ISNN 3030-3907

2026
JUNE
ISSUE - 6
VOLUME -4

DEVELOPMENT OF SCIENCE

scientific journal



Development of science

Ilmiy jurnal

IYUN 2026
Issue - 6, VOLUME – 4

ISSN 3030 -3907

Ilmiy jurnal OAK rayosatining 2024 yil 27 sentabrdagi 361-son qaroriga asosan 02.00.00 kimyo fanlari hamda 2025 yil 12 fevral 367- son qaroriga asosan 05.00.00 texnika fanlari bo‘yicha falsafa doktori (PhD) va fan doktori (DSc) ilmiy darajasiga talabgorlarning dissertatsiya ishlari yuzasidan dissertatsiyalari asosiy ilmiy natijalarini chop etish tavsiya etilgan milliy ilmiy nashrlar ro‘yxatiga kiritilgan.

BOSH MUHARRIR:
Temirov Alisher Hoshim o‘g‘li – texnika fanlari falsafa doktori (PhD),Dotsent.
TAHRIRIYAT KENGASH RAISI:
Fozilov Sadriddin Fayzullayevich – texnika fanlari doktori, professor
TAHRIRIYAT KENGASH A’ZOLARI

TEXNIKA FANLARI/ TECHNICAL SCIENCES/ ТЕХНИЧЕСКИЕ НАУКИ

Bozorov G‘ayrat Rashidovich
Buxoro Davlat Texnika Universiteti, professor
Abdurahmonov Olim Rustamovich
Buxoro Davlat Texnika Universiteti, professor
Adizov Bobur Zamirovich
O‘zbekiston Respublikasi Fanlar akademiyasi Umumiy va noorganik kimyo instituti, professor
Hayitov Ruslan Rustamjonovich
Buxoro Davlat Texnika Universiteti, professor
Jumayev Qayum Karimovich
Buxoro Davlat Texnika Universiteti, professor.
Berdiyev Dorob Murodovich
Islom Karimov nomidagi Toshkent Davlat Texnika Universiteti, professor
Maxmudov Rafiq Amonovich
Buxoro Davlat Texnika Universiteti, professor.
Tilloyev Lochin Ismatilloyevich
Buxoro Davlat Texnika Universiteti, dotsent.
Raxmonov Qahramon Sanakulovich
Buxoro Davlat Texnika Universiteti, dotsent.
Barakayev Nusratullo Rajabovich
Islom Karimov nomidagi Toshkent Davlat Texnika Universiteti, professor.
Jo‘rayev Xayrullo Fayziyevich
Buxoro Davlat Texnika Universiteti, professor.
Panoyev Erali Rajabboyevich
Buxoro Davlat Texnika Universiteti, dotsent.
Ataullayev Sherzod Nabiullyevich
Buxoro Davlat Texnika Universiteti, dotsent.
Murodov Malik Negmurodovich
Buxoro Davlat Texnika Universiteti, dotsent.
Axmedova Ozoda Bahronovna
Islom Karimov nomidagi Toshkent Davlat Texnika Universiteti.
Safarov Bahri Jumayevich
Buxoro Davlat Texnika Universiteti, dotsent.
Xaydarov Axtam Amonovich
Buxoro Davlat Texnika Universiteti, dotsent.
Safarov Jasur Alijon o‘g‘li
Buxoro Davlat Texnika Universiteti, dotsent.

KIMYO FANLARI/ CHEMICAL SCIENCES/ ХИМИЧЕСКИЕ НАУКИ

Axmedov Voxid Nizomovich
Buxoro Davlat Texnika Universiteti, professor
Umarov Baqo Bafoyevich
Buxoro Davlat Universiteti, professor
Kodirov Abduaxad Abduraximovich
Qarshi davlat Universiteti, professor
Qurbonov Mingniqul Jumagulovich
Qarshi davlat Universiteti, dotsent
Turemuratov Sharibay Naurizbaevich
O‘zbekiston Respublikasi Fanlar akademiyasi Qoraqalpog‘iston bo‘limi Bosh ilmiy kotibi, professor
Tursunov Kaxor Shonazarovich
Qarshi davlat Universiteti, professor
Do‘stov Hamro
Buxoro Davlat Texnika Universiteti, professor
Panoyev Nodir Shavkatovich
Buxoro Davlat Texnika Universiteti, dotsent.
Olimov Bobur Bahodir o‘g‘li
Buxoro Davlat Texnika Universiteti, dotsent.
Kasimov Sherzod Abduazimovich
Termiz Davlat Universiteti, professor.
Aliqulov Rustam Valiyevich
Termiz Davlat Universiteti, professor
Tropov Xamza Tursunovich
Samarqand Davlat Universiteti, professor

