Black Sea Journal of Agriculture
doi: 10.47115/bsagriculture.1656377

Open Access Journal
e-ISSN: 2618 – 6578

Research Article
Volume 8 - Issue 4 : 533-547 / July 2025

TECHNOLOGICAL TRANSFORMATION AND SUSTAINABLE AGRICULTURE: AUTOMATION SUPPORTED HOME-TYPE HYDROPONIC PRODUCTION SYSTEM APPLICATION

Muhammed Akif YENİKAYA[1*], Onur OKTAYSOY[1], Gökhan KERSE[1]

[1]*Kafkas University, Faculty of Economics and Administrative Sciences, 36100 Kars, Türkiye*

Abstract: Hydroponic farming systems, which offer sustainable solutions to the global water and food crisis, provide less water consumption and higher productivity compared to traditional farming methods. This study examines the contribution of automation-supported home-type hydroponic production systems to agricultural sustainability. The main purpose of the study is to compare automated and non-automated hydroponic systems in terms of plant growth rates, productivity and environmental effects and to reveal the advantages provided by automation. In the experimental application conducted within the scope of the research, the development of lettuce plants was observed for four weeks and the productivity differences of the two systems were analyzed. The results show that automation-supported systems provide more balanced growth compared to manually controlled systems, optimize nutrient and water use and accelerate the growth process of the plants. In addition, these systems reduce the margin of error in agricultural processes by minimizing human intervention. In the study, it was determined that hydroponic systems make significant contributions to environmental sustainability with low water consumption and enable local food production by encouraging urban agriculture. This research contributes to both academic literature and sectoral applications, revealing that automated hydroponic systems can be an effective alternative in food production. The findings highlight the importance of disseminating innovative practices for sustainable agriculture that save water and energy. The study is expected to form the basis for future research on hydroponic farming systems.

Keywords: Digital transformation, Sustainability, Hydroponic agriculture, Home agriculture, Automation supported hydroponic system

***Corresponding author:** Kafkas University, Faculty of Economics and Administrative Sciences, 36100 Kars, Türkiye
E mail: m.akifykaya@gmail.com (M. A. YENİKAYA)
Muhammed Akif YENİKAYA https://orcid.org/0000-0002-3624-722X
Onur OKTAYSOY https://orcid.org/0000-0002-8623-614X
Gökhan KERSE https://orcid.org/0000-0002-1565-9110

Received: March 12, 2025
Accepted: July 10, 2025
Published: July 15, 2025

Cite as: Yenikaya MA, Oktaysoy O, Kerse G. 2025. Technological transformation and sustainable agriculture: Automation supported home-type hydroponic production system application. BSJ Agri, 8(4): 533-547.

1. Introduction

The continuous increase in the world's population brings with it the inadequacy of limited natural resources, making water and food resources an increasing problem. The global water and food crisis is considered one of the most important and urgent problems of the contemporary world (Kheirinejad et al., 2021). This crisis is not only a matter of meeting basic human needs, but also a multidimensional problem that threatens the preservation of ecological balance and sustainable development.

Water is not only one of the basic elements of life but also plays a critical role in food production. However, the global depletion of water resources and pollution due to various factors threaten the sustainable use of this vital resource. In particular, climate change, rapidly growing population and inefficient use of water are among the main factors deepening the water crisis. Today, water scarcity has become a serious problem in many parts of the world, which has negatively affected and continues to affect both human life and ecosystems. Similarly, food production is significantly affected by water scarcity and other environmental factors. Agricultural activities face problems such as diminishing water resources, soil erosion and loss of productivity. Traditional farming methods, inefficient use of water and soil degradation disrupt food production and increase the risk to food security on a global scale. In addition, the impacts of climate change threaten to reduce agricultural productivity and adversely affect production processes, which could lead to greater crises in access to food in the future (Fedulova et al., 2023).

Urgent and comprehensive measures are needed to mitigate the impact of the global water and food crisis and ensure a sustainable solution in the long term. As a priority, it is of utmost importance to increase productivity in agricultural production, promote sustainable agricultural practices and effectively manage water resources. In this regard, it is important to strengthen policies to combat climate change, take measures to increase water and energy efficiency, and implement strategies to conserve natural resources.

Among the alternative solutions that can be developed against the water and food crisis, hydroponic agriculture stands out (Paige and Gell, 2023). Hydroponic systems, also known as soilless agriculture, require much less water use compared to traditional agricultural methods and allow for high productivity production in limited areas. This method is considered as an effective option to ensure the continuity of agricultural production, especially in regions where water resources are scarce (Kumar et al., 2023).

When statistical data from different sources are analyzed, the importance of hydroponic systems becomes even more evident. Indeed, conventional agricultural practices are the largest consumer of freshwater resources on a global scale, accounting for approximately 70% of total freshwater use (Velasco-Muñoz et al., 2018). This rate, which is quite high compared to the approximate rates of industrial (20%) and domestic use (10%), causes rapid depletion of water resources and becomes an important cause of the global water crisis (Huang et al., 2019). This situation reveals that traditional agricultural practices are not sustainable and have turned into a problem that requires measures to be taken.

Based on this point, in this study, the use of automation in hydroponic systems was discussed and an experimental application was made in this context. However, in the experimental study, the questions of whether production can be done in a home environment and by imitating daylight, and ultimately whether it will contribute to sustainability in this context have been partially answered. In addition, the study also shows the differences in production and productivity in a situation where technology is used intensively (with automation) compared to a less used situation (without automation). At these points, it is thought that it will contribute to both academic studies and individuals and businesses in the relevant sector.

2. Conceptual Framework

2.1. Agricultural Production

Agriculture is a critical sector that meets the basic nutritional needs of humanity, supports economic development and affects the sustainability of ecosystems. Considering global dynamics such as food security needs, population growth and climate change, it is of strategic importance to support agricultural production processes with efficient, sustainable and innovative methods (Jayachandran et al., 2022). In addition, the agricultural sector is the livelihood of millions of people around the world and is one of the main dynamics of rural development and economic growth. According to the Food and Agriculture Organization of the United Nations (FAO), the agricultural sector accounts for about 27% of total employment worldwide (FAO, 2023).

Agriculture, which is considered one of the oldest occupations of humanity in terms of employment, has evolved with different techniques and methods throughout history and is now practiced with various production models. Agricultural production techniques are divided into various categories depending on the technology and application methods used. Some of these can be defined as follows:

Traditional Agriculture: It is a form of production that is generally adopted by small-scale producers and involves agricultural practices that have been in place for many years. This method mostly has a low level of mechanization and includes sowing and planting activities based on the natural environment. Although traditional agriculture is a method that is based on local knowledge and experience, has low productivity, and does not meet the expectations of the day, it is the most common agricultural production model today due to reasons such as lack of financial resources and difficulty in accessing technical knowledge (Altieri and Nicholls, 2017).

Modern Agriculture: It is a production model that emerged with the integration of technological developments and mechanization into agricultural production. It aims to increase productivity through mechanical tools such as tractors, harvesters, agricultural machinery, as well as inputs such as chemical fertilizers, pesticides and modern irrigation systems. This method, which is generally preferred by large-scale producers and used in high-capacity agricultural operations, exhibits a structure focused on high productivity, low cost and quality (Ayeni and Olagoke-Komolafe, 2024).

Smart Agriculture: This model has emerged with the integration of digital technologies and data analytics-based applications, which are the main components of the Industry 4.0 approach, into agricultural processes. In this production model, systems such as GPS, sensors, drone technology and artificial intelligence are used to apply agricultural inputs such as water, fertilizers and pesticides more efficiently and sustainably (Sahoo, 2021). Smart agriculture offers producers a more effective management opportunity, especially through decision support systems to optimize resource use. This model, which attracts attention with its high efficiency outputs despite low resource use, is rapidly spreading (Pinto et al., 2024).

