Information system to enhance agricultural production efficiency based on sustainable development principles*

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Abstract

The increasing global demand for sustainable agricultural practices necessitates innovative solutions to optimize resource use and minimize environmental impact. This paper presents the information technology developed to automate and optimize the operation of a hydroponic system to improve energy and resource efficiency in sustainable agriculture. An automated control platform at the system's base continuously monitors key environmental parameters within the hydroponic facility, including water level, nutrient distribution, lighting, and energy consumption. The system can precisely regulate the processes by collecting real-time data on these variables, providing ideal conditions for plant growth. The hydroponic system is equipped with a set of sensors and actuators that control water flow, fertilizer supply, and lighting according to the needs of each plant. The developed spectral composition is based on combining the spectra of HPS and two peaks of photosynthetic efficiency. This combination of the spectrums complements each other, which allows photosynthesis to proceed as efficiently as possible. The system makes it possible to save up to 25% of electricity consumption without losing quality and quantity characteristics, to reduce the number of hours of illumination, and to be placed in cost-effective climatic conditions.

Keywords

Information technology, hydroponic system, dynamic lighting, sustainable development

1. Introduction

In 2015, the United Nations adopted the Sustainable Development Goals (SDGs), or the Global Goals, as a universal initiative to eradicate poverty, preserve the planet, and ensure peace and prosperity for all people by 2030 [1].

One solution that can help achieve these goals is using a recycled water supply system. It is crucial to achieving sustainable development goals by ensuring the rational use of water resources and contributing to the preservation of ecosystems [2-4]. In today's increasingly water-scarce world, recycled water systems allow water reuse, reducing water loss and minimizing the need for new water intake sources. This is especially important in regions with limited water resources and the context of climate change. Water reuse reduces the need for wastewater disposal, which helps to preserve marine ecosystems and reduce pollution. Water recycling systems can provide a stable and efficient water supply for agriculture, contributing to higher agricultural output and sustainability, even in drought regions. The use of circulating water systems helps save energy required for pumping and filtering water, reducing the overall water management cost. This also positively impacts the energy balance and contributes to the fight against climate change.

This paper presents the development of a model for an information system aimed at increasing the efficiency of agricultural production. The proposed system integrates cutting-edge technologies and practices to create a sustainable solution addressing water conservation and agricultural

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productivity. By leveraging advanced filtration, treatment processes, and recirculation mechanisms, the model seeks to enhance water use efficiency, reduce operational costs, and contribute to the broader goals of sustainable development.

The significance of this research lies in its potential to provide a scalable and adaptable framework for water recycling in various agricultural settings. Through a detailed examination of the system's design, implementation, and performance, this study aims to demonstrate how innovative water management strategies can drive significant improvements in agricultural efficiency and sustainability.

2. Related works

Advancements in aquaculture and hydroponic systems have gained significant attention in recent years, driven by the increasing need for sustainable and resource-efficient food production methods. Key research and innovations in these fields highlight progress in recirculating water systems and hydroponic technologies.

The patent [5] describes a recirculating water supply device. A recirculating water supply device for the production of organic products in aquaculture includes a tank for growing aquatic organisms, a light source, a compressor, an air sprayer, a piping system, a pump, a thin layer settling tank, cultivation of plants, according to the utility model, the system includes a tank with a dense plantation of herbivorous fish, with the possibility of introducing spirulina into their diet with a ratio of 5...15 ml per 100 liters of tank volume every five days.

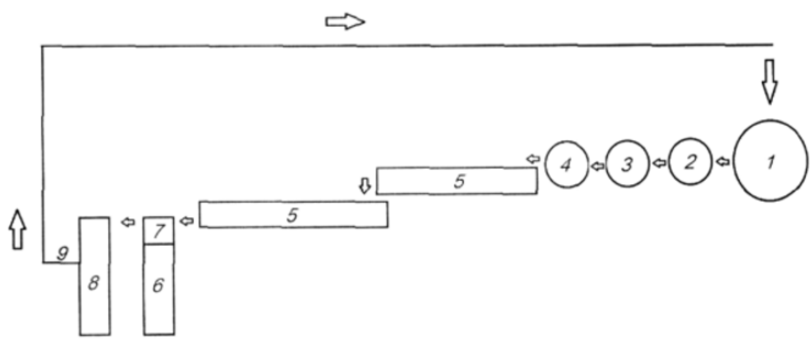

Figure 1: Scheme of recirculating water supply device [5].