IQTISODIYOT FANLARI/ ECONOMICS/ ЭКОНОМИЧЕСКИЕ НАУКИ

Nizamov Aslitdin Badreddinovich
Buxoro Davlat Texnika Universiteti, professor.
Boboyev Akmal Choriyevich
Buxoro Davlat Texnika Universiteti, professor.
Ergashxojayeva Shaxnoza Djasurovna
Toshkent davlat iqtisodiyot universiteti, professor
Saidaxmedova Nodira Ilxomovna
Toshkent davlat iqtisodiyot universiteti, professor
Muxsinov Bekzod Toxirovich
Buxoro Davlat Texnika Universiteti, dotsent.
Shakarov Qulmat Ashirovich
Renessans ta'lim universiteti,dotsent.
Jumaeva Zulfiya Qayumovna
Buxoro Davlat Texnika Universiteti, dotsent.
Norova Salomat Yusupovna
Buxoro Davlat Texnika Universiteti, dotsent.
Avezova Shaxnoza Maxmudjonovna
Buxoro Davlat Texnika Universiteti, dotsent.
Jalilov Jamshid G‘anijonovich
Toshkent davlat iqtisodiyot universiteti, dotsent
Xasanova Gulruh Djumanazarovna
Buxoro Davlat Texnika Universiteti, dotsent.

PEDAGOGIKA FANLARI/ PEDAGOGICAL SCIENCES / ПЕДАГОГИЧЕСКИЕ НАУКИ

Siddiqova Sadoqat G‘afforovna
Buxoro Davlat Texnika Universiteti, dotsent.
Zoyirov Erkin Xalilovich
Buxoro Davlat Texnika Universiteti, DSc, professor
Gaffarov Feruz Hasanovich
Puchon Universiteti, *professor*
Ruziyev Davron Yuldashevich
Buxoro Davlat Universiteti, professor
Muradova Firuza Rashidovna
Buxoro Davlat Texnika Universiteti, professor.
Yunusova Gulandon Samiyevna
Buxoro Davlat Texnika Universiteti, professor.
To‘xtayeva Zebo Sharifovna
Buxoro Davlat Texnika Universiteti, professor.
Navro‘zova Gulchixra Nigmatovna
Buxoro Davlat Texnika Universiteti, dotsent.
Uzoqova Laylo Polvonovna
Buxoro muhandislik – texnologiya instituti, dotsent.
To‘raqulova Marjona Qiyom qizi
Buxoro Davlat Texnika Universiteti, dotsent.
Muradova Zarina Rashidovna
Buxoro Davlat Texnika Universiteti, dotsent.
Murodov Sanjar Aslonovich
Buxoro Davlat Texnika Universiteti, dotsent.
Shodiyev Jahongir Jo‘raqulovich
Buxoro Davlat Texnika Universiteti, dotsent
Gaffarov Laziz Hasanovich
Buxoro muhandislik – texnologiya instituti, dotsent.

Tahririyat a’zolarning to‘liq ro‘yxati jurnalning www.devos.uz saytida keltirilgan.

Tahririyat hay’ati a’zolarining tarkibini o‘zgartirish hamda qo‘shimcha kiritish yoki tahririyat a’zoligidan chiqarish bosh muharrir tomonidan amalga oshiriladi.

ISSN 3030-3907

Development of science ilmiy jurnali 2024 yil 15 aprel kuni №256445 sonli guvohnoma bilan Davlat ro‘yxatidan o‘tgan.

To‘plam elektron ko‘rinishda (pdf formatida) mualliflarga taqdim etiladi. To‘plamga kiritiladigan maqolalarning mazmuni, ulardagi statistik ma’lumotlar va me’yoriy hujjatlarning to‘g‘riligiga hamda har qanday fikr - mulohazalarga mualliflarning o‘zlari mas’ul hisoblanadilar. Talablarga javob bermaydigan maqolalar to‘plamga kiritilmaydi. Tashkiliy qo‘mita maqola matnini qisqartirish, qisman tuzatish kiritish, seksiyalarga joylashtirish huquqiga ega.

