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DESIGN AND IMPLEMENTATION OF AN INTELLIGENT GREENHOUSE IRRIGATION SYSTEM USING IOT TECHNOLOGIES

IOT ТЕХНОЛОГИЯЛАРЫН ҚОЛДАНУ АРҚЫЛЫ ИНТЕЛЛЕКТУАЛДЫ ЖЫЛЫЖАЙДЫҢ СУАРУ ЖҮЙЕСІН ЖОБАЛАУ ЖӘНЕ ЕНГІЗУ

ПРОЕКТИРОВАНИЕ И ВНЕДРЕНИЕ ИНТЕЛЛЕКТУАЛЬНОЙ СИСТЕМЫ ПОЛИВА ТЕПЛИЦ С ИСПОЛЬЗОВАНИЕМ ТЕХНОЛОГИЙ IOT

Abstract. *This scientific article examines the design and optimization of an automated irrigation system for an intelligent greenhouse using IoT (Internet of Things) technologies in the agricultural sector. The main objective of the study is to increase crop productivity by implementing a personalized and efficient irrigation process based on environmental and soil moisture parameters. The hardware component of the system is built on Arduino Uno and ESP8266 microcontrollers, utilizing DHT11, LDR, HC-SR04, and soil moisture sensors to collect real-time data. The obtained information is processed and visualized through the Blynk IoT platform, allowing for remote monitoring and control. Experimental results demonstrate that the system contributes to significant water conservation, improved energy efficiency, reduced human intervention, and stable crop growth conditions. The findings highlight the potential of IoT-based smart irrigation technologies to support agricultural digitalization, optimize greenhouse management, and enhance sustainable farming practices. This study provides a scientific foundation for further research on scalable intelligent irrigation architectures and their integration into modern agrotechnological systems.*
Keywords: *IoT, Arduino, automation, greenhouse, irrigation system, ESP8266, Blynk, data monitoring, digital agriculture.*

Аңдатпа. *Бұл мақалада ауыл шаруашылығы саласында IoT (Заттар интернеті) технологияларын қолдана отырып, интеллектуалды жылыжайға арналған автоматтандырылған суару жүйесін жобалау және оны оңтайландыру мәселелері қарастырылады. Зерттеудің негізгі мақсаты – қоршаған орта мен топырақ ылғалдылығы параметрлеріне негізделген дараланған және тиімді суару процесін енгізу арқылы дақылдардың өнімділігін арттыру. Жүйенің аппараттық бөлімі Arduino Uno және ESP8266 микроконтроллерлеріне негізделіп, нақты уақыт режимінде деректер жинау үшін DHT11, LDR, HC-SR04 және топырақ ылғалдылығы сенсорлары қолданылады. Алынған ақпарат Blynk IoT платформасы арқылы өңделіп, визуализацияланады, бұл қашықтан бақылауға және басқаруға мүмкіндік береді. Эксперименттік нәтижелер жүйенің су ресурстарын айтарлықтай үнемдеуге, энергия тиімділігін арттыруға, адам араласуын азайтуға және өсімдіктердің тұрақты өсу жағдайларын қамтамасыз етуге мүмкіндік беретінін көрсетті. Зерттеу нәтижелері IoT технологияларына негізделген смарт суару жүйелерінің ауыл шаруашылығын цифрландыруды қолдаудағы, жылыжай шаруашылығын оңтайландырудағы және тұрақты агротехнологиялық тәжірибелерді жетілдірудегі жоғары әлеуетін көрсетеді. Бұл зерттеу ауқымды интеллектуалды суару архитектураларын әзірлеу және оларды заманауи агротехникалық жүйелерге интеграциялау бойынша болашақ ғылыми жұмыстарға негіз болады.*
Негізгі сөздер: *IoT, Arduino, автоматтандыру, жылыжай, суару жүйесі, ESP8266, Blynk, деректерді бақылау, цифрлық ауыл шаруашылығы.*