In a study [6], authors compare leaf-to-air temperature differences among the radiation sources and environments by applying a common mechanistic energy-balanced model. The described model indicates that light-emitting diode (LED) technology reduces leaf temperature compared to high-pressure sodium (HPS) technology. These results allow researchers and the horticulture industry to make informed decisions when employing these technologies.

Paper [7] presents the improvement of the current traditional hydroponic method by providing a system that can monitor and control the important elements to help the plant grow smoothly. That system is efficient and user-friendly and combines a traditional hydroponic system, an automatic control system, and a smartphone. In a study [8], authors explain six types of hydroponic systems based on plant nutrient supply technology: Wicking system, deep water culture DWC, drip system, aeroponics, ebb and flow system, and nutrient film technique (NFT). Paper [9] introduces a self-fertigation hydroponic system that fosters sustainability and boosts agricultural productivity in remote locations. That system achieves efficient plant growth with minimal resource use, optimizing water and nutrient management to create favorable growing conditions while conserving essential resources. In paper [10], a cost-effective automated vertical hydroponic system using an IoT platform has been implemented. The authors studied and calculated hydroponic system parameters such as suitable temperature, light wavelength, etc. Also, they provided web and mobile interfaces to increase system accessibility. Paper [11] discusses developing and implementing a hydroponic system that uses renewable energy for autonomous operation. The authors propose a solution that combines an automated hydrolysis system with renewable energy sources, such as solar panels or wind turbines, to support sustainable and self-sufficient plant cultivation. In a study [12], authors investigate the effect of different hydroponic systems on lettuce growth. The aim of the study was to evaluate how different hydroponics methods, such as deep water culture (DWC), drip irrigation, and nutrient feeding technique (NFT), affect the biometric parameters and yield of lettuce plants. The study showed that the type of hydroponic system plays a crucial role in the growth and development of lettuce. The use of the NFT system is the most effective for growing lettuce due to the optimal supply of nutrients and oxygen to the plants.

3. Model description

3.1. Requirements for the information system

The information system should support management and decision-making in the agricultural sector, increasing efficiency by automating management processes, monitoring crops, tracking resources, and optimizing the use of additional nutrients, water, machinery, and other resources.

Therefore, the following requirements are developed for the information system:

- The system must automatically monitor and regulate key parameters such as the pH of the solution, Electrical conductivity (EC) of the nutrient solution, Oxygen levels in the water, Water and air temperature, and Humidity levels.
- The system must detect deviations from normal conditions and automatically notify operators or initiate corrective action. Keep records and control the use of fertilizers, pesticides, water, and machinery.
- The system must manage resources such as automated nutrient dispensing, lighting control, irrigation management (control the frequency and amount of irrigation for each zone of the hydroponic system), and water recirculation (ensuring efficient water use and preventing water stagnation) [13].
- The system should provide detailed reports on water, fertilizer, energy consumption, and equipment operation times for efficient resource management.
- Farmers should have access to the system via a mobile or web application, allowing for remote control of hydroponic system parameters, notifications about issues, and the ability to quickly adjust settings.

Hydroponic systems, as a part of information systems, are designed to ensure the efficient use of water resources by re-cleaning and returning water to the system without significant additional freshwater intake. Such devices help to minimize water losses, reduce environmental impact, and increase the economic efficiency of agricultural production [14,15]. The main tasks of these systems are to purify used water, remove pollutants, maintain the balance of trace elements, provide optimal conditions for plant growth, and maintain aquatic life. Key parameters in hydroponics, such as pH balance, regulation of nutrient levels, and optimal environmental conditions, are maintained by controlling several factors. These include light intensity, electrical conductivity, total dissolved solids, temperature, humidity, air circulation, and water management. By precisely managing these variables, an ideal environment for plant growth is achieved [16,17].

The requirements for hydroponic systems are determined by the goals of ensuring efficient system operation, reliability, economy, and environmental compatibility. The main requirements for such a system are:

- Minimize water consumption: The water must be reused with minimal losses. This is important to reduce water consumption, especially in regions with limited access to fresh water [18, 19].
- High recycling rate: The volume of water that can be reused after treatment must be as high as possible. The system must recover at least 90-95% of the water.

