamination and eutrophication. By minimizing water consumption and nutrient runoff, aquaponics contributes to the protection and conservation of valuable natural resources. Resource efficiency is another crucial implication of aquaponics. The integrated nature of the system allows for efficient use of resources such as water, nutrients, and space. Water in aquaponic systems is used in a closed-loop, significantly reducing water requirements compared to conventional agriculture. The circulation of nutrients within the system ensures efficient utilization by plants, minimizing waste and maximizing resource efficiency. Additionally, it can be implemented in diverse locations, including urban areas and areas with limited agricultural land, making efficient use of available space. This efficient use of resources contributes to a more sustainable and resilient food production system.

Aquaponics also has implications for food security. The ability to produce both fish and crops in a single integrated system provides a diversified and reliable source of food. Aquaponics can be practiced year-round, ensuring a consistent supply of fresh produce regardless of season or climate. This aspect is particularly relevant in regions where traditional agriculture faces challenges such as water scarcity, extreme weather events, or limited access to arable land. By implementing aquaponics, communities can increase their food self-sufficiency and reduce dependence on external food sources. It can be adapted to different scales, from small community systems to large commercial operations, contributing to local food production and reducing dependence on long-distance food transportation.

The economic viability of aquaponics is also a significant implication. Although initial setup costs may be higher than traditional farming methods, aquaponics can provide a sustainable and profitable long-term solution. The reduced need for external inputs, lower water consumption, and continuous production can lead to cost savings and increased profitability over time. Additionally, aquaponics can create economic opportunities and support local economies by providing fresh produce and fish for local markets and communities.

Overall, aquaponics presents a promising and innovative approach to sustainable agriculture, addressing challenges related to resource efficiency, food security, and environmental sustainability. Its integrated and circular nature holds the potential to revolutionize the way we produce food, making it a key player in the quest for a more sustainable and resilient food system for the future.

The economic viability is a crucial implication of aquaponics. Although the initial setup costs may be higher compared to traditional farming methods, aquaponics has the potential to be profitable in the long run. The integration of fish and crop production allows for multiple sources of income, as both fish and plant products can be sold. Additionally, it has the capacity to produce high-value crops and special fish species, which can command premium prices in the market. Moreover, by optimizing resource utilization and minimizing waste, aquaponics can improve overall production efficiency and reduce production costs. As the demand for sustainable and locally grown food increases, aquaponic systems present a viable business opportunity for farmers and entrepreneurs.

Another important implication of aquaponics is its potential for urban agriculture and revitalizing urban spaces. As urban populations continue to grow, the availability of agricultural land becomes limited. Aquaponics offers a solution by utilizing vertical spaces and rooftops, abandoned buildings, and other urban areas for food production. Transforming unused spaces into productive aquaponic systems allows urban communities to have access to fresh, locally grown food while enriching urban environments. This integration of food production into the urban landscape promotes a more sustainable and resilient urban ecosystem. Additionally, aquaponics aligns with the principles of circular economy and resource conservation. The closed-loop system of aquaponics emphasizes recycling and reusing resources. The principles of circular economy, such as waste reduction, resource conservation, and promoting regenerative practices, are inherently incorporated into aquaponics.

Aquaponics also has implications in education and community involvement. As a multidisciplinary field, aquaponics provides opportunities for hands-on learning and research. Educational institutions, from schools to universities, can integrate aquaponics into their curricula, allowing students to gain practical knowledge in areas such as biology, chemistry, engineering, and sustainable agriculture. Moreover, aquaponic systems can be used as educational tools to raise awareness about sustainable food production and environmental responsibility in communities. Through community gardens, workshops, and outreach programs, aquaponics can actively contribute to empowering and creating new roles in sustainable food production and living.

Another potential implication of aquaponics lies in its ability to mitigate the environmental impact of conventional agriculture. Traditional agricultural practices often involve the use of chemical fertilizers, pesticides, and herbicides, which can have detrimental effects on soil health, water quality, and biodiversity. Aquaponics eliminates the need for these inputs, reducing reliance on harmful chemicals and promoting ecological farming practices. By transitioning to aquaponic systems, farmers can contribute to conserving ecosystems and promoting biodiversity conservation.

7. Limitations of Aquaponics and Future Directions

Although aquaponics holds great promise for sustainable agriculture, it is essential to recognize its limitations and challenges. Understanding these limitations can guide future research and development efforts to overcome these obstacles and improve the efficiency and scalability of aquaponic systems.

One of the main limitations of aquaponics is the complexity of managing and maintaining the system. Achieving and maintaining the optimal balance of water quality parameters, such as temperature, pH, dissolved oxygen, and nutrient levels, can be challenging. Changes in fish density, introduced feed, and nutrient uptake by plants can influence these parameters, requiring constant monitoring and adjustments. The dynamic nature of aquaponic systems demands expertise and careful management to ensure the health and productivity of both fish and plants.

