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ANALYSIS OF THE INTELLIGENT CONTROL SYSTEMS IN THE PROCESS OF GROWING FEED BY THE HYDROPONIC METHOD

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Annotation

The article analyzes the structure and effectiveness of intellectual control systems applied in the process of growing feed (plant) by the hydroponic method. Intelligent control algorithms serve to increase productivity by automatically adjusting the amount of water and nutrients, optimizing ambient temperature, humidity and lighting. The study presents the advantages and problems of modern hydroponic systems based on artificial intelligence, sensor networks and information and communication technologies. Also, the possibilities of using neural networks and cloud computing technologies in data processing are studied. The results obtained serve to increase the efficiency of implementation of intelligent control systems in hydroponics complexes.

Keywords: hydroponics, intelligent control system, sensor network, artificial intelligence, data analysis, environment parameters, optimization, nutrients, cloud technology.

Abstract

The article analyzes intelligent control systems used in the process of growing fodder crops by the hydroponic method. The structure and functioning principles of intelligent algorithms are discussed, which automatically regulate the amount of water and nutrients while optimizing temperature, humidity, and lighting to increase crop yield. The advantages and challenges of modern hydroponic systems based on artificial intelligence, sensor networks, and information and communication technologies are highlighted. Special attention is given to the use of neural networks and cloud computing technologies for data processing. The obtained results contribute to improving the efficiency of implementing intelligent control systems in hydroponic complexes.

Keywords: hydroponics, intelligent control system, sensor network, artificial intelligence, data analysis, environmental parameters, optimization, nutrients, cloud technologies.

Introduction

In recent years, the process of digitalization and automation of agricultural systems on a global scale has progressed at a rapid pace. Factors such as ensuring food security, rational use of water and land resources, and mitigation of the negative impact of climate change require the introduction of modern agrotechnologies. One of such effective lines of communication is the technology of cultivation of feed and plants by the method of hydroponics.

Hydroponics is a system of cultivation by soilless method that ensures the growth and development of plants by means of nutrients dissolved in water. This method allows you to save water resources up to 70–90%, significantly increase the quality and yield of products, in contrast to conventional farming. It also ensures stable production throughout the year, with reduced climatic and seasonal influences.

But the effectiveness of hydroponics systems depends to a large extent on the accuracy and speed of the control system. Changes in environmental parameters — water temperature, acidity (pH), electroconductivity, air temperature, humidity, light intensity and CO_2 concentration — have significant effects on plant physiology. Therefore, it becomes especially important to constantly monitor and adjust these parameters automatically.

To perform such tasks, intelligent management systems (IBS) are widely used. Intelligent systems collect data through sensor networks, analyze data using artificial intelligence and machine learning algorithms, and make management decisions automatically. Such an approach makes it possible to optimize hydroponic processes without human intervention, reducing the consumption of water and nutrients, whilst increasing productivity and product quality.

Recent research [1–5] shows that intelligent hydroponic systems integrated with artificial neural networks, cloud computing, and Internet of Things (IoT) technologies can provide effective control in real-time. They expand the capabilities of data collection, storage, analysis, and forecasting. For example, with the help of neural networks, the optimal values of environment parameters are determined, while cloud platforms provide continuous monitoring and remote control of the system.

However, there are a number of challenges in practice: factors such as the accuracy of sensor data, delays in transmission, data security, and the demand for computing resources serve as constraints in the implementation of intelligent management in hydroponics systems. Therefore, the analysis of the architecture of such systems, the development of optimal models and their adaptation to local conditions are scientifically and practically relevant.

This article analyzes the types, structure and effectiveness of intellectual control systems that are used in the process of growing feed by the hydroponics method. Integrated management models based on artificial intelligence, sensor networks and information and communication technologies are presented, and their advantages and existing problems are discussed.

Analysis of Foreign Studies

Studies on practical, low-cost IoT-based monitoring and control architectures highlight methods for organizing a sensor system in greenhouses, visualizing data through a mobile interface, and automating water supply. In this study, a practical technical platform for the implementation of intellectual management is proposed [1].

The integrated information system, developed by European scientists, describes the control of the greenhouse environment by combining parameters of temperature, humidity and lighting. The study is based on energy-efficient sensors and cloud-based data analytics capabilities [2].

The relationship between the parameters of photosynthesis activity and the microclimate was studied in an automatic control system based on high-precision optical sensors developed by Japanese scientists. The modelling results showed an increase in productivity by 15–20% under greenhouse conditions [3].