- Cleaning efficiency: The system must effectively remove pollutants (organic matter, chemicals, biological pollutants) and maintain water quality standards that are appropriate for agricultural or aquacultural purposes.
- Stability of water quality indicators: The system must maintain stable pH, oxygen, nitrogen, salinity, and other parameters for the normal functioning of biological processes.
- Low energy costs: Recirculating water supply devices must be energy efficient, including pumping systems, compressors, and filtering units. Optimal energy use reduces operating costs.
- Integration with renewable energy sources: The system must support using solar or wind energy to reduce environmental impact.
- Suitable growing conditions: The system requires a specific growing environment, such as glass beads, rock wool, and sponges [20, 21].
- Minimizing emissions and effluents: The system must minimize the generation of harmful waste and wastewater that can negatively impact the ecosystem.
- Process automation: The system must be automated, allowing all processes, including treatment, recycling, and water quality monitoring, to be controlled with minimal human intervention.
- Low operating costs: Operation and maintenance costs must be kept to a minimum to ensure the system is cost-effective.
- Accessibility of technology: Technology must be available for widespread use in the agricultural sector, especially for small and medium-sized farms.

3.2. Model for information system

In an information system, effective monitoring and control of various environmental factors —such as nutrient levels, pH, temperature, and humidity—are crucial for optimal plant growth [22]. A well-structured network topology can significantly enhance the efficiency and reliability of such systems. Below are key components and considerations for the network topology of a hydroponic system:

- The central control unit (server). This unit manages data from various sensors and devices throughout the system, allowing for centralized monitoring and control
- Sensor nodes are distributed throughout the hydroponic setup to monitor critical parameters
- Actuators, which control physical components of the system based on sensor data
- Router, which connected to server and Internet
- Client devices such as mobile or laptop

Star topology is selected for this system, which is shown in Figure 2. The sensor nodes and actuators connect directly to the central control unit. This topology simplifies wiring and troubleshooting, as each device can be managed independently. However, the central unit represents a single point of failure [23,24]. Multiple routers are integrated to segment the network into different zones or subnets. Each router connects to the central hub and manages its own set of devices, such as computers, cameras, and sensors.

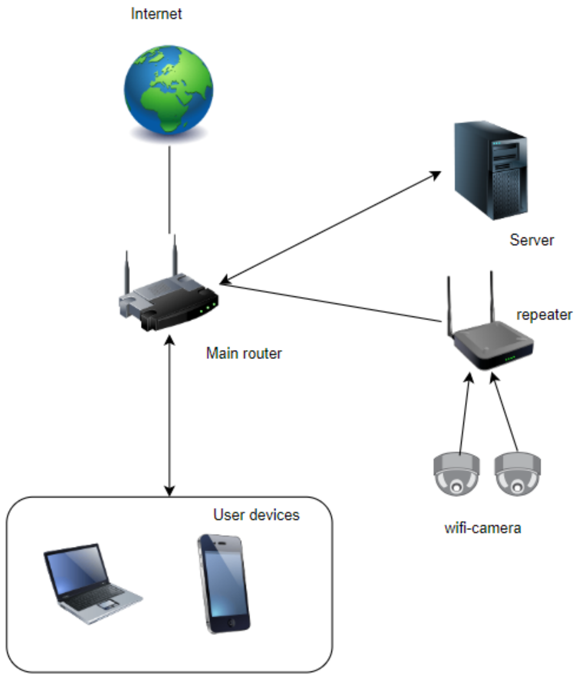

Figure 2: Network topology of the developed system.

Devices within the network connect to their respective routers using Ethernet cables or wireless connections. Each router serves as an access point, allowing devices to communicate with one another and the central hub.

These sensors help automate processes, ensuring that plants receive the right conditions for growth. Below are the common types of sensors used in information systems: temperature sensors, pH sensors, humidity sensors, and light sensors [25].

Once these sensors collect data, they must transmit it to a central control system for analysis and action. WebSocket provides a reliable and efficient method for this real-time communication. The sensor data is sent to the server in real-time using the established WebSocket connection. Since WebSocket allows full-duplex communication, the client and server can send and receive messages simultaneously. The server can also send commands back to the client or actuators (like pumps or lights) to adjust the environment based on sensor readings. This feedback loop is crucial for maintaining optimal growing conditions. Users can monitor the sensor data in real-time through a web application or mobile interface connected to the server, allowing for convenient oversight of the hydroponic system.