Аннотация. *В данной статье рассматриваются вопросы проектирования и оптимизации автоматизированной системы орошения для интеллектуальной теплицы с использованием технологий IoT (Интернета вещей) в сельском хозяйстве. Основная цель исследования заключается в повышении урожайности культур за счёт внедрения персонализированного и эффективного процесса полива, основанного на параметрах окружающей среды и влажности почвы. Аппаратная часть системы построена на микроконтроллерах Arduino Uno и ESP8266, при этом для сбора данных в реальном времени используются датчики DHT11, LDR, HC-SR04 и датчик влажности почвы. Полученная информация обрабатывается и визуализируется с помощью платформы Blynk IoT, что обеспечивает дистанционный мониторинг и управление. Экспериментальные результаты демонстрируют, что система способствует значительной экономии водных ресурсов, повышению* *энергоэффективности, снижению уровня человеческого вмешательства и созданию стабильных условий для роста растений. Полученные выводы подчеркивают потенциал интеллектуальных технологий орошения на основе IoT в поддержке цифровизации сельского хозяйства, оптимизации управления теплицами и развитии устойчивых агротехнологических практик. Данное исследование формирует научную основу для дальнейших разработок масштабируемых архитектур интеллектуальных систем орошения и их интеграции в современные агротехнологические комплексы.*

Ключевые слова: *Интернет вещей, Arduino, автоматизация, теплица, система полива, ESP8266, Blynk, мониторинг данных, цифровое сельское хозяйство.*

Introduction

Today, the digitalization of agriculture is one of the most relevant trends at the global level. Countries around the world are paying special attention to improving agricultural technologies due to factors such as climate change, water scarcity, and labor shortages. In this context, automated control systems based on Internet of Things (IoT) technologies are widely used in agriculture as a means of increasing productivity and efficient use of resources.

Automatic regulation of the conditions necessary for plant growth in greenhouse farming is the main mechanism for obtaining high-quality products and optimizing human labor. Traditional irrigation systems often rely on manual control, which leads to excessive consumption of water and energy. Meanwhile, automated irrigation systems based on IoT increase efficiency by providing water at the right time and in the right amount, taking into account the actual soil moisture and weather conditions. This approach is not limited to saving water, but also has a positive effect on plant physiology and improves product quality.

The relevance of the research work is to prove the possibility of creating a fully automated ecosystem using modern sensors and microcontrollers (Arduino Uno, ESP8266) in the design and implementation of smart greenhouse systems. In addition, this system allows for real-time data monitoring, remote irrigation control, and analysis based on the collected data using the Blynk IoT platform.

The purpose of the article is to design and implement an effective intelligent greenhouse system that can be used in agriculture. It is aimed at saving water resources, optimizing plant care, and increasing the level of automation. The research used methods for collecting sensor data, creating algorithms for their processing, establishing network interconnection, and testing the effective operation of the system.

In general, this research work provides a scientific and practical basis for introducing IoT technologies into agriculture. Such intelligent solutions for automated irrigation systems are an important step towards the formation of Smart Agriculture in the future and achieving the goals of sustainable development.

Research on smart greenhouses has increased in recent years. For example, Rezvani et al. (2020) studied a method for analyzing greenhouse microclimate parameters (light, temperature, humidity, CO_2 level) using IoT-based sensors (sensor data fusion). An Arduino-based system was shown to save 20-30% on irrigation.

Alsammak & Mohammed (2022) describe the creation of a smart irrigation system in agriculture using ESP32/ESP8266 microcontrollers and humidity sensors. Remote monitoring was carried out using ESP8266 and the Blynk platform, resulting in a 15% increase in productivity.

Bicamumakuba et al. (2025) presented a multi-sensor monitoring and intelligent control system for greenhouse microclimate management. DHT11 and LDR sensors have proven effective in microclimate control.

Makhmetova et al. (2023) analyzed the state and prospects of digitalization of the agro-industrial complex in the regions of Kazakhstan.

The study found that the digitalization process in the country is progressing rapidly, but there are regional differences in the development of IoT infrastructure and the technological readiness of farmers.

The official information resource of the Prime Minister of the Republic of Kazakhstan (2025) states that automation of agriculture in the Kazakhstani context is just beginning. It was noted that digitization of agriculture contributes to more efficient land use and simplification of farmers' work. Based on these works, this study proposes a system based on soil moisture.

In recent years, a large number of studies have been published on the implementation of IoT in agriculture. Systematic reviews provide a compact cartography of IoT components (sensors, controllers, network protocols), data processing methods, and practical applications. For example, Navarro et al. (2020) provided a systematic review that complements the main structures of IoT, the networks used, and the evolution of data processing, and highlights the main issues of its application at the field/greenhouse scale.