Greenhouse Agriculture: One of the most important limiting factors of agricultural production is environmental conditions. Weather conditions such as extreme heat, extreme cold, drought and heavy rainfall can have negative impacts on agricultural activities. Greenhouse agriculture is a production method that provides the opportunity to grow plants in a controlled environment in order to minimize these negativities. By optimizing plant growth, this system allows for off-season production and increases agricultural productivity (Farooq et al., 2022; Soussi et al., 2022).

Hydroponic Agriculture: Hydroponic farming is an agricultural method based on growing plants in nutrient-rich water solutions, as opposed to traditional soil-based cultivation (Bunyuth and Mardy, 2024). This production model, which is realized without the need for soil, allows plants to grow faster and obtain higher yields by allowing them to receive nutrients directly from the liquid environment. While hydroponic systems significantly reduce water consumption by recycling water, they also allow production under controlled conditions (Kumar et al., 2023).

The focus of this study is the hydroponic agricultural production model. In this context, the hydroponic production approach will be discussed in more detail.

2.2. Hydroponic Agricultural Production

In today's world, problems such as rapidly increasing population, visible climate change and decreasing agricultural areas have made it imperative to develop highly efficient and innovative methods to respond to these conditions in food production (Reddy et al., 2023). However, concerns about the sustainability of traditional agricultural methods have increased the need for new technologies in the agricultural sector and alternative agricultural systems have become increasingly important (Gakhar, 2021). At this point, hydroponic agriculture stands out as an innovative agricultural technique with high productivity that allows plants to be grown in nutrient solution without using soil (Resh, 2022).

Hydroponic agriculture is based on the principle of providing the nutrients and flora structure that plants need to grow directly dissolved in water (Srivani and Manjula, 2019). In this system, production is carried out by positioning the plant roots in water or using different devices in contact with the nutrient solution. In this way, problems such as nutrient deficiencies / incompatibilities, harmful organisms and diseases that may occur in the soil are prevented, while water and nutrients are used more efficiently (Shareef et al., 2024).

The advantages of hydroponic agriculture compared to conventional agriculture include water saving, higher productivity, year-round production, suitability for storey production and less need for pesticides, which are vital for agricultural production (Palande et al., 2018).

Hydroponic systems are divided into different categories depending on the methods and technologies used. Nutrient Film Technique (NFT), Deep Water Culture (DWC), Wick System, Drip System and Aeroponic System are some of these categories (Kumar et al., 2021). In the NFT system, the nutrients needed by the plant are delivered to the roots by continuously flowing the nutrient solution as a thin film through the root zone (Mohammed and Sookoo, 2016). In the DWC method, the roots of plants are grown by directly immersing them in an oxygenated nutrient solution (Nursyahid et al., 2021). In aeroponic systems, the plant roots are completely suspended, and the nutrient solution is supplied by spraying directly onto the roots through misting (Kumari and Kumar, 2019). In a drip system, the nutrient solution is dripped onto the roots at regular intervals in a controlled nutrient supply process (Waller et al., 2016). Each of these methods offers different advantages depending on the type of plant to be grown, environmental conditions and scale of production.

One of the most important advantages of hydroponic agriculture is the significant water savings in terms of agricultural water consumption (which accounts for 70% of potable water resources) (Velasco-Muñoz et al., 2018). Compared to conventional agriculture, water use can be reduced by up to 90% in hydroponic systems (Mielcarek et al., 2024). This is because water is continuously circulated and reused in closed-loop systems and losses due to evaporation are minimized. This makes hydroponic farming a strategic food production method, especially in regions where water resources are scarce (Gruda, 2019). In addition, production without the risk of soil erosion is considered an important advantage in terms of agricultural sustainability (Nalwade and Mote, 2017). In addition, compared to conventional agriculture, more crops can be grown per unit area in hydroponic systems and the growth period of crops can be shortened due to condition optimization and high productivity can be achieved (Resh, 2022). As a matter of fact, the fact that hydroponic systems require less space offers a significant advantage especially in urban agriculture applications and mediates the expansion of agriculture by being applied in idle areas within the city (Shareef et al., 2024). Another important advantage is that this production model reduces the use of pesticides, which have very negative effects on human health. While soil-borne diseases and pests are common in conventional agriculture, such risks are minimized in hydroponic systems (Nalwade and Mote, 2017). As a result, the need for pesticides and chemical fertilizers is reduced, minimizing environmental impacts and providing healthier products to consumers (Gruda, 2019). At the same time, hydroponic agriculture can be sustained regardless of climatic conditions, allowing uninterrupted production throughout the year (Srivani and Manjula, 2019).

Despite the advantages of hydroponic farming, the system also has some challenges. Initial costs are high, and technology requirements are higher than in conventional agriculture (Resh, 2022). Especially technical details such as continuous monitoring of water chemistry, maintaining nutrient balance and controlling oxygen levels are important for the successful operation of hydroponic systems (Kumar et al., 2021). Furthermore, technical problems such as power outages and pump failures can cause damage to plants (Amalfitano et al., 2017). In order to minimize such problems, automation systems and smart sensors are used to make hydroponic farming processes more reliable (Palande et al., 2018).

Considering these qualities, hydroponic agriculture offers a more sustainable, efficient and resource-saving production method compared to conventional agriculture (Reddy et al., 2023). Especially considering the increasing population and decreasing agricultural areas, it is predicted that most, if not all, of the food production in the future will be realized through hydroponic systems (Resh, 2022). However, for the system to become widespread, costs need to be reduced, technical infrastructure needs to be strengthened, and education and transformation policies need to be developed to encourage farmers to adapt to this technology (Shareef et al., 2024). Hydroponic agriculture is considered not only as an alternative production method but also as a revolutionary approach that shapes the future of agriculture (Gakhar, 2021).

2.3. Automation Supported Hydroponic System

Hydroponic systems enable more efficient and controlled production compared to traditional agriculture. However, precise water, nutrient and light management is required to ensure that these systems operate at optimum levels (Reza et al., 2025). Manual management of these variables in traditional hydroponic systems is both open to human error and costly in terms of time (Putra et al., 2024). In this context, the integration of automation techniques is considered an important step for hydroponic systems to become more efficient, sustainable and scalable (Maldonado et al., 2019).

Automation in hydroponic systems generally involves monitoring and regulating the pH level of the nutrient solution, water temperature, oxygen content, electrical conductivity (EC) and water level, and monitoring ambient humidity and temperature values with the help of microcontrollers, sensors and actuators (Kuncoro et al., 2021). Thanks to smart automation systems, these parameters can be continuously controlled to provide optimum growth conditions and enable plants to develop faster and healthier (Aliac and Maravillas, 2018). Another important advantage of automation integration in hydroponic systems is the reduction of the need for human intervention and the minimization of error margin in agricultural production. In these models, the data obtained through sensors can be processed into cloud-based systems via a microcontroller to monitor the necessary irrigation, fertilization and acidity, and environmental conditions can be adjusted instantly (Siregar et al., 2016). In this way, more efficient production can be achieved by preventing water and nutrient waste, while a significant decrease in production costs can be achieved (Maldonado et al., 2019). Automated integrated hydroponic systems can be moved to a more advanced level in technical and technological terms with the integration of internet of things (IoT) technologies. Thus, producers can manage the production process through remote monitoring and control systems regardless of location (Nwulu et al., 2021). Especially in large-scale production facilities, such intelligent automation systems have the potential to significantly increase production efficiency while reducing labor requirements (Jain and Kaur, 2024).