Cron jobs are used as tools for automating scheduled tasks to the cloud storage. In the context of these information systems, cron jobs can be employed to synchronize sensor data with the cloud at specified intervals. This ensures that the latest data is regularly updated without requiring manual intervention.

Storing historical data in the cloud is crucial for hydroponic systems as it allows for long-term analysis, trend identification, and decision-making based on past performance. For this system, use CSV file format. CSV files tend to have a smaller file size than other formats (like JSON or XML), especially for large datasets with repetitive values. This can lead to reduced storage costs in cloud environments. The simplicity of CSV files leads to lower processing overhead in terms of both storage and computational resources. This is especially important for small to medium-sized hydroponic operations that may not have extensive infrastructure. Also, it does not enforce strict schema requirements, allowing you to add or remove fields as necessary without complex schema modifications. This flexibility can benefit evolving hydroponic systems where new sensors or parameters may be introduced.

The model aims to unify the design and set up optimal lighting for specific crops. This result is achieved by the fact that the lighting system consists of 4 linear lamps with a radiation spectrum of

350-800 nm, 50 W, and the height of the lamp is 600...650 mm for uniform illumination of the useful area of the tray with vegetative crops.

The common features of the applied device are a tank, a light source, a compressor, an air sprayer, a piping system, a pump, a thin layer settling tank, and a plant cultivation tank.

A distinctive feature of the device is that the lighting system consists of 4 linear lamps with a radiation spectrum of 350-800 nm, 50 W, and installation height of 600...650 mm for uniform illumination of the useful area of the tray with vegetative crops.

The utility model is explained graphically, where Figure 3 shows a diagram of a recirculating water supply device for growing agricultural products [26].

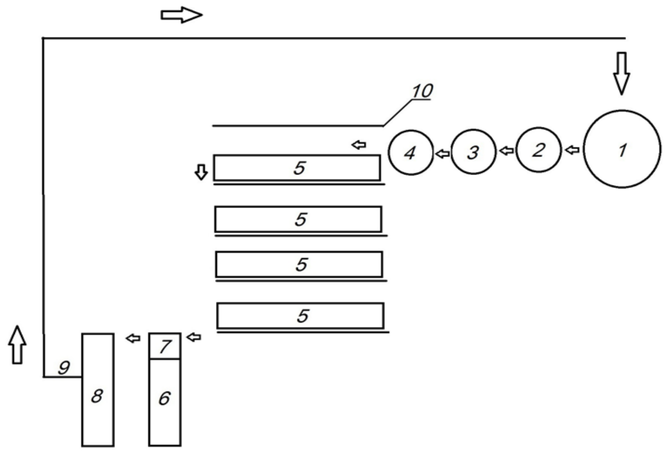

Figure 3: Scheme of the proposed hydroponic system [26].

A recirculating water supply device for growing agricultural products has:

1. Tank
2. Mechanical filters
3. Biological filters
4. Pump
5. Tanks with plants (lettuce leaves, strawberries, vegetables, etc.)
6. Ozonation unit
7. Ozonator
8. Aeration unit
9. Clean water supply line
10. Light source

The tanks for plant cultivation are equipped with a light source consisting of four linear lamps with a radiation spectrum of 350-800 nm, 50 W; the height of the lamp is 600...650 mm for uniform illumination of the useful area of the tray with vegetative crops.

The operating mode of the lighting system is designed to simulate natural sunlight conditions, thereby optimizing the growth environment for plants. The system operates on a 12-hour cycle, aligning with the natural daylight duration in many regions, ensuring plants receive consistent light for photosynthesis. The scheme is implemented and shown in Figure 4.

Figure 4: Hydroponic system implementation: a) tank with plants; b) hydroponic module.

The lighting system incorporates an 'east-west' mode to mimic the gradual increase and decrease of sunlight intensity during sunrise and sunset. This mode involves two transitional periods: one at the start of the lighting cycle, simulating sunrise, and one at the end, simulating sunset. Each transition lasts for one hour, during which the light intensity gradually changes.