ISSN 3030-3907

IOT OR ARDUINO-BASED AUTOMATIC CONTROL OF HUMIDITY AND TEMPERATURE IN GREENHOUSE CONDITIONS

Jabborov Alisher Oltiboyevich
Tashkent Institute of Chemical Technology
Email: alisheroltiboyevich@gmail.com
Urolov Akbar Ziyadullayevich
Tashkent Institute of Chemical Technology
Email: fxakbarurolov99@gmail.com

Annotatsiya. Qishloq xo‘jaligida issiqxona mikroiqlimini boshqarish hosildorlikni oshirish, suv va elektr energiyasidan samarali foydalanish hamda inson mehnatini kamaytirishda muhim ahamiyatga ega. Harorat va namlikni boshqarishning an’anaviy usullari ko‘p vaqt talab qiladi, mehnat sarfini oshiradi va ko‘pincha barqaror natijalarni ta’minlay olmaydi. Ushbu tadqiqotda IoT texnologiyasi va Arduino mikrokontroller platformasi asosida ishlab chiqilgan avtomatik boshqaruv tizimining tuzilishi, ishlash prinsipi hamda samaradorligi yoritilgan. Tizim tarkibiga DHT22 harorat va namlik sensori, tuproq namligi sensorlari, shuningdek, ventilyator, suv nasosi va isitkich kabi ijro mexanizmlari kiritilgan. O‘lchangan ma’lumotlar real vaqt rejimida qayd etilib, bulutli tizimga uzatiladi. Tadqiqot natijalari shuni ko‘rsatadiki, ishlab chiqilgan avtomatlashtirilgan boshqaruv tizimi issiqxonadagi haroratni ±0,8 °C aniqlikda ushlab turish hamda havoning nisbiy namligini 60–70% oralig‘ida barqarorlashtirish imkonini beradi. Bundan tashqari, qo‘lda boshqarish usuli bilan taqqoslaganda, suv sarfi 20% ga, elektr energiyasi iste’moli esa 15% ga kamaygani aniqlandi. Taklif etilayotgan yechim arzon, ishonchli va samarali bo‘lib, O‘zbekiston sharoitida kichik va o‘rta fermer xo‘jaliklari uchun qo‘llashga mos keladi hamda kelgusida keng miqyosda joriy etish imkoniyatiga ega.

Kalit so‘zlar: Arduino, IoT, issiqxona, avtomatlashtirish, harorat, namlik, aqlli issiqxona, aqlli qishloq xo‘jaligi, mikroiqlimni boshqarish, sensorlar, DHT22, ESP32, tuproq namligi, suv nasosi, ventilyator, PID rostlash, On–Off boshqaruv, energiya samaradorligi, suv tejamkorligi, resurslarni boshqarish, aqlli sug‘orish, simsiz sensor tarmoqlari, Blynk, bulutli texnologiya, real vaqt rejimida monitoring, energiya tejash, issiqxona iqlimi, avtomatik sug‘orish, o‘lchash tizimlari.

Аннотация. В сельском хозяйстве управление микроклиматом теплицы имеет важное значение для повышения урожайности сельскохозяйственных культур, эффективного использования водных и энергетических ресурсов, а также снижения затрат человеческого труда. Традиционные методы регулирования температуры и влажности требуют значительных временных и трудовых затрат и зачастую не обеспечивают стабильных результатов. В

ISSN 3030-3907

данном исследовании рассматриваются структура, принцип работы и эффективность автоматизированной системы управления, разработанной на основе технологии IoT и микроконтроллерной платформы Arduino. В состав системы входят датчик температуры и влажности DHT22, датчики влажности почвы, а также исполнительные механизмы, такие как вентилятор, водяной насос и нагреватель. Измеренные данные регистрируются в режиме реального времени и передаются в облачную систему. Результаты исследования показывают, что разработанная автоматизированная система управления способна поддерживать температуру в теплице с точностью ±0,8 °C и стабилизировать относительную влажность воздуха в диапазоне 60–70%. Кроме того, по сравнению с ручным способом управления расход воды был снижен на 20%, а потребление электроэнергии — на 15%. Предлагаемое решение является недорогим, надежным и эффективным для малых и средних фермерских хозяйств в условиях Узбекистана, а также имеет перспективы для дальнейшего широкомасштабного внедрения.

Ключевые слова: Arduino, IoT, теплица, автоматизация, температура, влажность, умная теплица, умное сельское хозяйство, управление микроклиматом, датчики, DHT22, ESP32, влажность почвы, водяной насос, вентилятор, PID-регулирование, On–Off управление, энергоэффективность, водосбережение, управление ресурсами, интеллектуальное орошение, беспроводные сенсорные сети, Blynk, облачные технологии, мониторинг в режиме реального времени, энергосбережение, тепличный климат, автоматический полив, измерительные системы.