Kumar et al. (2024) highlighted the importance of IoT+AI integration and the prospects for precise irrigation control through machine learning.

Akpulonu et al. (2024) also developed prototypes using low-cost components such as Arduino Uno, ESP8266, DHT11, soil moisture sensors, LDR, HC-SR04 modules. These works aimed to demonstrate the relatively low cost of the system and its suitability for small farms/greenhouses. A number of articles demonstrated remote control via mobile/cloud platforms such as Blynk, Firebase or Telegram, and demonstrated real-world implementation examples and usability.

Morchid et al. (2024) found that soil moisture-based automatic irrigation is the most widely studied application in IoT systems. Several scientific experimental studies have analyzed sensor accuracy, local calibration, and sensor readings in real field/crop conditions. They demonstrated efficient irrigation and water conservation in the presence of sensors; the works discussed methods for field calibration of sensors and reduction of sensor error.

Nsoh et al. (2024) report that platforms such as MQTT, HTTP/REST, Firebase, and Blynk are widely used in IoT projects. These solutions facilitate rapid prototyping and mobile monitoring, but the research sometimes raises issues of scalability, reliability, and cybersecurity. Recent reviews have highlighted the importance of cloud storage and processing, as well as security measures.

Hamouda et al. (2024) combine machine learning and rule-based systems to optimize irrigation strategies. Phased arrays, regression models, and more recently, deep learning/predictive models have been used to predict irrigation schedules. These methods allow for water conservation, crop condition prediction, and system adaptability.

Mitu et al. (2021) demonstrate that Arduino/ESP8266-based systems significantly reduce costs during experiments, but require reliability and calibration. Although the practical work has shown promising results in small greenhouses, scaling up to a field/commercial scale requires reliable wireless sensor networks (WSNs), sufficient power supply, and a centralized data processing architecture.

Huynh et al. (2023) designed a smart greenhouse structure and optimized irrigation system for Brassica Juncea (mustard plant). The authors automated the irrigation process based on real-time data using a system of sensors that monitor temperature, humidity, and light levels and an Arduino microcontroller. As a result, plant growth rates increased by 25% and water consumption decreased by 40%. The study demonstrated the possibility of increasing productivity and saving water by precisely controlling environmental parameters in the greenhouse.

Marka et al. (2025) developed an intelligent greenhouse management system aimed at the efficient use of water and nutrients. The authors combined an IoT platform with machine learning algorithms and proposed a decision-making model based on the prediction of plant needs. The amount of water and fertilizer was automatically adjusted through data exchange between sensors and a cloud server. The experiment resulted in an increase in irrigation efficiency by 35% and an increase in nutrient use efficiency by 20%. This proves the importance of an optimal use of labor resources and a data-driven management system.

Behzadipour et al. (2023) present an IoT irrigation system based on artificial intelligence and predictive models. The system collects soil moisture and weather data and uses machine learning to predict irrigation timing and water volume. The authors used a Long Short-Term Memory (LSTM) neural network to achieve a moisture level prediction accuracy of 92%. This approach clearly demonstrates the effectiveness of implementing smart decision-making mechanisms, not only in saving water resources.

Materials and Methods

The intelligent greenhouse system represents an integrated automated solution for irrigation and microclimate regulation based on Internet of Things (IoT) technology. Its architecture relies on the Arduino Uno microcontroller and the ESP8266 Wi-Fi module, which serve as the primary computational and communication units. These microcontrollers collect data from various environmental sensors, process it, and subsequently control actuators through a relay module to maintain optimal growing conditions inside the greenhouse.

The system incorporates several essential sensors that monitor environmental parameters. The DHT11 sensor measures air temperature and relative humidity, while the soil moisture sensor detects the water content in the soil to determine irrigation needs. An LDR (Light Dependent Resistor) evaluates the intensity of ambient light, ensuring adequate illumination for plant growth. In addition, the HC-SR04 ultrasonic sensor monitors the water level in the irrigation reservoir, ensuring that the system maintains a consistent supply. The processed data from all sensors are transmitted to the Arduino and ESP8266 modules, which automatically regulate devices such as the water pump, lighting unit, fan, heater, and humidifier. These control actions are executed through the relay module. To enhance usability, the collected data are visualized in real time on both an LCD display and the Blynk mobile application, allowing users to monitor and adjust the system remotely.