At the beginning of the lighting cycle, the luminaire's power output increases steadily from 0 W to 200 W over the course of one hour, simulating the gradual rise of the sun in the morning. This allows the plants to adapt to the increasing light intensity, reducing the shock that could occur with a sudden increase in brightness. The 200 W power level represents the peak output of the luminaire, equivalent to full sunlight during the day. This level is maintained for the duration of the active light cycle, providing a stable and optimal environment for plant growth.

As the day progresses and the 12-hour lighting period ends, the system initiates the sunset simulation. Over the course of the final hour, the luminaire's power output gradually decreases from 200 W to 0 W, mirroring the natural dimming of light as the sun sets. This gradual reduction in light intensity allows plants to adjust to lower light levels, preparing them for the nighttime phase. This dynamic lighting approach not only enhances plant growth by providing a natural-like light environment but also reduces energy consumption by avoiding unnecessary high-intensity lighting during transitions. The smooth transitions between light intensities minimize plant stress, promoting healthier growth and better yields. Additionally, by simulating the natural light cycle, the system supports the circadian rhythms of both plants and the ecosystem within the controlled environment, leading to more efficient use of light energy and overall improved agricultural productivity.

Tank 1 is filled with water, and the water enters tank 5 (where lettuce leaves, vegetables, etc. are cultivated), installed with a height difference to ensure water overflow. Tanks 5 for cultivating plants are equipped with a light source 10, which consists of four linear lamps.

Water enters the mechanical two and biological three filters from the tanks, after which the purified water is pumped by pump 4 to columns 6,8, where it is ozonated and enriched with oxygen-aerated. After passing through successive levels of purification, the water enters tank 1. During the entire cycle, at each stage, the plants “accumulate” the required substances, and the water is gradually purified by filters and circulated back to tank 1.

The system's reservoir is filled with water and then directed to the tanks where crops such as salad leaves and vegetables are grown. The tanks are arranged in a cascading pattern with a height difference to ensure the gravitational flow of water between them. This makes it possible to effectively use the natural water flow to irrigate crops evenly without additional energy consumption for circulation.