Abstract. In agriculture, managing the greenhouse microclimate is of great importance for increasing crop yield, ensuring efficient use of water and electricity, and reducing human labor. Traditional methods of controlling temperature and humidity are time-consuming, labor-intensive, and often fail to provide stable results. This study presents the design, operating principle, and efficiency of an automatic system developed using IoT technology and the Arduino microcontroller platform. The system incorporates a DHT22 temperature-humidity sensor, soil moisture sensors, as well as actuators such as a fan, water pump, and heater. Data are recorded in real-time and transmitted to a cloud-based system. The results show that the automated control system is capable of maintaining the greenhouse temperature with an accuracy of ±0.8 °C and stabilizing humidity within the 60–70% range. Moreover, compared to manual control, water consumption was reduced by 20% and electricity usage by 15%. The proposed solution is low-cost, reliable, and efficient for small and

ISSN 3030-3907

medium-sized farms in Uzbekistan, with the potential for large-scale implementation in the future.

Keywords: Arduino, IoT, greenhouse, automation, temperature, humidity, smart greenhouse, smart agriculture, microclimate control, sensors, DHT22, ESP32, soil moisture, water pump, fan, PID control, On–Off control, energy efficiency, water saving, resource management, smart irrigation, wireless sensor networks, Blynk, cloud technology, real-time monitoring, energy saving, greenhouse climate, automatic irrigation, measurement systems.

INTRODUCTION.

Materials and Methods

In recent years, the use of digital technologies in agriculture, particularly IoT (Internet of Things) and microprocessor-based control systems, has expanded significantly. Specifically, the implementation of automated systems in greenhouses contributes to increasing crop yield, conserving water and energy resources, and reducing errors caused by the human factor. As highlighted in the article “Smart Greenhouse Environmental Control Using IoT-Based Sensing”, the primary objective is to maintain microclimate parameters at constant and optimal levels to ensure favorable conditions for plant growth [1].

Within the scope of this study, the developed automation system consists of two main components: hardware and software. The Arduino Uno microcontroller was selected as the central controller, since it is open-source, widely used for managing various sensors and actuators, supported by extensive libraries, and characterized by a simple interface. In addition, the ESP32 microcontroller can also be utilized as an alternative, as it provides higher processing speed and, as noted in “ESP32 features integrated Wi-Fi and Bluetooth capabilities for IoT applications” [2], offers direct connectivity to the internet.

In the sensor unit, the high-precision DHT22 temperature and humidity sensor was selected. This sensor is capable of measuring temperature with an accuracy of ±0.5 °C and relative humidity with an accuracy of ±2%. As stated in “The DHT22 sensor provides calibrated digital output of temperature and humidity” [3], its advantages lie in reliable and calibrated measurements. To measure soil moisture, a soil moisture sensor was installed, allowing continuous monitoring of the water content in the root zone and optimization of the irrigation process. The placement of sensors inside the greenhouse was also scientifically justified: they were installed at heights of approximately 1–1.2 m, where air currents have minimal influence. As a result, measurement reliability was increased, ensuring the effective operation of the entire system (Fig. 1).

ISSN 3030-3907



Figure 1. Experimental setup in the greenhouse based on Arduino/ESP32 microcontroller with DHT22 and soil moisture sensors

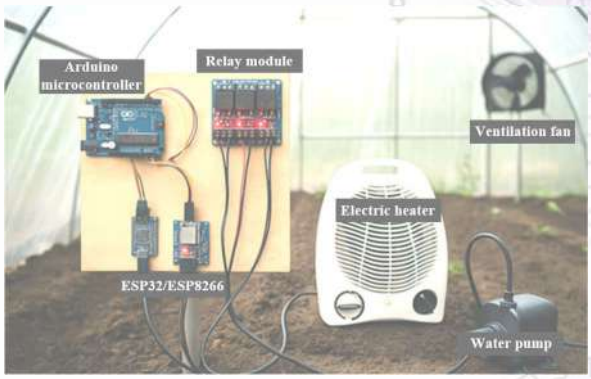


Figure 2. Control system for fan, heater, and pump using Arduino/ESP32

As noted above, achieving a stable microclimate in greenhouses requires not only high-accuracy sensors but also actuators that are closely integrated with them. Based on the data received from the sensors, the actuators are activated to automatically regulate the internal conditions of the greenhouse. The fundamental principle here is that the ***sensor → microcontroller → actuator chain*** must operate seamlessly, since otherwise the overall efficiency of the system may decrease significantly. As emphasized in "Actuators in greenhouse automation play a key role in maintaining environmental balance by controlling ventilation, heating and irrigation subsystems" [4], actuators are indeed essential for sustaining optimal environmental conditions.