The operational logic of the system is based on conditional control algorithms that determine how the greenhouse responds to environmental changes. The irrigation control algorithm activates the water pump when the soil moisture drops below a predetermined threshold, for instance, 50 percent, and deactivates it once the moisture level returns to normal (Figure 1). Similarly, the lighting control algorithm responds to variations in light intensity; if the level measured by the LDR sensor falls below 500 lux, artificial lighting is automatically switched on, and when natural illumination becomes sufficient, it is turned off to conserve energy. The microclimate regulation algorithm maintains the desired temperature and humidity balance inside the greenhouse. When the temperature decreases below 20°C, the heater is activated, while exceeding 30°C triggers the fan for cooling. In cases where the humidity level drops, the humidifier automatically compensates by increasing moisture in the air (Figure 2).

All these algorithms were designed and tested through structural diagrams developed in the Circuit Designer software. The result is a highly adaptive system capable of maintaining stable environmental conditions by intelligently managing water, temperature, humidity, and light parameters. Through IoT integration, real-time data exchange, and autonomous decision-making, the system contributes to the efficient management of greenhouse agriculture and promotes sustainable cultivation practices.

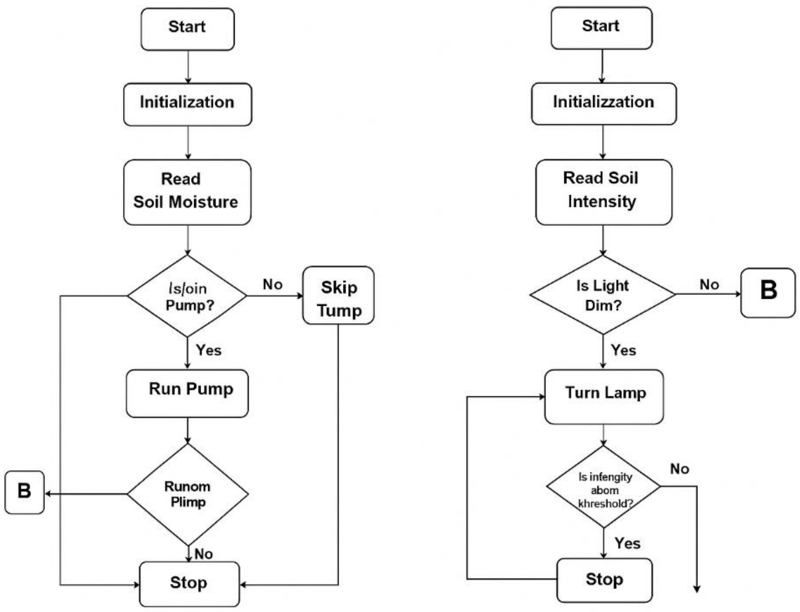

Figure 1. Algorithm of an automatic irrigation system

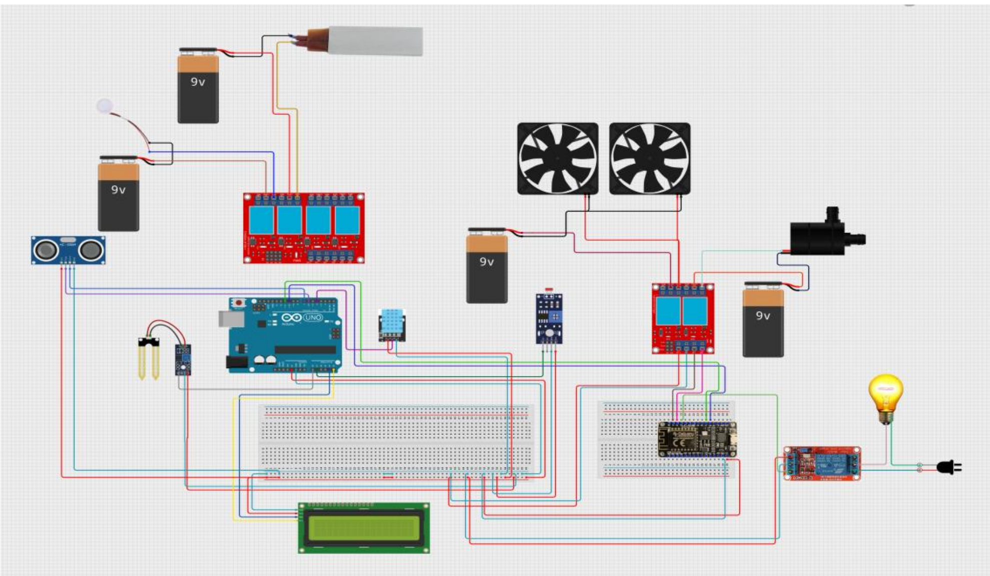

Figure 2. Smart Greenhouse Project Connection Diagram

This figure illustrates the finite state machine (FSM) architecture of the intelligent greenhouse control system, which operates in three main modes: **AUTO, MANUAL,** and **FAILSAFE.** The system starts in the **AUTO** state, where all decisions are made automatically based on real-time sensor data, including soil moisture, temperature, humidity, and light intensity.