Although it is a relatively new approach, automation integration in hydroponic systems has been addressed by various researchers in literature, and some experimental application studies have been carried out in addition to theoretical approaches. At this point, a study by Kuncoro et al. (2021) showed that an automation system that monitors and optimizes parameters such as pH level, electrical conductivity (EC), water level, and temperature increases plant size and yield. Similarly, Aliac and Maravillas (2018) revealed that IoT-based hydroponic management systems increase agricultural productivity by improving remote monitoring and decision-making mechanisms. In a different study by Mahajan et al. (2022), it was revealed that systems equipped with microcontrollers ensure optimal nutrient uptake by plants and significantly increase water savings. A study by Maldonado et al. (2019) has shown that automated nutrient regulation systems improve product quality and make large-scale hydroponic farming operations much easier to manage and much more efficient. Again, a system developed by Nwulu et al. (2021) integrated hydroponic systems with a mobile application, allowing farmers to access instant data and change system settings remotely. The study suggests that this system prevents many negative scenarios experienced in the production process and, although initially opposed due to complexity, was quickly adopted by farmers. Finally, another study by Jain and Kaur (2024) has shown that hydroponic systems using automation lead to higher productivity and product quality than systems that do not use automation. In addition, it is stated in the study that the economic return caused by the increase in quality and productivity has the potential to amortize the investment made for the installation of automation systems in a short time.

Studies in the literature reveal that automation integration in hydroponic systems increases agricultural productivity and significantly improves water and energy savings. In this context, in order to contribute to the existing literature, a model integrated with automation systems and suitable for home use was designed and a prototype was produced in this study. A practical study was conducted to test the functionality of the model, and the findings were analyzed.

The main objective of the study is to demonstrate the advantages of automation-assisted hydroponic systems compared to conventional hydroponic systems and to show that this model with minimal structure design can be used not only in agricultural production areas but also in home environments.

3. Materials and Methods

The system developed in this study is divided into 3 phases: monitoring, automation and IoT application. At the center of the model used to implement the system is the WEMOS D1 R32 microprocessor with integrated Wi-Fi and Bluetooth modules that can effectively interface with the necessary sensors and hardware (Figure 1).

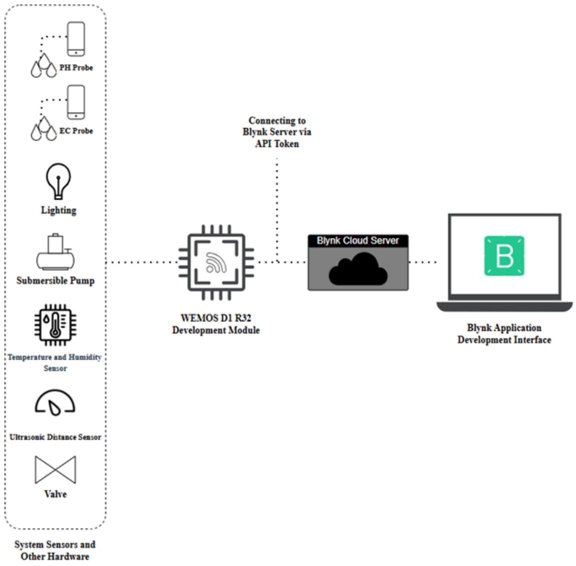

Figure 1. System design overview.

The system design overview presented in Figure 1 shows an IoT-based structure that collects data from various sensors and hardware and enables processing and remote control of this data. Key components of the system include pH and EC measurement sensors, temperature and humidity sensors, ultrasonic distance sensor, submersible pump, valve and lighting, which are integrated into the WEMOS D1 R32 development module. The WEMOS D1 R32 transmits the collected data via an API token to the Blynk cloud server, which stores the data and makes it available to the user. The system can be monitored and controlled through the Blynk application development interface. This structure is used as an effective method for real-time monitoring and control of environmental parameters.

Monitoring: Since plants are sensitive to the smallest changes in their environment, it is essential to monitor the factors affecting them. Regular monitoring of ambient temperature and humidity, pH and EC (Electrical Conductivity) levels in the tank, as well as the level of liquid in the tank is vital.

Automation: Growing crops manually using hydroponics is a challenging process, so a certain level of automation is recommended. Based on the knowledge that plants perform respiration and photosynthesis during the day and only respiration at night, the LED grow lights can be adjusted to mimic the sunrise and sunset times. Similarly, pH and EC values and water level can be adjusted through automation according to the needs of the plant species.

IoT Application: Once the design is achieved, a tool is needed to remotely control, monitor and also automate the system. For this purpose, Blynk, a widely used platform for IoT projects, was preferred.

3.1. Prototype Design

A 3-tier hydroponic system, shown in Figure 2, which allows 48 seedlings to be grown simultaneously, was chosen as the prototype model. This system is designed to achieve high productivity in limited spaces and has a PVC pipe system that allows the circulation of water and nutrient solution in each layer to support the growth of the plants. The water tank at the bottom allows the nutrient solution to be stored. This solution is transported to the upper layers by means of a submersible pump located in the tank. In addition, LED plant growth lamps on each layer support photosynthesis of plants by mimicking the sunlight spectrum.

The system has a modular framework and stands out with its portability and lightness. The system has an infrastructure that can be easily integrated with IoT-based automation devices to monitor and control parameters such as pH, EC, temperature, humidity, water level. With these features, the model is both an ideal prototype for suitability testing for commercial use and an innovative example of vertical agriculture technologies.

Figure 2. Hydroponic system prototype.

3.2. Hardware Design

According to the hydroponic system block diagram given in Figure 3, the two main components of the system are monitoring and automation. The monitoring component provides real-time monitoring of parameters such as temperature and humidity values, pH level, EC value and tank liquid level. This data is processed by the Wemos D1 R32 (ESP32) microcontroller and transmitted to the user via the Blynk server.

On the automation side, the system works with a pH-lowering peristaltic pump, peristaltic pumps that adjust nutrient values and relays that control LED lights. These components are automatically controlled based on data from monitoring sensors. In addition, a power supply unit is used for uninterrupted operation of the system. This integrated structure is designed to provide both efficient monitoring and effective automation.

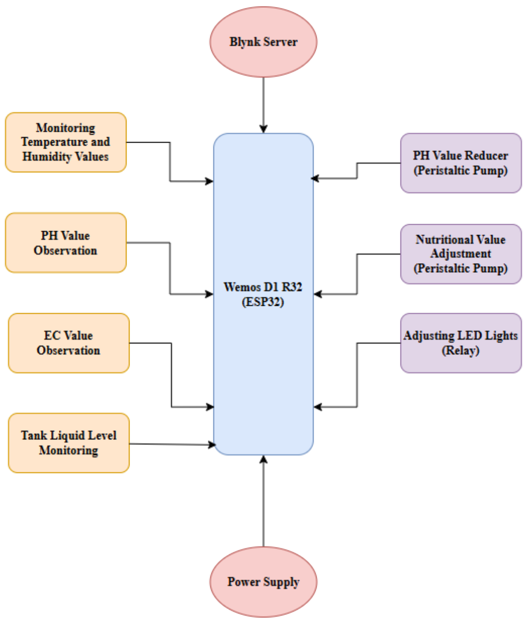

Figure 3. Hydroponic system block diagram.