Another limitation of aquaponics is the limited range of plant species that can thrive in these systems. While many leafy greens and herbs perform well in aquaponics, certain crops with specific nutrient requirements may not be suitable for cultivation. Research efforts can be directed towards identifying and optimizing the cultivation of a broader range of crops in the aquaponic environment. This would improve the diversity of food produced and increase the economic viability of aquaponic operations.

Additionally, selecting the appropriate fish species for aquaponics is also an important consideration. Some fish species may have specific dietary requirements, growth rates, or environmental preferences that do not perfectly align with the conditions offered in aquaponic systems. Future research can focus on evaluating and improving the performance of different fish species in aquaponic environments. This would allow farmers to select fish species that fit well with the specific conditions of their aquaponic systems, maximizing both fish health and overall system productivity.

While aquaponics has proven successful in small-scale and research settings, scaling up to commercial production can be challenging. Factors such as operational costs, market demand, and infrastructure requirements need to be carefully considered. Future research can address the scalability of aquaponics by developing cost-effective designs, optimizing resource use, and improving system efficiency. Additionally, studies on the economic and commercial viability of aquaponics can provide valuable insights to support the growth of commercial aquaponic ventures.

Finally, the knowledge gap in specific aquaponic research and standardization is a limitation that needs to be addressed. While aquaponics has garnered attention, comprehensive research is still needed to address specific challenges and optimize system performance. Developing standardized protocols, guidelines, and best practices for system design, water quality management, and crop selection would benefit practitioners and ensure consistent and reliable outcomes. Collaborative efforts among researchers, industry professionals, and policymakers can contribute to filling these knowledge gaps and promoting long-term sustainability and widespread adoption of aquaponics.

8. CONCLUSIONS

In conclusion, aquaponics offers a unique and integrated approach to sustainable agriculture, combining fish farming with hydroponic crop production. The various types of aquaponic systems, developments in Romania, and extensive literature review provide a comprehensive overview of the field. Aquaponics has gained significant global interest due to its versatility, adaptability, and potential for sustainable food production. Ongoing research continues to improve our understanding of aquaponics, addressing critical aspects such as system design, water quality management, plant selection, and fish health. By integrating scientific knowledge with practical applications, aquaponics has the potential to revolutionize agriculture and contribute to a more sustainable and resilient food system.

Aquaponics has numerous implications for sustainable agriculture. Its environmentally friendly approach, efficient resource use, contribution to food security, and economic viability make it a promising and attractive alternative to conventional agricultural methods. As the global population continues to grow, and pressures on natural resources and agricultural systems rise, adopting innovative and sustainable practices like aquaponics becomes crucial for ensuring resilient and safe food supply for future generations. The implications of aquaponics for sustainable agriculture are significant and far-reaching. The environmental sustainability, resource efficiency, contribution to food security, and economic viability position aquaponics as a promising solution for the future of food production. By minimizing water consumption, reducing nutrient runoff, and efficiently using resources, aquaponics offers a more sustainable alternative to conventional agriculture. The integrated nature of aquaponic systems ensures a reliable and diversified food source, enhancing food security in different regions. Furthermore, aquaponics presents economic opportunities through the production of high-value crops and special fish species. Ongoing research and development in the field of aquaponics will further optimize system performance and expand their potential contribution to sustainable agriculture and food systems. The implications of aquaponics extend beyond the immediate benefits mentioned earlier and have the potential to address broader societal and environmental issues.

The implications of aquaponics for sustainable agriculture are vast and encompass a wide range of aspects. From environmental sustainability and resource efficiency to food security, economic viability, urban revitalization, circular economy principles, education, and community involvement, aquaponics offers a holistic approach to addressing the challenges of modern agriculture. As the demand for sustainable food production continues to grow, aquaponics represents a viable and promising solution that integrates fish and plant cultivation, minimizes resource use, and promotes resilient and self-sustaining food systems. With ongoing research, technological advancements, and the adoption of aquaponics on a larger scale, the positive implications for sustainable agriculture will continue to expand and contribute to a more sustainable and secure future.

While aquaponics offers numerous advantages for sustainable agriculture, it is important to acknowledge its limitations. Challenges related to system management, crop and fish selection, scalability, and standardization require further research and innovation. Addressing these limitations will contribute to the continued development and advancement of aquaponics, making it a more accessible, efficient, and viable method of food production for the future. By focusing on these aspects, aquaponics can accomplish its potential as a sustainable and productive method of food production for the future.

Aquaponics offers a sustainable alternative to conventional agriculture by integrating fish farming with hydroponic plant cultivation. Advancements in IoT, AI, and automation have propelled the field forward, enabling greater efficiency and sustainability. However, addressing challenges like scalability, species selection, and standardization is essential for widespread adoption. Continued research and innovation will position aquaponics as a cornerstone of sustainable agriculture.

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