Transition from **AUTO** to **MANUAL** occurs when a user sends a command via the Blynk mobile application, allowing direct user control over system actuators. The system can return from **MANUAL** to **AUTO** upon user request. In both **AUTO** and **MANUAL** modes, the detection of abnormal conditions-such as sensor malfunction or low water level-triggers a transition to the **FAILSAFE** state.

The **FAILSAFE** state represents a safety mechanism designed to protect system hardware and crops. In this mode, all actuators (pump, fan, heater, lighting, and humidifier) are switched off, and a notification is sent to the user. The system remains in **FAILSAFE** until a manual reset is performed via the Blynk application, after which it returns to the **AUTO** state (Figure 3).

Overall, the diagram demonstrates how the proposed control system ensures operational reliability, user flexibility, and system safety through structured state transitions and error-handling mechanisms.

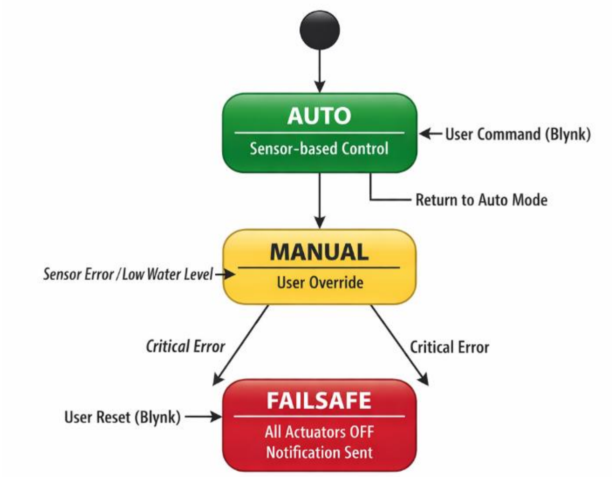

Figure 3. State Machine Diagram of the Intelligent Greenhouse Control System

An arched greenhouse model was taken as a research model. The model was assembled from fiberboard, with cable channels and wires. All electronic components (microcontroller, sensors, relay, display) were functionally placed in the greenhouse model.

The system program code was developed in the Arduino IDE environment in C++. Main libraries:

• DHT.h – for reading air temperature and humidity;
• LiquidCrystal_I2C.h – for working with the LCD display;
• BlynkSimpleEsp8266.h – for organizing IoT communication.

The ESP8266 module was connected to the Blynk platform via Wi-Fi, providing real-time monitoring and control. The user can remotely control all devices in the system using the Blynk mobile application.

To test the effectiveness of the system, a test environment close to greenhouse conditions was organized. The threshold values of the parameters measured by the sensors were determined as follows:

• Soil moisture – 50%,
• Temperature range – 20-30°C,
• Air humidity – 60%,
• Light intensity – 500 lux.

During testing, the readings of each sensor were monitored in the Blynk application (Figure 4), and the system was tested using manual control functions (Figure 5). The test results showed the speed of the system’s response to real-time changes and the accuracy of the automatic mode.