3.2.1. Wemos D1 R32 (ESP32)

The Wemos D1 R32 microcontroller is an open-source platform for IoT applications. The Wemos D1 R32, which is used as the center of our system, is a high-performance microcontroller. With a typical operating voltage of 3.3V, this device consumes approximately 240mA current during data transmission and 20mA current during reception. The device has a dual-core processor and can operate at a CPU clock frequency of up to 240 MHz. The Wemos D1 R32 is also equipped with Wi-Fi and Bluetooth capabilities and supports data transmission speeds up to 150 Mbps (Espressif Systems, 2023).

The Wemos D1 R32 microcontroller shown in Figure 4 was chosen because it has enough GPIO pins (digital and analog) to connect all the sensors used in our system, offers high processing power, and is equipped with Wi-Fi and Bluetooth features. These features enable the system to effectively meet monitoring and automation requirements.

Figure 4. Wemos D1 R32.

3.2.2. Ambient Temperature and Humidity Monitoring

In hydroponic systems, temperature and humidity are critical environmental parameters that directly affect plant growth and development. Temperature plays a decisive role in seed germination, root development and overall growth rate by affecting plant metabolism and photosynthesis processes. Low temperatures can pose a risk of frostbite, while high temperatures can cause adverse effects on plants such as leaf burn, excessive moisture loss and water stress. Similarly, humidity levels play a vital role in plant water balance and transpiration processes. Maintaining optimal moisture levels supports plant water uptake, reduces disease risk and improves plant health. Therefore, continuous monitoring of temperature and humidity in hydroponic systems and keeping them within ideal ranges is important for maximum productivity and sustainable production (Resh, 2022).

In the system developed for the above reasons, the DHT21 sensor shown in Figure 5 was used for temperature and humidity measurements. This sensor stands out compared to other temperature and humidity sensors with its high accuracy and wide measurement range. DHT21 provides reliable measurements with ±0.3°C temperature accuracy and ±2% humidity accuracy, enabling monitoring of ideal environmental conditions for plant growth. The sensor has a temperature measurement range of -40°C to 80°C and a humidity measurement range of 0% to 100% (Aosong Electronics, 2023).

Figure 5. DHT21.

The sensor's fast response time and stable performance make it possible to continuously and precisely monitor environmental parameters, making it a preferred choice for use in the developed system.

3.2.3. Monitoring Potential Hydrogen (PH) Value

The Potential Hydrogen (pH) value, which expresses the acidic or basic (alkaline) properties of a solution, is evaluated on a scale of 1 to 14. A value of 7 is considered neutral, a value below 7 is considered acidic, and a value above 7 is considered basic. It is known that each plant requires different pH levels in line with its unique growth requirements. For example, some plants thrive in an acidic environment, while others perform better in a neutral or basic environment. Table 1 shows the pH ranges that some plants need to grow. These pH values are critical for the healthy development of plants and maximum yield.

Table 1. Sample pH values

Plant Type	Ph
Banana	5,5 - 6,5
Melon	5,5 - 6,5
Strawberry	6,0
Bean	6,0
Potatoes	5,0 - 6,0
Tomatoes	6,0 - 6,5
Onion	6,0 - 6,7
Carrot	6,3
Lettuce	6,0 - 7,0
Corn	6,0
Mint	5,5 - 6,0

Source: Heaney (2017).

In the developed system, the Atlas Scientific pH module, visualized in Figure 6, was used to monitor the pH level of the liquid in the tank. The Atlas Scientific pH module is designed to meet these requirements by providing high-accuracy measurements. The module receives the 59 mV signal produced by the pH probe for each pH unit and converts this low-voltage signal into digital data that the microcontroller can process with the help of an internal amplifier (Atlas Scientific, 2024a). Thanks to these features, accurate monitoring of pH levels has been achieved in developed system.

Figure 6. Atlas Scientific pH module.

3.2.4. Monitoring Electrical Conductivity (EC) Value

In hydroponic systems, Electrical Conductivity (EC) is a vital parameter in determining the nutrient balance required for healthy growth and efficient development of plants by measuring the ion concentration in the nutrient solution. Keeping EC levels in the correct range optimizes plant growth (Savvas and Gruda, 2018). Table 2 presents the recommended EC (Electrical Conductivity) ranges for sample plants grown in hydroponic systems. The values indicated are intended to determine the optimal level of ionic solution in line with the needs specific to the plant species.

Table 2. Sample pH values

Plant Type	EC
Banana	1,8 - 2,2
Melon	2,0 - 2,5
Strawberry	1,8 - 2,2
Bean	2,0 – 4,0
Potatoes	2,0 - 2,5
Tomatoes	2,0 - 5,0
Onion	1,4 - 1,8
Carrot	1,6 - 2,0
Lettuce	0,8 - 1,2
Corn	1,6 - 2,4
Mint	2,0 - 2,4

Source: Heaney (2017).

Low EC levels can lead to nutrient deficiencies, while high EC levels can cause root burns and other growth problems. Providing appropriate EC ranges plays a critical role in supporting plant growth and achieving maximum efficiency.

In the developed system, the Atlas Scientific EZO-EC Module, visualized in Figure 7, was used to precisely monitor the EC value of hydroponic solutions. The Atlas Scientific EZO-EC Module can meet the requirements of different plant species by offering a wide measurement range from 0.07 µS/cm to 500,000 µS/cm. It increases measurement precision thanks to its ±2% accuracy rate and automatic temperature compensation feature. The module can operate between 3.3V and 5V with low power consumption and supports high impedance inputs. These features enable its integrated operation with the microcontroller and real-time data processing capacity (Atlas Scientific, 2024b).

Figure 7. Atlas Scientific EC module.

3.2.5. Led Grow Light

In the developed system, an LED grow lamp was used to optimize the growth processes of plants. These LEDs support photosynthesis and plant development. The system ensures that the LEDs operate in automatic mode between morning and evening hours (in order to mimic daylight), and outside of this period, the LEDs are turned off to save energy. The LEDs used play an important role in improving the necessary growth conditions for the plants to be grown in the system with their energy efficiency, long life and appropriate wavelength emission features.

3.2.6. Tank Liquid Level Monitoring

Monitoring the tank liquid level in hydroponic systems is of critical importance in terms of continuously providing the water and nutrient solution that plants need. In the developed system, the HC-SR04 ultrasonic sensor, visualized in Figure 8, was used to measure the tank liquid level.

Figure 8. HC-SR04.

The HC-SR04 ultrasonic sensor is a low-cost and highly accurate distance measurement device. It offers an effective solution in applications such as monitoring tank liquid levels using ultrasonic sound waves in distance measurement. This sensor has the capacity to measure between 2 cm and 400 cm and operates with an accuracy rate of ±3 mm. HC-SR04 emits sound waves with its Trig pin and calculates the distance by detecting the returning wave with its Echo pin. Thanks to these features, continuous and precise monitoring of tank liquid levels in hydroponic systems is provided (RoboticsBD, 2023).

Figure 9 shows a flow diagram created to provide automatic control of environmental conditions of the developed hydroponic system.

The system is established with the aim of continuously monitoring and managing parameters such as temperature, humidity, tank liquid level, pH and Electrical Conductivity (EC). The process starts with starting the system and checking the Wi-Fi connection. When the Wi-Fi connection is established, the system updates the data via the Blynk platform and the values such as temperature, humidity, pH, EC and liquid level received from the sensors are read. This data is transmitted to the Blynk application for remote access by the user. If the pH level is above the specified threshold value, the pH pump is activated, and the level is reduced. EC values are evaluated according to whether they are in the optimal range. If the values are outside the desired range, the A and B nutrient pumps are operated together to adjust the nutrient density in the solution. If the tank liquid level falls below the threshold value, the tank valve is opened, and the liquid level is increased by adding water. Light management is carried out automatically depending on the time of day. While the LED growth lamps are activated during the day, these lamps are turned off in the evening to save energy. The reason for this is that the unit under study is intended for home use, and therefore, it is suitable for plant growth in environments without daylight. All these processes are carried out by continuously analyzing the data obtained from the sensors and automatically operating the system components based on this data. In this way, the efficiency of the system is increased, and manual intervention is minimized.