In this study, several key actuators were tested. The fan ensured continuous air circulation, removed excess heat, and evenly distributed humidity inside the greenhouse. The heater prevented temperature drops during the winter season, thereby creating favorable conditions for the vegetative development of plants. To increase humidity levels, both a water pump and an ultrasonic humidifier were employed. As noted in "The ultrasonic humidifier generates fine water droplets which help to rapidly increase the relative humidity of the greenhouse air" [5], this process is scientifically supported. All of these actuators were connected to the Arduino or ESP32 through a relay module. The relay module served as an isolator between high-voltage devices and low-voltage control signals, thereby ensuring system safety and reliability.

Additional protective measures were implemented to ensure the reliable operation of the actuators. To safeguard the devices from excessive humidity and temperature, they were placed in plastic enclosures compliant with the IP54 standard. Power was supplied through 12 V/10 A sources, while the microcontrollers operated with the help of a 5 V stabilizer. Furthermore, thermal

ISSN 3030-3907

fuses, emergency stop buttons, and visual warning LEDs were integrated into the system. As highlighted in "Protective measures such as fuses and emergency stop switches ensure long-term operational reliability in automated greenhouses" [6], these solutions enhanced long-term system reliability and further strengthened electrical safety (Fig. 3).

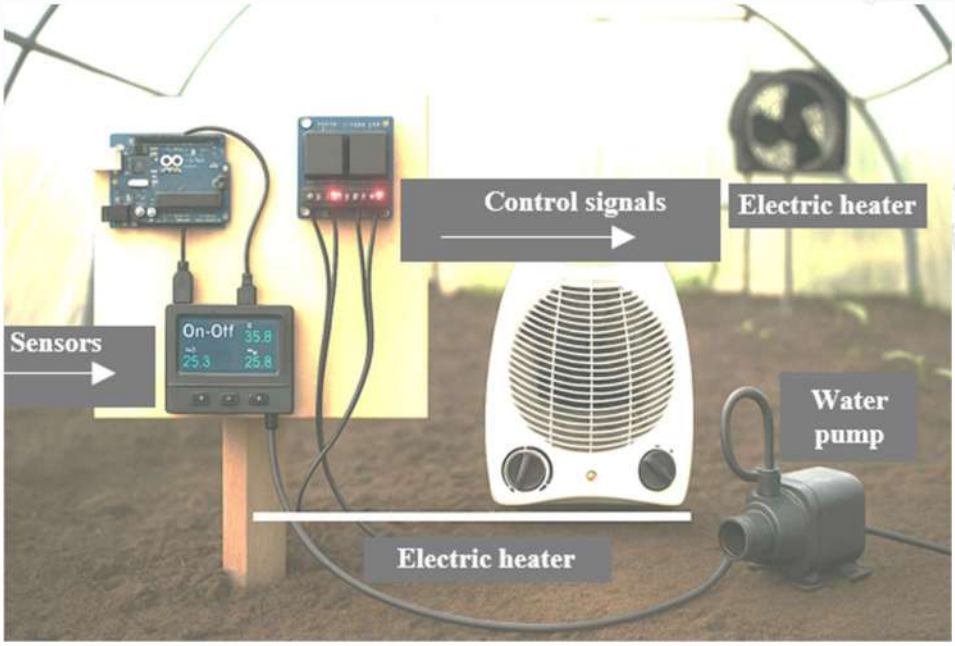


Figure 3. Arduino/ESP32-based system operating with On–Off and PID control algorithms in the greenhouse

Once the capability to control the greenhouse environment through actuators was established, software development became equally important for further improving system performance. In fact, regardless of how accurate the sensor data may be, without effective control algorithms it is difficult to maintain stable conditions inside the greenhouse. Therefore, during the research process, the software component was developed in the Arduino IDE environment, and two control approaches—On–Off control and PID control algorithms—were tested. These two methods produced different outcomes in regulating temperature and humidity within the greenhouse; however, their comparison made it possible to identify the most optimal control strategy.

The On–Off algorithm is one of the simplest control methods, where actuators are automatically switched on or off once the parameters reach predefined thresholds. For instance, when the air temperature inside the greenhouse rises to 26 °C, the fan is activated, and when it drops to 24 °C, the fan is turned off. Similarly, when humidity falls below 60%, the pump is switched on, and it is turned off once humidity reaches 70%. The advantage of this algorithm lies in its simplicity and fast response. However, its main drawback is that it can sometimes lead to abrupt fluctuations, making it difficult to maintain parameters at stable levels [7].