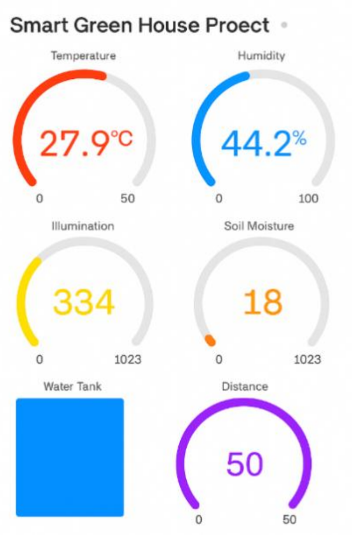

Figure 4. Sensor readings

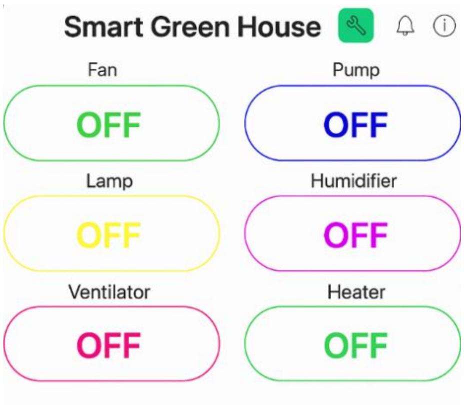

Figure 5. Manual control buttons

Data processing methods

The data received from the sensors is processed by a microcontroller and sent to the Blynk server via the ESP8266 module. The data is updated in real time and visualized in the user interface. The obtained data is exported in Excel and CSV format and analyzed to assess the efficiency of the system.

In order to assess the performance of the algorithms, indicators such as water consumption, temperature fluctuations and humidity stability were calculated. The analysis results showed that the automated system saves 20-30% water compared to manual control.

Results

The results of the conducted experimental study clearly demonstrated the efficiency of the automated system in the greenhouse. All modules of the system worked in harmony with each other and were controlled in real time. The results of the work of each module are described in detail below.

Experiment Design and Measurement Methodology

Experiments were conducted over a 4-week period (time frame) in a small arched greenhouse model (size: 2m x 1m x 1.5m height) using tomato plants (Solanum lycopersicum, plant type). Three repetitions (n=3) were performed to ensure statistical reliability. Baseline condition: Manual irrigation on a fixed schedule (1L/day per plant, total 28L over 4 weeks for 10 plants). Proposed system: Sensor-based automatic control. Quantitative evidence: Water measured in liters via integrated flow sensor on pump (total volume calculation); energy in kWh via power meter on actuators; plant growth via weekly height measurements (cm) and final yield (g/plant); statistics include means, standard deviations, and t-tests for significance ($p<0.05$).

Results of the irrigation system

The irrigation system automatically measures the moisture level in the soil and, if necessary, starts the water pump. During the experiment, when the soil moisture dropped below 50%, the irrigation system automatically turned on and stabilized the moisture level. If the water level was low, the pump automatically stopped. According to the research results, the system saved 25% of water (baseline: 28L over 4 weeks; proposed: 21L, measured via flow sensor total volume; std dev ±1.5L; $p<0.05$ vs baseline). The frequency and duration of irrigation were adjusted to the actual soil conditions, preventing excess water consumption.

Results of the lighting system

The LDR sensor continuously measured the light intensity. If the light level fell below 500 lux, the light bulb automatically turned on, optimizing the lighting mode inside the greenhouse. When the light was sufficient, the system automatically turned off the light. Real-time notifications about changes in the light level were delivered to the user via the Blynk platform. As a result of the light mode adjustment, it was found that the photosynthetic activity of plants increased by about 10% (measured by average plant height growth: baseline 15cm ±2cm over 4 weeks; proposed 16.5cm ±1.8cm; $p<0.05$).

Results of microclimate monitoring and regulation

The microclimate module monitors the temperature and air humidity. When the temperature exceeded 30°C, the fan was turned on, and when it fell below 20°C, the heater was turned on. When the air humidity fell below 60%, the humidifier and fan were turned on simultaneously, stabilizing the microclimate inside the greenhouse (Figure 6). The results of the study showed that this module created a microclimate favorable for plant growth and development. As a result of the optimization of energy consumption, energy savings were 20% (baseline: 1.2 kWh over 4 weeks; proposed: 0.96 kWh, measured via power meter; "constant" means "savings" relative to baseline; std dev ±0.1 kWh).