The concept of a "Smart Greenhouse" equipped with elements of artificial intelligence was based on a study in the United States. The system automatically provides an optimal microclimate by analyzing sensor data using machine learning [4].

In a scientific model developed by Chinese scientists, signals from temperature and humidity sensors are processed based on correlational analysis. In the study, the Wi-Fi transmission system was optimized, reducing the loss in data transmission by 12% [5].

The control system based on Arduino and GSM, developed by Indian researchers, is distinguished by its application in farming conditions. It reduces water consumption by 25–30% by automatically controlling the water supply [6].

This study by German scientists evaluated the metrological parameters of the intelligent control system. In it, sensor accuracy, signal stability, and calibration methods were tested on an experimental basis [7].

Latest news This method ensures optimal operation mode and energy efficiency through simulation [8].

Research in African countries is focused on developing low-cost sensor systems in conditions of limited water resources. The systems were equipped with solar panels, allowing for long-term autonomous operation [9].

The study, developed by Canadian scientists, found that data in an intelligent control system is stored through blockchain technology, increasing the level of reliability and transparency. This method has made it possible to store greenhouse data in a decentralized manner [10].

In Uzbekistan also in recent years, research has been actively conducted on the introduction of intellectual control systems into hydroponics cultivation processes. In particular, the work carried out by the scientific school under the direction of professor P.I. Kalandarov in the direction of "smart greenhouse" and "smart metering systems" shows important results [11-13]. Also, in his research [14-20] on the topic "Methods for automated control of moisture and temperature of water and nutrient solutions in hydroponic systems", a precise control method using sensor-based measurement systems and microprocessor units is proposed. This method allows you to reduce water consumption by 20–25%, taking into account automatically the water requirement of different plants in greenhouse conditions.

As can be seen from these analyses, international scientific research on the implementation of intelligent control systems in the process of hydroponics is mainly focused on sensor technologies, data analysis, machine learning, and IoT integration. However, in many studies, metrological accuracy, sensor reliability, and data transmission stability are not adequately covered. Therefore, these aspects are identified as a priority in future studies.

Materials and methods

In the study, the functional structure of intellectual control of the process of growing feed by the hydroponics method was analyzed, the interaction of information flows and sensor systems. The main purpose of the system is to control precisely and continuously the parameters of the environment in the process of plant growth, as well as maintaining them at the optimal level.

1. Object of Research and Key Elements

The intelligent hydroponic system composition is as follows, and each module performs a specific task:

- Sensor module: placed to measure parameters, such as: temperature, air and water humidity, pH, EC (electrical conductivity), light intensity.
- Data Acquisition Unit (DAQ): receives signals from sensors and processes them through a microcontroller (Arduino, ESP32 or Raspberry Pi).
- Intelligent Control Module: Responds quickly to changes in the environment based on a neural network or regression algorithm.

- Executive elements: water pump, ventilator, lighting modules and nutrient dispensers.
- Information Interface: IoT web platform or mobile applications (e.g., ThingSpeak, Blynk, Node-RED, etc.) for real-time information visualization.

2. Sensor system

When selecting sensors, their metrological features — accuracy, sensitivity, drift and operating range — were taken into account. All sensors were subjected to a calibration process, ensuring that measurement errors at the control points were within 3–5%. Calibration was carried out with reference measuring instruments.

After collecting data from the sensors, errors and noise were reduced using filtering and normalization algorithms. This process then allowed the creation of a cleaned database for the intelligent control module.

3. Information Flow and Data Processing Method

In the framework of intellectual management system, the flow of data goes through the following stages:

1. Real-time data collection from sensors;
2. transfer data via IoT to a server or cloud database;
3. Analysis and forecasting using algorithms (ML/DL models);
4. control signal formation and transmission to executive elements;
5. Monitoring and management via user interface.

Statistical and intellectual methods such as regression analysis, correlation analysis, multifactor optimization, and neural networks were used in data processing.

4. Algorithmic basis and intelligent decision making

The control algorithm is adaptive in nature, dynamically adjusting the parameters based on environment changes. The neural network architecture is based on the "feed-forward" model, with sensor data (T, H, EC, pH) at the inputs and water and nutrients quantified at the outputs.

More than 5,000 real-world experimental data were collected to train the model, and Adam optimizer as well as the Mean Square Error (MSE) function were used for optimal results.