ISSN 3030-3907

Therefore, to ensure more precise and accurate regulation, the PID algorithm was applied. As noted in "PID controllers are widely used in process control because of their ability to provide stable and accurate regulation" [8], this approach has proven effectiveness. The PID controller continuously computes the system output based on the error value, thereby maintaining high accuracy. Its mathematical expression is given as follows:

$$u(t) = K_p \cdot e(t) + K_i \int e(t)dt + K_d \cdot \frac{de}{dt}.$$

Here, K_p – is the proportional coefficient, K_i – is the integral coefficient and K_d is the derivative coefficient.. During the study, the PID coefficients were first determined using the Ziegler–Nichols tuning method and then fine-tuned manually through experimental adjustments. The results showed that the PID algorithm maintained the greenhouse temperature with an accuracy of ±0.8 °C and stabilized humidity within the 60–70% range. This provided optimal control of the greenhouse microclimate (Fig. 2).

One of the most important aspects of the greenhouse control system was the possibility of remote monitoring and control based on IoT (Internet of Things). Relying solely on local control creates several limitations; for instance, if the user is not physically present at the greenhouse, it becomes difficult to track the process or respond quickly to changes. Therefore, in this study, ESP8266 and ESP32 microcontrollers were tested. These devices connect directly to cloud servers via built-in Wi-Fi modules and transmit sensor data in real time. As emphasized in "IoT-based greenhouse systems enable remote control and data logging through Wi-Fi connected microcontrollers" [9], this solution demonstrates the relevance and practicality of IoT integration in greenhouse automation.

In this system, data exchange was carried out using the MQTT protocol. Temperature, humidity, and soil moisture readings from the sensors were updated every two seconds and transmitted to the server. Commands to the actuators were sent on separate topics, which ensured accurate and rapid control. In addition, users were able to monitor and control the greenhouse remotely. For this purpose, the Blynk mobile application was employed, allowing all parameters to be observed in real time, while manual control could also be performed when necessary. In cases of internet disconnection, the system stored data on a microSD card or in the internal memory of the ESP32, thereby preventing interruptions in monitoring. As stated in "Offline data logging ensures continuous greenhouse monitoring even during network interruptions" [10], this feature enhanced system reliability.

The greenhouse model was constructed with dimensions of 1.5 × 1 × 1 meters, covered with polyethylene film, and designed to minimize external

ISSN 3030-3907

airflow. Experiments were conducted under Tashkent conditions for 72 hours, comparing manual control with automatic operation. The results were analyzed in terms of water consumption, electricity savings, and the stability of temperature and humidity. The findings confirmed that the IoT-based greenhouse system not only provided efficient monitoring but also demonstrated practical significance for future expansion into larger-scale applications (Figs. 1 and 2).

RESULTS.

The research outcomes demonstrated the development of a highly efficient system capable of automatically controlling greenhouse microclimate parameters—namely air temperature, relative humidity, and soil moisture. The system was theoretically validated through modeling in the MATLAB/Simulink environment and practically tested under experimental conditions to confirm its reliability and effectiveness.

According to the findings, maintaining stable microclimate parameters essential for optimal plant growth is challenging when using traditional control methods. The main reason is that the greenhouse environment is highly sensitive to external factors: variations in ambient temperature, fluctuations in solar radiation intensity, dynamic changes in wind speed, atmospheric pressure shifts, and other natural processes rapidly alter the internal conditions of the greenhouse.

Therefore, the implementation of the automated system not only enabled continuous monitoring and precise control of parameters but also ensured long-term stability, created optimal growth conditions for plants, optimized the use of water and energy resources, and significantly enhanced the overall efficiency and safety of greenhouse operations. From a scientific and technical perspective, these results confirm the high relevance and applicability of automation in greenhouse management.

Practical experiments showed that although the control system based on the simple On–Off algorithm responded quickly to sensor inputs, it was not sufficiently accurate in maintaining stable parameters. Specifically, temperature values oscillated around the setpoint within a range of ±2.5 °C (Fig. 4), while humidity fluctuated within ±6% (Fig. 5). Such variations were found to potentially have negative effects on plant physiological processes. This indicates that despite its simplicity, the On–Off algorithm is not adequate for ensuring a stable greenhouse microclimate.