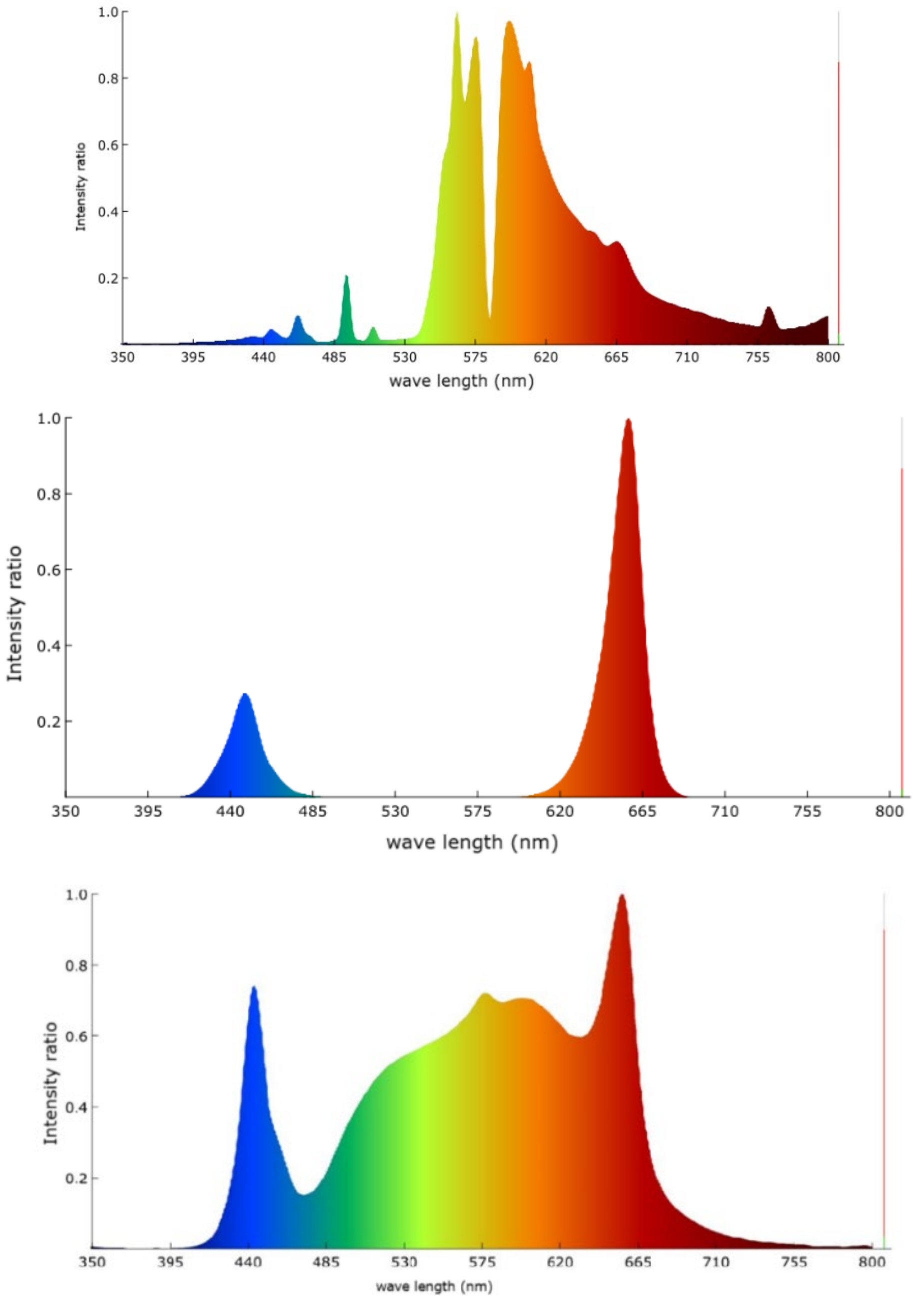

Figure 5: The spectral composition of the lamps: a) HPS GAVITA PRO DE 1150w b) PHILIPS green power led top light drb hb 400v 230w c) Both composition.

After passing through the plant tanks, the water enters a mechanical filter, where large particles are removed. The water then enters a biological filter and is biologically purified using special microorganisms that neutralize organic impurities. The purified water is pumped to the columns, where it is further processed: ozonation and oxygen saturation (aeration) occur in the columns. Water's Ozonation helps disinfect it, and aeration increases the concentration of dissolved oxygen, which is important for plants and microorganisms in the system.

Once this process is complete, the purified water is returned to the tank, completing the recirculation cycle. At each stage of this process, the plants absorb the necessary nutrients, and the water is purified gradually through filters and plant media, ensuring the system's stable and efficient operation. The lighting system consists of 4 linear lamps with a radiation spectrum of 350-800 nm, with one common 200 W power supply, made of an aluminum profile on which 30 cm long LED boards with built-in white 3528 LEDs with a color temperature of 4000K and red 3030 LEDs with a wavelength of 660 nm, manufactured by seul semiconductor, are installed. The spectral composition of these lamps was derived experimentally and is shown in Figure 5. To provide uniform illumination of the growing surface, it is necessary to use lighting devices with a power output of 50 W, mounted at a height of 600-650 mm. This height allows optimal light distribution over the entire growing area, facilitating uniform plant development and maximum photosynthetic efficiency.

By investigating the effect of different lighting spectra in hydroponic systems with the same nutrition and comparing the results with other sources, it is determined that the effectiveness of the developed spectral composition is based on the combination of the spectra of HPS and two peaks of photosynthetic efficiency. This combination of the spectrums complements each other, which allows photosynthesis to proceed as efficiently as possible. This spectrum is complete because it provides optimal coverage of all the key spectrums necessary for healthy plant growth. This helps to increase productivity and energy efficiency in hydroponic systems. Table 1 shows the characteristics of the spectral composition in Figure 5.