3.3. Software Design

The system software is developed on the Arduino IDE platform, which is widely used in IoT projects thanks to its user-friendly interface and extensive library support. Arduino IDE is an open-source development environment and provides easy integration with various microcontroller boards. Arduino IDE is based on C and C++ programming languages in the software development process. Arduino offers users a simplified version of these languages and provides a comprehensive set of libraries for developing microcontroller-based projects.

Additional libraries such as the Blynk library were included in the development process of the system software. These libraries facilitated communication with IoT-based devices and fulfilled basic functions such as processing sensor data and controlling devices. The software enables monitoring environmental parameters, making real-time decisions on these parameters and managing automation processes. In addition, features such as Wi-Fi connection and integration with the Blynk server were effectively implemented thanks to the flexible programming infrastructure of the Arduino IDE.

The system was loaded onto its microcontroller via a code written in the Arduino IDE and configured to be used in the automation of the hydroponic system. The software has a cyclical working principle to enable sensor data to be read, analyzed and devices to be controlled.

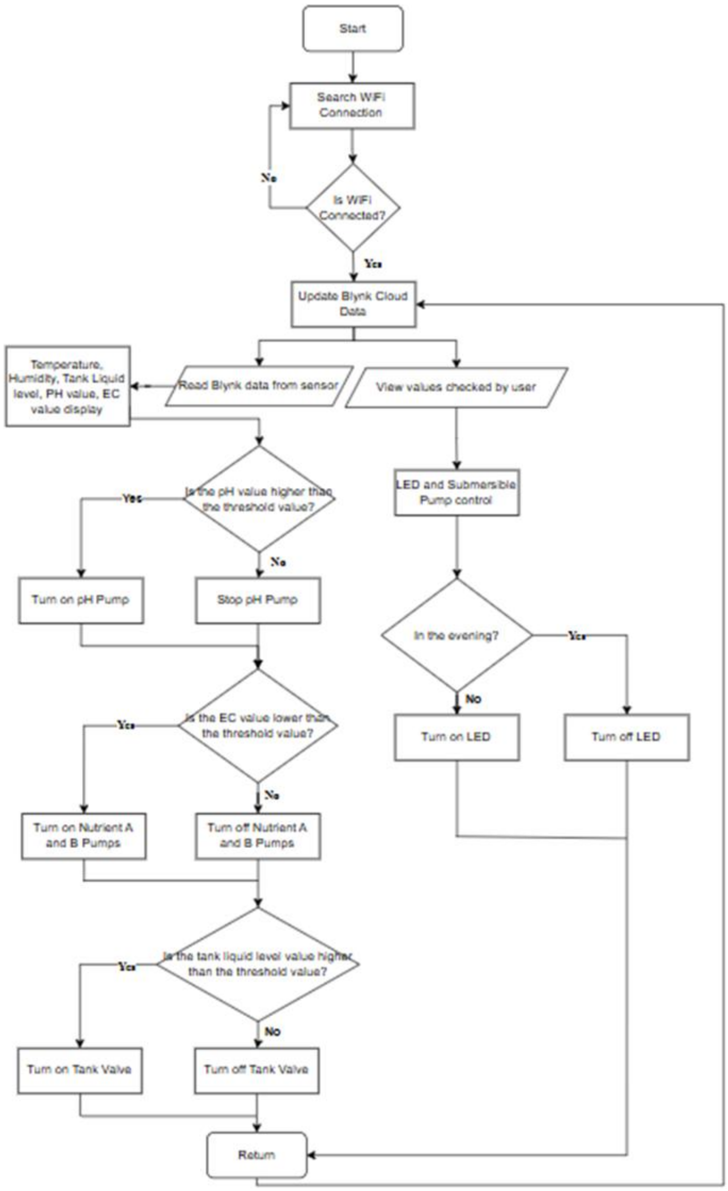

Figure 9. System design flow diagram.

3.4. Integration of System with IoT Application Platform

In the developed system, the Blynk application was used to monitor and control hydroponic environmental parameters (temperature, humidity, pH, EC, tank liquid level). The system transfers the data received from the sensors to the Blynk application, allowing users to observe this data remotely in real time. At the same time, the operation of system components such as pH and nutrient pump control and tank liquid level control can be easily managed via the Blynk application.

Blynk is a user-friendly platform that provides features such as remote monitoring, control and data visualization in IoT projects. This platform, which works through mobile devices and cloud-based services, enables easy management of IoT devices. Blynk stands out as an ideal tool especially for real-time monitoring of sensor data and remote control of hardware components. The platform is compatible with microcontrollers such as Arduino, ESP32, NodeMCU and allows users to create a customized interface. The interface of the developed system was developed on the Blynk platform to visualize the relevant data and provide user interaction and is given in Figure 10.

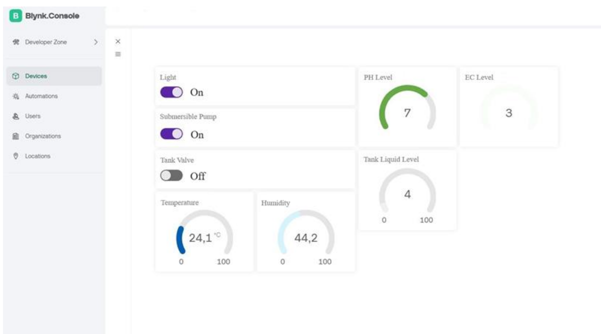

Figure 10. System interface.

The use of Blynk tokens plays a critical role in integrating the hardware used in the cloud-based Blynk platform. Blynk tokens are unique authentication codes required to establish a secure connection between hardware (e.g. microcontrollers such as NodeMCU or ESP32) and the Blynk server. This token (Figure 11), which is produced specifically for the system developed via Blynk, is defined on the microcontroller via the Arduino IDE, allowing the system to communicate with the cloud server.

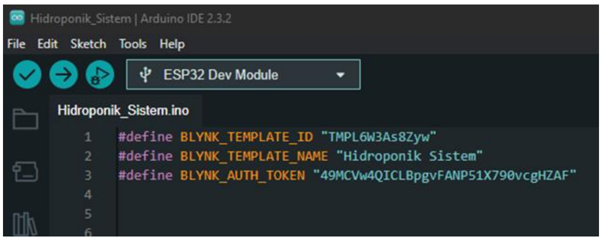

Figure 11. Blynk token.

The Blynk platform provides a powerful infrastructure for managing system components through triggers in automation processes. Triggers enable the system to continuously monitor environmental parameters and automatically perform certain actions when predetermined threshold values are reached.

The dashboard in the Blynk application makes it easy to set and monitor triggers. Threshold values, timers and other trigger parameters can be defined directly through a graphical interface. Real-time notifications and control options ensure effective management of the system.

Figure 12 shows the EC trigger mechanism used in the developed system. The trigger is configured to automatically activate the EC pump when the EC value falls below a certain threshold level, and to automatically deactivate the EC pump when it rises above a certain threshold level.

Figure 12. EC trigger mechanism.

Figure 13 shows the pH trigger mechanism used in the developed system. The trigger is configured to automatically deactivate the pH pump when the pH value rises above a certain threshold level, and to automatically activate the pH pump when it falls below a certain threshold level.