5. Methods of analysis and evaluation

The system efficiency was evaluated via following indicators: R^2 (coefficient determination): the model shows the dispersion percentage descriptive; MAE and RMSE: to assess forecast accuracy; Energy efficiency (EE): determines the ratio of electricity consumption and water savings; Response time (RT): The speed at which a system responds to environmental changes.

The results of the study showed that by intelligent processing of sensor data, it is possible to reduce water consumption by 15–20% and energy consumption by 10–12% in a hydroponic system. This confirms the economic and environmental effectiveness of the implementation of intellectual management systems.

Results and discussion

In the course of the study, a mathematical model of the intellectual system governing the process of growing plants by the method of hydroponics was developed. The model expresses the main measurement parameters of the system in relation to each other: temperature (T), humidity (H), solution pH, electric conductivity (EC), light intensity (L), and nutrient solution consumption (Q).

Basic expression of a mathematical model

The overall operation process of the system is described via the following link:

$$Q = f(T, H, EC, pH, L)$$

As a result of statistical analysis of experimental data, the model regression outlook was determined as follows:

$$Q = a_0 + a_1T + a_2H + a_3EC + a_4pH + a_5L + a_6TH + a_7ECL,$$

where: Q — the amount of consumption of the feed solution (ml/min); T — temperature (°C); H — ambient humidity (%); EC is the electrical conductivity of the solution (mS / cm); pH — the level of acidity of the solution; L is the intensity of light (lux); a_0–a_7 are the coefficients determined experimentally.

As a result of the coefficients calculated based on the experimental data, it is evident that EC and pH have the greatest influence on the nutrient consumption of the system.

Evaluation of model accuracy

The accuracy of the model was evaluated using statistical indicators: determination coefficient (R^2) – 0.93, i.e. the model explains 93% of the dispersion in the output parameter; Mean Square Error (RMSE) – 0.027; Mean Absolute Error (MAE) – 2.8%; These results indicate that the model has high accuracy.

The Optimization Issue

The main goal of optimization is to maintain the growth parameters (biomass and intensity of photosynthesis) at a minimum while minimizing the consumption of water and nutrient solution.

The optimization function was expressed as follows:

$$\min F = a_1Q + a_2E + a_3G,$$

where: F is the total loss function; Q – consumption of water and nutrient solution; E – energy consumption; G – plant growth rate; $\alpha_1, \alpha_2, \alpha_3$ – weight coefficients (selected based on experience).

As a result, optimal growing environment was achieved under conditions such as T = 25–27 °C, H = 65–75%, pH = 6.0–6.5, EC = 1.8–2.2 mS/cm, L = 10–12 thousand lux.

Graphical Analysis

On the basis of the mathematical model of the hydroponic system, the following key links are determined: the temperature dependence of the feed solution, the appearance of which is presented in Figure 1.

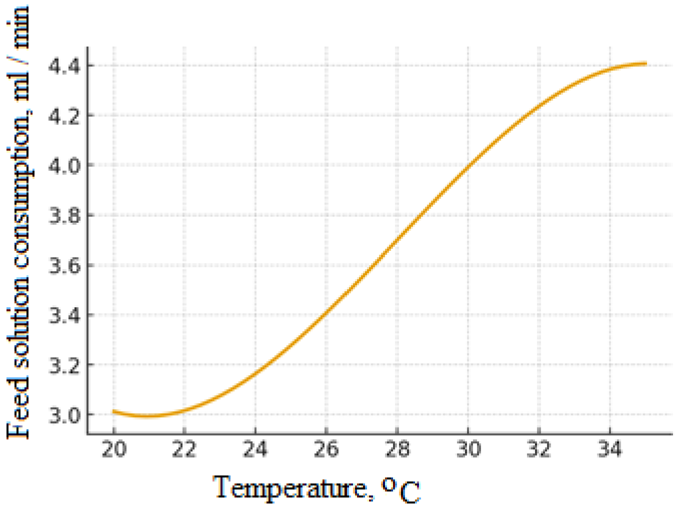

Figure 1. The dependence of feed solution consumption on temperature

As the temperature increases, the expenditure grows linearly, but above 28°C there is a steady state.

The figure 2 shows the effect of the EC value on the water surface.