ISSN 3030-3907

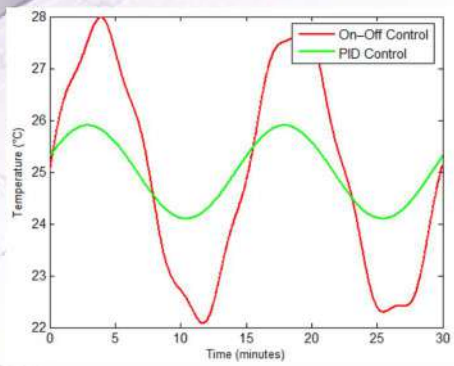


Figure 4. Comparison of temperature over time under On–Off and PID control

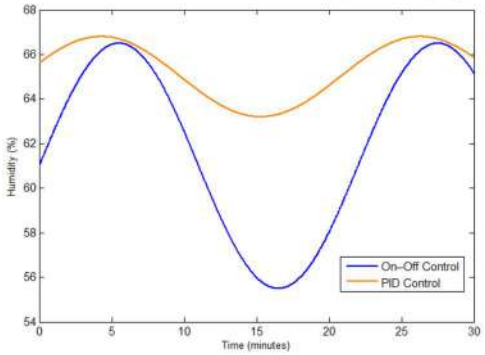


Figure 5. Comparison of humidity over time under On–Off and PID control

In addition, the results of mathematical modeling conducted in the MATLAB/Simulink environment closely corresponded to the experimental observations. The simulations confirmed that although the On–Off algorithm allowed the system to respond quickly, it had limitations in maintaining stability within the optimal range. These findings scientifically support the conclusion that the On–Off control strategy is restricted in its capabilities and can only be effectively applied in small-scale greenhouses or during the initial experimental stages. Consequently, the study highlighted the necessity of employing more advanced control algorithms in greenhouse automation.

When the PID control algorithm was applied, the outcomes were significantly more effective and scientifically sound. During practical experiments, the PID regulator maintained the greenhouse temperature with an accuracy of ±0.8 °C relative to the setpoint, while relative humidity was consistently controlled within the 60–70% range. Such results created highly favorable conditions for plant physiological processes, since a stable microclimate without abrupt fluctuations positively influenced photosynthesis, respiration, and nutrient absorption. Furthermore, the PID algorithm smoothed transient processes and reduced the stabilization time of the greenhouse climate (Fig. 6).

The MATLAB/Simulink simulations also confirmed these observations: with PID control, the system reached a stable state within 6–8 minutes, whereas under On–Off control, stabilization required 18–20 minutes.

ISSN 3030-3907

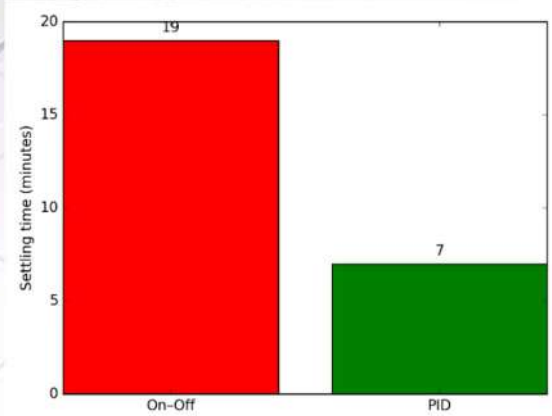


Figure 6. Comparison of stabilization time in On–Off and PID control systems

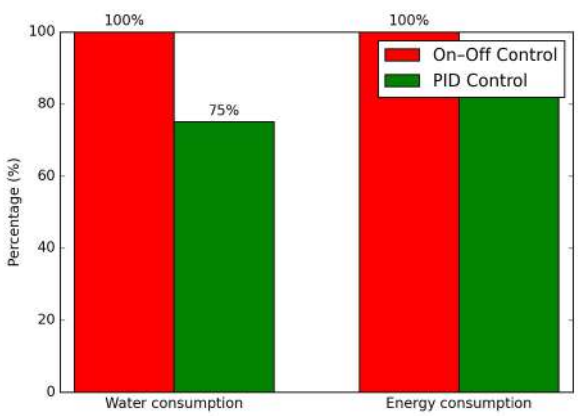


Figure 7. Comparison of resource consumption under On–Off and PID control

In addition to maintaining precise control of environmental parameters, the PID controller also improved the efficiency of resource utilization. Specifically, water consumption was reduced by 20–25% because soil moisture was kept within the optimal range, eliminating the need for excessive irrigation. Electricity consumption decreased by 10–15% since the fan and heater operated only when necessary, thereby reducing unnecessary actuator switching (Fig. 7). These outcomes indicate that, in practice, the proposed system can significantly lower the operating costs of greenhouse farms.