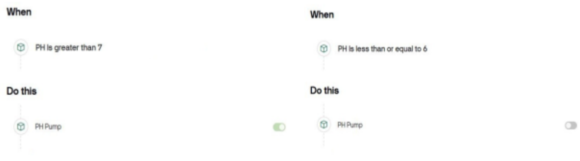

Figure 13. PH trigger mechanism.

Figure 14 shows the tank liquid level trigger mechanism used in the developed system. The trigger is configured to automatically close the tank valve when the tank liquid level rises above a certain threshold level, and to automatically open the tank valve when it falls below a certain threshold level.

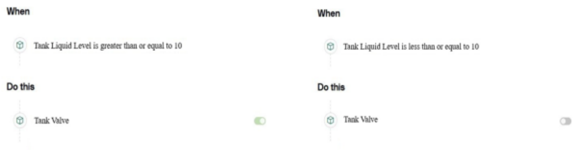

Figure 14. Tank liquid level trigger mechanism.

With the trigger mechanisms mentioned above, human intervention is minimized, and operational processes are automated. In this way, the efficiency of the system is significantly increased, and environmental conditions are guaranteed to be kept at an optimum level. In addition, this structure, which supports the efficient and sustainable use of resources, reduces energy consumption and increases system performance and reliability.

4. Results

In this study, the growth processes of lettuce plants cultivated in both the automation-supported and non-automated hydroponic systems were monitored through weekly photographic documentation. These images served as a visual dataset, enabling a comparative analysis of plant development in both systems.

The visual records captured key developmental milestones of the lettuce plants, allowing for a detailed examination of differences in growth rate, leaf expansion, color intensity, and overall morphological features between the two groups. Notably, the plants grown in the automation-supported system exhibited faster and more uniform growth, with larger leaf structures and healthier coloration observed from the second week onward. In contrast, plants in the non-automated system showed slower development and more variability in leaf size and color.

These findings clearly indicate that automation positively influences plant development by providing more stable environmental conditions and consistent nutrient delivery, which enhances overall growth performance.

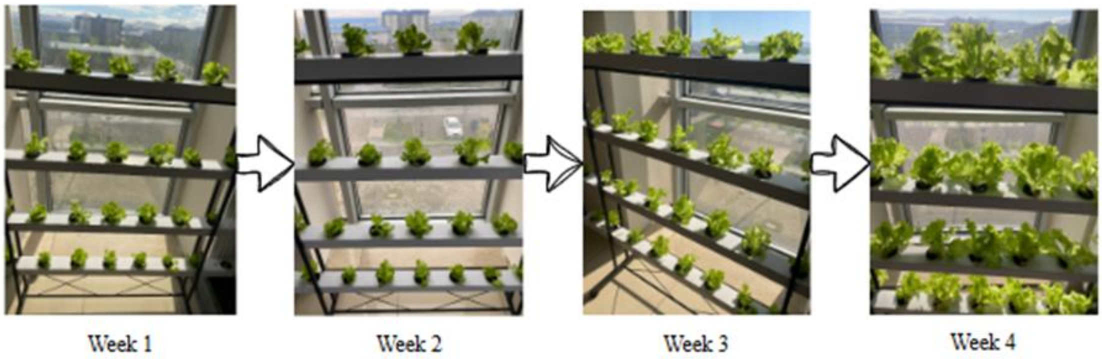

Figure 15. Plant development process in non-automated hydroponic farming (Weeks 1-4).

In the visual given in Figure 15, although plant growth in the non-automated hydroponic system generally follows a positive course, some irregularities were observed in the growth processes due to the manual control of the system. Manual adjustment of water and nutrient balance was one of the main factors affecting plant development. Different growth rates and structural changes were observed in the plants, especially in the third and fourth weeks, and it was understood that it was difficult to provide a stable development curve without automation support.

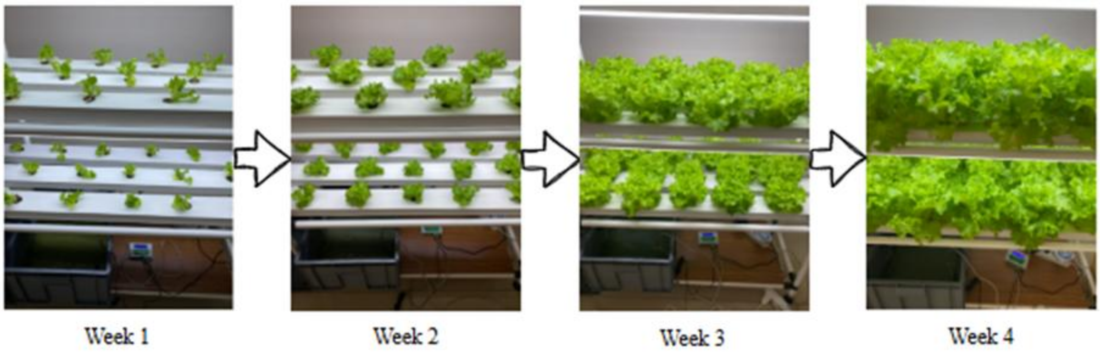

Figure 16. Plant development process in automation-supported hydroponic agriculture (Weeks 1-4).

In the visual given in Figure 16, it was observed that the growth of lettuce plants in the automation-supported hydroponic system was more regular and faster. The system continuously optimized the water and nutrient balance, ensuring that the plants grew in ideal conditions. In this process, a significant increase in growth rate and healthier development in the plant structure were observed compared to the non-automated hydroponic system. The constant nutrient balance and regular watering cycle provided by automation were an important factor in increasing plant productivity by reducing the need for manual intervention.

Table 3. Weekly development comparison of lettuce plants in automated and non-automated hydroponic systems

Weeks	Non-Automated Hydroponic System	Automation Supported Hydroponic System
Week 1	Plants are in the rooting process, small leaves are present, growth is limited. Nutritional balance is provided manually.	The plants are in the rooting process, but the environment is constant, the nutrient balance and irrigation are automatically optimized.
Week 2	Leaf growth has started, but different development speeds are observed. There are irregularities since feeding and watering are done manually.	Plants grow homogeneously, leaf density has increased. Thanks to automation, the nutrient balance is kept constant.
Week 3	There are differences in growth rate among plants, some plants are more developed while others are lagging behind. Leaf density is at medium level.	Plants have grown significantly, leaf width is greater, growth is uniform, and plants are healthy.
Week 4	Plants are largely developed, but structural differences are evident due to nutrient and water imbalance. Some plants are smaller or pale.	Plants have reached full growth, leaves are large, healthy and vibrant. Growth is homogeneous and yield is high.

The analyses performed in accordance with the visuals given in Figures 15 and 16 show that automation-supported hydroponic systems provide faster, more homogeneous and more efficient plant growth compared to manually managed systems. Since the nutrient balance, water level and pH control are continuously optimized in the automated system, a more even and healthy development is observed in the plants. In contrast, irregularities occurred in the growth rate in the non-automated system, some plants lagged behind while others grew faster. It was observed that the leaf size was significantly larger in the automated system, especially from the 2nd week onwards, and the plants were fully developed and ready for harvest by the 4th week. These results reveal that the use of automation in hydroponic systems offers a critical advantage in terms of increasing agricultural productivity and ensuring stable and sustainable growth.