Table. 1
The characteristics of the spectral composition

Characteristic name	Description	Value
PAR(mW/cm^2)	Photosynthetic active radiation	3.547
PPFD (umol/ m^2/s)	Total photosynthetic photon flux density	166.425
PPFD_UV (umol/ m^2/s))	Photosynthetic photon flux density in the UV spectrum	0.096
PPFD_B (umol/ m^2/s)	Photosynthetic photon flux density in the blue spectrum	23.739
PPFD_G (umol/ m^2/s)	Photosynthetic photon flux density in the green spectrum	70
PPFD_R (umol/ m^2/s)	Photosynthetic photon flux density in the red spectrum	73,2
PPFD_FR (umol/ m^2/s)	Photosynthetic photon flux density in the near-infrared	3.524
PPFD_IR (umol/ m^2/s)	The flux density of photosynthetic photons in the far-infrared range	0.254
Kppfv(umol/s/klm)	Photon/lumen ratio	14.855
YPFD(umol/n/s)	Output photon flux density	152.551
EchA(mW/cm^2)	Radiation energy at the beginning of the 350 nm range	0.000
EchB(uW/cm^3)	Radiation energy end of the range 1050 nm	0.000
Ep(mW/cm^2)	Radiation energy in the fg zone of 525 nm	3.069
Eb(mW/cm^2)	Radiation energy in the fr zone of 445 nm	0.620
Ey(mW/cm^2)	Radiation energy in the fg zone of 660 nm	1.497
Er(mW/cm^2)	Radiation energy in the fg zone of 630 nm	1.366
Euv(mW/cm^2)	Radiation energy in the fg zone of 395 nm	0.003
Efr(mW/cm^2)	Radiation energy in the fg zone of 880 nm	0.000
Ec(mW/cm^2)	Radiation energy in the fg zone of 750 nm	0.000
Erb Ratio	Measurement stability ratio	2.204
E(lx)	Light intensity in lux	3648
Candle E(fc)	The light intensity in candelas	437.33
CCT(K)	Light color temperature	3650
Ra	Color rendering index	87.5
Ee(mW/cm^2)	Total radiation energy	3.646
S/P	Light to shadow ratio S/P	1.576
Dominant(nm)	Dominant wavelength	580.20
Purity(%)	Spectrum purity	35.6
HalfWidth(nm)	Half spectral width	154.5
Peak(nm)	Peak of the spectrum	659.8
Center(nm)	Central wavelength value in the spectrum	592.8

After a series of experiments, the table demonstrates a comparative characteristic of the efficiency of the LED lighting system in the same climatic conditions for the same plant variety, with the difference in photoperiod of illumination. The spectral composition of the lighting allowed the reduction of the photoperiod to 12 hours. It thus introduced a 12/12 (day/night) light culture cycle, which will save electricity without losing the biochemical composition of the plant (see Table 2).

A distinctive feature of the claimed device is that the lighting system consists of 4 linear lamps with a radiation spectrum of 350-800 nm, 50 W power, and lamp installation height of 600...650 mm for uniform illumination of the useful area of the tray with vegetative crops. The derived spectrum makes it possible to 1) save up to 25% of electricity consumption without losing quality and quantity characteristics, 2) reduce the number of hours of illumination, and 3) be placed in cost-effective climatic conditions.

Table. 2
The characteristics of basil grow experiments

Temperature °C	Humidity %	Light Intensity umol/ m2/s.	Lighting period h	Source
20	60-70	166	12	Current
20-25	60-70	200-300	14-16	[27]
18-26	60-70	100-300	12-16	[28]
22	60-70	350-370	14-16	[29]
22-26	60-70	300-400	16	[30]

By incorporating these features, the device represents a significant step forward in sustainable agricultural technology, supporting economic and ecological goals. This approach highlights the potential of integrating science-driven solutions into modern farming practices, paving the way for more efficient and sustainable food production systems.

4. Conclusions

In this article, an information system model aimed at increasing the efficiency of agricultural production in line with the principles of sustainable development was developed. Studies have shown that optimized hydroponic technologies contribute to more efficient use of water and energy resources, minimizing environmental impact.

The system allows for continuous monitoring of environmental parameters (pH, temperature, humidity) in real-time. The developed information system for hydroponics provides many advantages that significantly enhance the management and productivity of growing operations. By leveraging real-time monitoring, data analytics, and automation, farmers can optimize their processes, improve yields, and contribute to more sustainable agricultural practices.

The basis of the developed utility model is the task of unifying the design with the possibility of replacing the tanks during the growing season, increasing the useful area for growing plants, and setting up optimal lighting in accordance with the needs of specific crops. Water is added only as it is absorbed by plants, evaporated or removed from the system. The developed utility model will be reproduced repeatedly and will be used as a device for recirculating water supply in agricultural production.

This approach aligns with global efforts to balance food security with environmental stewardship, contributing to reduced greenhouse gas emissions, efficient resource utilization, and developing resilient agricultural systems. As such, this technology represents a significant step forward in achieving sustainable development goals in agriculture.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

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