Overall, the application of the PID algorithm was found to provide clear advantages over On–Off control in greenhouse microclimate regulation. Its main strengths include higher accuracy, stable operation, energy and water efficiency, and greater resilience to external environmental fluctuations. Both experimental and simulation results fully supported one another, confirming that an automated system based on PID control can be effectively applied in greenhouses with high efficiency.

In general, the findings from practical experiments and MATLAB/Simulink modeling demonstrated that an IoT-integrated, PID-based automated greenhouse system offers multiple advantages compared to traditional On–Off control. Such a system not only stabilizes microclimate parameters with high precision but also ensures efficient use of energy and water resources, reduces unnecessary actuator operation, and enhances long-term system reliability. Furthermore, the integration of IoT modules provided the ability for remote monitoring and control, allowing users to manage greenhouse conditions from any location. This feature holds substantial practical significance for modern agriculture.

The scientific results confirmed that automated control systems based on the PID algorithm are highly effective in creating optimal microclimates for plant

ISSN 3030-3907

growth. Compared to On–Off control, they minimize fluctuations and ensure stability, thereby playing a vital role in achieving consistent yields, reducing resource consumption, and lowering production costs. Consequently, the concept of the system developed in this study can be applied not only to small-scale experimental greenhouses but also to large-scale industrial facilities. These findings demonstrate that the proposed approach is both relevant and promising for the application of digital technologies in agriculture, sustainable resource management, and ensuring long-term agricultural development.

CONCLUSION.

During the research, an IoT-integrated system based on Arduino/ESP32 microcontrollers was developed and experimentally tested for automatic control of temperature and humidity in greenhouse conditions. The results showed that although the simple On–Off algorithm enabled rapid response to parameter changes, it lacked sufficient accuracy for stable regulation and often caused sharp fluctuations inside the greenhouse. In contrast, the PID algorithm proved highly effective in maintaining stability, successfully controlling temperature within ±0.8 °C and humidity within the 60–70% range.

Moreover, PID control reduced unnecessary actuator switching, which lowered electricity consumption by up to 10–15% and water consumption by 20–25%. MATLAB/Simulink modeling further validated the experimental findings, clearly demonstrating the advantages of PID-based control. As a result, this approach proved to be an efficient solution for creating a stable greenhouse microclimate, optimizing resource use, and reducing operational costs.

Overall, the study confirmed that IoT-based greenhouse systems regulated by PID algorithms represent a promising direction for modern agriculture. Such systems ensure stable crop yields, enable water and energy savings, and improve long-term reliability. These results are of practical, economic, and scientific importance not only for small-scale experimental greenhouses but also for large-scale industrial facilities and modern agro-complexes.

REFERENCES

1. Zhang, Y., et al. (2021). IoT-based greenhouse environment monitoring. *Computers and Electronics in Agriculture*, 181, 105951.
2. Kumar, S., & Patel, R. (2020). Smart farming using Arduino and IoT. *International Journal of Agricultural Technology*, 16(4), 45–56.
3. Prasad, R. & Rookie, V. (2021). IoT Applications in Smart Agriculture. *Springer*.
4. Aliyev, M., et al. (2022). Wireless sensor networks in controlled environment agriculture. *Sensors*, 22(11), 4021.

ISSN 3030-3907

5. Roy, S., et al. (2019). Design of automated greenhouse system. *International Journal of Engineering Research*, 8(5), 33–40.
6. Kim, J., & Park, S. (2020). Low-cost automation in greenhouse climate control. *Applied Sciences*, 10(14), 4823.
7. Patel, K. & Singh, A. (2020). Implementation of On-Off control in agriculture automation. *International Journal of Emerging Technology*, 11(2), 115–122.
8. Pahuja, R. & Kumar, P. (2021). PID-based greenhouse temperature and humidity control system. *International Journal of Control and Automation*, 14(1), 55–68.
9. Ogata, K. (2010). *Modern Control Engineering*. Prentice Hall.
10. Rahman, M., et al. (2021). IoT-based smart greenhouse management. *Journal of Agricultural Informatics*, 12(2), 67–78.
11. Shi, L., et al. (2020). MQTT protocol performance in IoT-based agriculture. *Future Internet*, 12(9), 151.
12. Awan, A., et al. (2018). IoT-based smart irrigation and monitoring system. *International Journal of Advanced Computer Science and Applications*, 9(8), 388–395.

ISSN 3030-3907