5. Discussion and Conclusion

In this study, an application was taken into consideration for a home-type production based on hydroponic system and this system was integrated with automation. Moreover, the system in question was compared with the output obtained by the non-automated hydroponic system and it was determined that there was a significant difference in terms of plant growth. In the findings obtained, it was observed that a crop with the required standards was obtained with the automation-supported hydroponic system, and this crop matured in a short time of 4 weeks, therefore it was determined that lettuce, which needs 70-90 days to reach maturity when planted in spring (Beşirli et al., 2021), could be consumed in a shorter time. These experimental findings provided the following contributions in terms of social, economic and environmental aspects.

First of all, the automation-supported hydroponic system contributes to sustainability - especially environmental sustainability. Namely, the increasing population worldwide and the lack of awareness and inadequacy in the management of agricultural lands will soon lead to a scarcity of agricultural lands and will increase the need for methods that will provide quality and efficiency in a smaller area (Kannan et al., 2022). At this point, it is expected that hydroponic system agricultural applications will partially meet this need in a significant part of agriculture, although not in every area. Because, as mentioned before, hydroponic systems allow the use of unused areas in urban areas in agricultural activities (Shareef et al., 2024), while also enabling the cultivation of more products per unit area, shortening the growth period and high productivity (Resh, 2022). Furthermore, this system, which saves up to 90% in water use compared to traditional agriculture (Mielcarek et al., 2024), also makes a great contribution to the protection of drinkable water resources, which is among the most important problems of today. On the other hand, as seen in this study, this system reduces fertilizer and pesticide dependency and prevents damage to the environment. Therefore, the damage to underground and aboveground living spaces and resources caused by chemical drugs and fertilizers used in the traditional method is minimized thanks to this system, contributing to environmental sustainability.

Secondly, the hydroponic system contributes to society and community. As seen in this study, a hydroponic system supported by automation does not require as much labor as in traditional agriculture. Therefore, it is clear that this situation, which was observed with a small prototype in this study, will also provide savings in terms of labor in a larger systematic production. Moreover, this study has shown that agriculture with hydroponic systems can also be applied in home environments. In other words, it can be said that it enables urban agriculture, and in this context, it contributes to increasing the subjective well-being provided by production in people living far from agriculture and especially to introducing our children, who are the trustees of the future, to production. Contributions such as increasing food safety, providing access to fresh fruits and vegetables and leading to healthier nutrition can also be added to these.

Thirdly, this system also has economic benefits. Although these systems may initially seem disadvantageous in terms of high costs, they can amortize the cost in a short time by increasing productivity in the long term compared to traditional agriculture or other systems. The automated system also enables agricultural enterprises to reduce their input costs by ensuring the optimal use of resources such as labor, water, and time. At the same time, these systems create opportunities to support small enterprises operating in this field and help decrease reliance on imported products. This is because fresh products obtained through such systems can be marketed locally, allowing businesses to access daily, fresh produce at a lower cost while minimizing their vulnerability to global food market fluctuations.

It is thought that the findings of the study also contribute to the relevant field. As a matter of fact, in the study, significant differences were observed in the output of the system where technology was used effectively (automated) and less (non-automated) in terms of plant growth, and the advantages of an automation-based hydroponic system in terms of efficiency were clearly seen. Therefore, with these findings obtained in the study, the studies of Kuncoro et al. (2021), Maldonado et al. (2019) and Jain and Kaur (2024) in the literature were supported and the studies to be carried out in this field were guided. Technological transformation manifests itself in every area of life and brings convenience. It is used in many sectors from education to health, from banking to industry and trade, artificial intelligence and automation make life easier as well as cost-effective (Topçuoğlu et al., 2022). The agricultural sector (and therefore agricultural enterprises) is also one of these sectors where technology is used. Thanks to technological transformation, costs in agricultural production are reduced (in the long term) and productivity is increased, contributing to economic, social and environmental sustainability. For this reason, there is a need for academic studies that will guide, and support businesses operating in this field and encourage those who are considering entering the sector.

Beyond the economic, social and academic contributions explained above, it is also useful to state the limitations of the study. One of these limitations is that the study was conducted on a single product (lettuce). It is recommended that the studies to be conducted should be conducted on different products and especially focus on products that will provide high returns and provide time and place benefits. Moreover, although an automated system was used and an increase in efficiency was achieved at this point, the energy used for this automation was not taken into account. In the studies to be conducted, additions can be made to the design for energy consumption in question, such as solar panels, where the energy to be used can be directly produced. Therefore, in the studies to be conducted, especially the cost factor can be taken into account, and such calculations can be considered alongside production and efficiency. Furthermore, by considering factors such as savings (e.g. water), energy used and carbon footprint obtained in automated hydroponic systems, the contributions of these systems to the agricultural sector and businesses in this sector, and ultimately their effects in the context of sustainability, can be determined. It can also be said that the quality parameters such as nutritional value, flavor profile and shelf life of the product obtained in the study are ignored as a limitation. It is recommended that the studies to be conducted take this situation into account. Finally, considering all the limitations mentioned above, conducting interdisciplinary projects and studies, especially the involvement of social science researchers in the process, will provide a better understanding of these systems with their social and economic dimensions. Because the output obtained with these systems is not only technical developments, but also the products of an economic, social and environmental transformation process. Therefore, the involvement of researchers from disciplines such as engineering, agriculture and biology, as well as sociology, psychology, business, economics and public administration in the process will help the developments in the field and their acceptance.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	M.A.Y.	O.O.	G.K.
C	50	25	25
D	50	25	25
S	80	10	10
DCP	70	15	15
DAI	70	15	15
L	20	40	40
W	40	30	30
CR	40	30	30
SR	90	5	5
PM	50	25	25
FA	100	0	0

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

Acknowledgments

This study is based on data derived from the project numbered 2023-SB-71, supported by the Scientific Research Projects Unit of Kafkas University. I would like to express my sincere gratitude to Kafkas University Scientific Research Projects Unit for their generous funding and support, which enabled this research.

References

Aliac CJG, Maravillas E. 2018. IOT hydroponics management system. In: 2018 IEEE 10th Int Conf Humanoid Nanotechnol Inf Technol Commun Control Environ Manag (HNICEM), pp: 1-5.

Altieri MA, Nicholls CI. 2017. The adaptation and mitigation potential of traditional agriculture in a changing climate. Clim Change, 140: 33-45.

Amalfitano C, Del Vacchio L, Somma S, Cuciniello A, Caruso G. 2017. Effects of cultural cycle and nutrient solution electrical conductivity on plant growth, yield and fruit quality of 'Friariello' pepper grown in hydroponics. Hortic Sci, 44(2), pp:54-59.

Aosong Electronics. 2023. DHT21 Temperature and Humidity Sensor Datasheet. Aosong Electronics Co., Ltd. (accessed date: March 10, 2025). Available at: https://www.aosong.com

Atlas Scientific. 2024a. EZO-pH Circuit Datasheet. Atlas Scientific. (accessed date: March 10, 2025). Available at: https://www.atlas-scientific.com

Atlas Scientific. 2024b. EZO-EC Circuit Datasheet. Atlas Scientific. (accessed date: March 10, 2025). Available at: https://www.atlas-scientific.com

Ayeni O, Olagoke-Komolafe O. 2024. Environmental impact of modern agricultural practices: Strategies for reducing carbon footprint and promoting conservation. Int J Manag Entrep Res, 6(9), pp:56-64.

Beşirli G, Sönmez İ, Albayrak B, Polat Z. 2021. Organik marul yetiştiriciliği. T.C. Tarım ve Orman Bakanlığı, Tarımsal Araştırmalar ve Politikalar Genel Müdürlüğü, pp: 45.

Bunyuth Y, Mardy S. 2024. Hydroponic systems: an overview of benefits, challenges, and future prospects. Indones J Soc Econ Agric Policy, 1(1): 10-18.