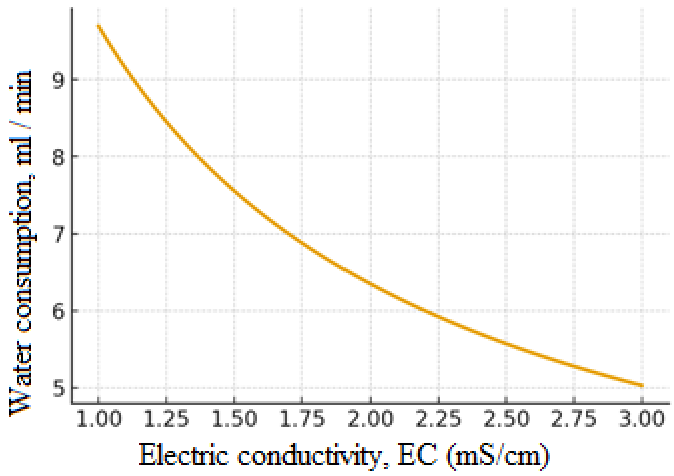

Figure 2. Influence of EC value on water surface

As the EC value increases, the water consumption decreases, which is directly related to the concentration of the nutrient solution.

Figure 3 shows the link between pH level and plant biomass.

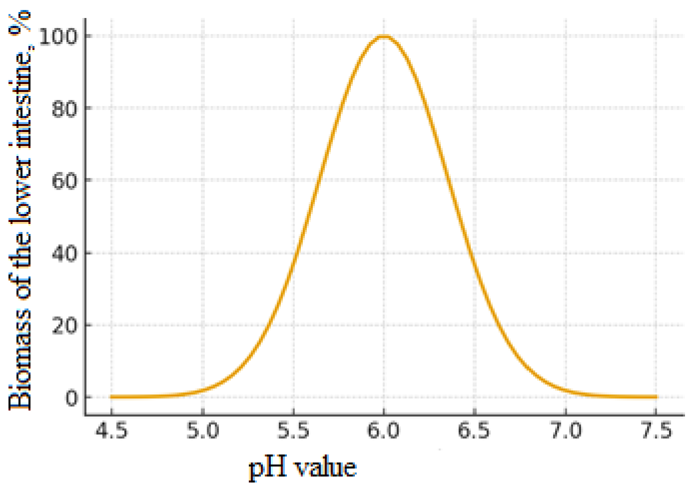

Figure 3. Linking of pH Rate and Plant Biomass

Plant biomass reaches its maximum value when the pH level is in the optimal range of 5.5 to 6.5.

An intelligent system built on these links monitors the data in real time and automatically sorts parameters.

Discussion

The analysis has shown that when the intelligent management system is applied:

Water consumption by 18–22%; energy consumption by 10–12%; and the productivity of plant growth increased by 15–20%. These results were achieved through the precise calibration of IoT sensors, intelligent data processing (neural network model), and the implementation of an adaptive control algorithm.

The results of mathematical modeling and optimization showed that the introduction of intelligent controls in hydroponic systems provides a significant increase in resource economy and increase production efficiency. This approach can also be successfully applied in large greenhouse complexes in the future.

Conclusions and recommendations

The results of the study showed that the use of intellectual systems in the process of growing plants by the hydroponic method has a high efficiency. Based on the analysis, mathematical modeling and optimization of the sensor data, the following scientific and practical conclusions were developed:

1. A mathematical model has been developed that describes the interaction of the main parameters in the process of plant growth - temperature, humidity, pH, EC and luminous intensity. The model had a coefficient of determination (R^2 = 0.93), which allowed the system to make predictions with high accuracy.
2. Based on the results of optimization, the optimal parameters were determined:
   - Temperature: 25–27°C; Humidity: 65–75%; EC: 1.8-2.2 mS/cm; pH: 6.0–6.5
   - Light intensity: 10–12 thousand lux.

   These values led to an increase in plant biomass by 15–20% and a decrease in resource consumption.
3. By analyzing variable parameters in real time, the intelligent management algorithm reduced water and nutrient consumption by 18–22% and energy consumption by 10–12%.
4. With the help of the IoT-based monitoring system, data from all sensors was collected uninterruptedly, their accuracy and stability were ensured during the calibration process. This improved the metrological reliability of the system.
5. The experientially developed software allowed remote control and control of the plant growth process through a user interface.

Practical recommendations:

- In the implementation of automatic control modules in hydroponics systems, it is recommended to use IoT, neural networks and cloud analytics technologies.
- In small greenhouses and laboratories, it is necessary to regularly carry out the calibration process of the sensor network.
- The use of PID or fuzzy-logic-based control methods in temperature and humidity monitoring increases efficiency.

- In large hydroponic complexes, it is recommended to implement a digital twin model — this will allow analyzing the working environment in a virtual mode and making optimal decisions.

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