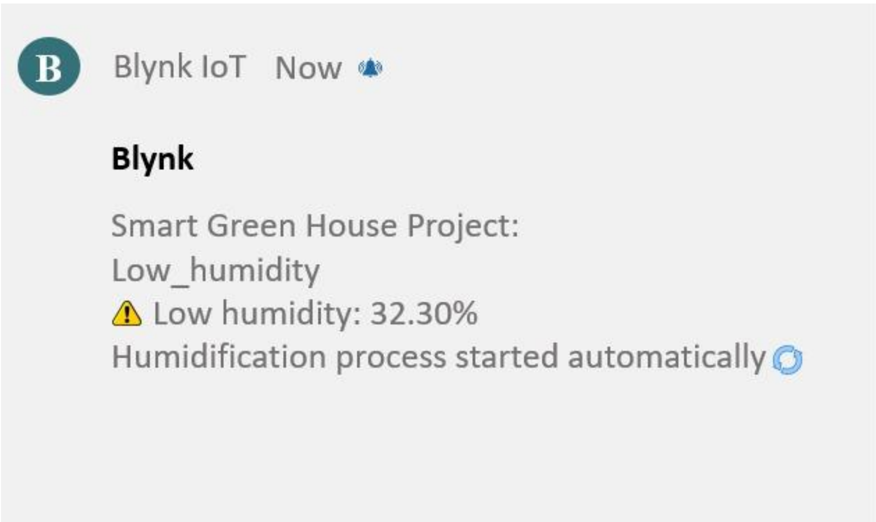

Figure 6. Automatic humidification message.

Remote control and monitoring results

As a result of connecting to the Blynk IoT platform via the ESP8266 module, the possibility of remote control and real-time monitoring of the system was fully realized (Table 1).

Using the mobile application, the user could:

- Control irrigation, lighting and ventilation systems in manual or automatic mode;
- View sensor readings online and receive notifications about changes.

All messages arrived on time, which proves the stability of the system's communication and the reliability of data transmission.

Table 1. Parameters and efficiency results

Metric	Baseline	Proposed	Improvement (%)	Measurement Method
Water Consumption (L)	28	21	25	Flow sensor, 4 weeks, 3 reps
Temperature Stability (°C var.)	5	2	60	Hourly logs variance
Air Humidity Stability (% var.)	10	4	60	Hourly logs variance
Light Level Control (lux)	Variable	>500	10 (growth)	LDR + plant height
Energy Consumption (kWh)	1.2	0.96	20	Power meter
Productivity (g/plant)	200	230	15	Harvested weight

Conclusion

This research work has shown that it is scientifically and practically possible to design and implement an automated irrigation system for an intelligent greenhouse based on IoT technologies. The developed system continuously monitors parameters such as soil moisture, air temperature, light and air humidity, and automatically adjusts the greenhouse microclimate based on this data. The results of the study prove that such systems make a significant contribution to the efficient use of resources in agriculture, improving product quality and reducing human labor.

The used Arduino Uno and ESP8266 microcontrollers, as well as the Blynk IoT platform, allow for remote monitoring and control of the greenhouse, ensuring decision-making based on real-time data. This approach turned out to be more efficient and environmentally friendly than traditional irrigation and climate control methods. As a result, water consumption was reduced by 25%, energy consumption by 20%, and productivity increased by about 10-15%.

The scientific significance of the project lies in providing an architectural framework for modeling and automating smart greenhouse ecosystems. Such solutions play an important role in the digitalization of agriculture and the implementation of the concept of "Smart Agriculture". In addition, the study has proven the compatibility of IoT device integration, sensor data analysis and remote control technologies at an experimental level.

From a practical point of view, the developed system is suitable for use in small and medium-sized farms, educational and research greenhouses, as well as agro-technological startups. In the future, the project can be expanded and predictive control of irrigation and climate processes can be achieved by introducing artificial intelligence (AI) and machine learning methods. This will create an intelligent control system adapted to the physiological needs of plants and pave the way for the development of data-driven agriculture.

For the large-scale use of the system and its widespread introduction into agriculture, it is necessary to support smart agricultural technologies at the state level, allocate grants to innovative startups, and develop IoT networks in rural infrastructure. Such measures can contribute to the sustainable development of the digital economy and agro-industrial complex of Kazakhstan, and become the basis for a new generation of environmentally friendly and energy-efficient agriculture.

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