Espressif Systems. 2023. ESP32 Technical Reference Manual. Espressif Systems. (accessed date: March 10, 2025). Available at: https://www.espressif.com

FAO. 2023. The State of Food and Agriculture 2023: Revealing the True Cost of Food to Transform Agrifood Systems. FAO, Rome. (accessed date: March 10, 2025). Available at: https://openknowledge.fao.org/items/1516eb79-8b43-400e-b3cb-130fd70853b0

Farooq MS, Riaz S, Helou MA, Khan FS, Abid A. 2022. A survey on IoT in agriculture for the implementation of greenhouse farming. IEEE Access, 10: 1-15.

Fedulova S, Zadoia A, Shkura I, Komirna V, Savchenko M. 2023. Determining the impact of virtual water scarcity risk on the global food crisis 2022 as a result of hostilities. East-Eur J Enterp Technol, 1(13): 121.

Gakhar A. 2021. Sustainable alternative farming techniques—an Indian perspective. Plant Arch, 21(1), pp:45-56.

Gruda NS. 2019. Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems. Agronomy, 9(6): 298.

Heaney MB. 2017. Electrical conductivity. In: Webster JG (ed.), Measurement, Instrumentation, and Sensors Handbook. CRC Press, London, UK, pp:57-59.

Huang Z, Hejazi M, Tang Q, Vernon CR, Liu Y, Chen M, Calvin K. 2019. Global agricultural green and blue water consumption under future climate and land use changes. J Hydrol, 574: 242-256.

Jain S, Kaur M. 2024. Automated vs. semi-automated hydroponics: quantifying automation effects on plant growth. Int J Electr Comput Eng Syst, 15(8): 687-694.

Jayachandran A, Scholar PR, Jain S, Saini S, Maurya P, Subhasmita S, Kumar K, Scholar SP, Kiran B. 2022. Hydroponics: an art of soil less farming. Pharma Innov J, 11(9): 1049-1053.

Kannan M, Elavarasan G, Balamurugan A, Dhanusiya B, Freedon D. 2022. Hydroponic farming–A state of art for the future agriculture. Mater Today Proc, 68: 2163-2166.

Kheirinejad S, Bozorg-Haddad O, Gude VG. 2021. The water, food and energy nexus. In: Water Resources. Springer, Cham, pp: 175.

Kumar S, Kumar S, Lal J. 2023. Assessing opportunities and difficulties in hydroponic farming. Bhartiya Krishi Anusandhan Patrika, 38(1): 56-64.

Kumar S, Singh M, Yadav KK, Singh PK. 2021. Opportunities and constraints in hydroponic crop production systems: a review. Environ Conserv J, 22(3): 401-408.

Kumari R, Kumar R. 2019. Aeroponics: A review on modern agriculture technology. Indian Farmer, 6(4): 286-292.

Kuncoro CBD, Asyikin MBZ, Amaris A. 2021. Development of an automation system for nutrient film technique hydroponic environment. In: Proc 2nd Int Semin Sci Appl Technol (ISSAT 2021), pp: 437-443.

Mahajan P, Gupta S, Sachdeva S. 2022. Automation in hydroponic systems: a sustainable pathway to modern farming. In: Proc 2022 IEEE Int Conf Serv Oper Logist Inform (SOLI), pp: 1-7.

Maldonado AIL, Reyes JMM, Breceda HF, Fuentes HR, Contreras JAV, Maldonado UL. 2019. Automation and robotics used in hydroponic system. Urban Horticulture, London, UK, pp: 23-26.

Mielcarek A, Kłobukowska K, Rodziewicz J, Janczukowicz W, Bryszewski KŁ. 2024. Water nutrient management in soilless plant cultivation versus sustainability. Sustainability, 16(1): 152.

Mohammed SB, Sookoo R. 2016. Nutrient film technique for commercial production. Agric Sci Res J, 6(11): 269-274.

Nalwade R, Mote T. 2017. Hydroponics farming. In: Proc 2017 Int Conf Trends Electron Inform (ICEI), pp: 645-650.

Nursyahid A, Setyawan TA, Sa'diyah K, Wardihani ED, Helmy H, Hasan A. 2021. Analysis of Deep Water Culture (DWC) hydroponic nutrient solution level control systems. IOP Conf Ser Mater Sci Eng, 1108(1): 012032.

Nwulu N, Suka D, Dogo E. 2021. Automated hydroponic system integrated with an Android smartphone application. In: Examining the Impact of Deep Learning and IoT on Multi-Industry Applications. IGI Global, pp: 227-248.

Paige K, Gell L. 2023. Solving food insecurity and agricultural challenges with hydroponics. J Student Res, 12(4), pp:56-58.

Palande V, Zaheer A, George K. 2018. Fully automated hydroponic system for indoor plant growth. Procedia Comput Sci, 129: 482-488.

Pinto R, Patil D, Joseph N, Barreto C, Khan S. 2024. Smart agriculture using IoT. Int J Multidiscip Res, 6(3), pp:125-135.

Putra SD, Heriansyah H, Cahyadi EF, Anggriani K, Jaya MHIS. 2024. Development of smart hydroponics system using AI-based sensing. J Infotel, 16(3): 474-485.

Reddy KJ, Mishra R, Sreekumar G, Saikanth DRK. 2023. Future of hydroponics in sustainable agriculture. Adv Farm Technol, 108.

Resh HM. 2022. Hydroponic food production: A definitive guidebook for the advanced home gardener and the commercial hydroponic grower. CRC Press, Boca Raton, pp: 621.

Reza MN, Lee KH, Karim MR, Haque MA, Bicamumakuba E, Dey PK, Chung SO. 2025. Trends of soil and solution nutrient sensing for open field and hydroponic cultivation in facilitated smart agriculture. Sensors (Basel), 25(2): 453.

RoboticsBD. 2023. HC-SR04 Ultrasonic Sensor Datasheet. Robotics Bangladesh. (accessed date: March 10, 2025). Available at: https://roboticsbd.com

Sahoo J. 2021. Optimal secure placement of IoT applications for smart farming. In: 2021 8th Int Conf Internet Things: Syst Manag Secur, pp: 1-6.

Savvas D, Gruda N. 2018. Application of soilless culture technologies in the modern greenhouse industry—a review. Eur J Hortic Sci, 83(5): 280-293.

Shareef U, Rehman AU, Ahmad R. 2024. A systematic literature review on parameters optimization for smart hydroponic systems. AI, 5(3): 1517-1533.

Siregar S, Sari MI, Jauhari R. 2016. Automation system hydroponic using smart solar power plant unit. J Teknol, 78(5-7).

Soussi M, Chaibi MT, Buchholz M, Saghrouni Z. 2022. Comprehensive review on climate control and cooling systems in greenhouses under hot and arid conditions. Agronomy, 12(3): 626.

Srivani P, Manjula SH. 2019. A controlled environment agriculture with hydroponics: variants, parameters, methodologies and challenges for smart farming. In: 2019 Int Conf Inf Process (ICINPRO), pp: 1-8.

Topçuoğlu E, Kavak O, Kaygın E. 2022. Analysis of MHRS as a management information system in health with technology acceptance model. Int J Bus Sci Appl (ULISBUD), 2(1): 1-16.

Velasco-Muñoz JF, Aznar-Sánchez JA, Belmonte-Ureña LJ, Román-Sánchez IM. 2018. Sustainable water use in agriculture: A review of worldwide research. Sustainability, 10(4): 1084.

Waller P, Yitayew M. 2016. Hydroponic irrigation systems. J Irrig Drain Eng, 142(4): 369-386.