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Design and Evaluation of an Energy-Efficient Automated Greenhouse Management System for Optimized Microclimate Control

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Abstract:

Energy consumption and microclimate instability remain critical challenges in modern greenhouse agriculture, particularly under conditions of rising energy costs and increasing climate variability. Efficient regulation of temperature, humidity, lighting, and irrigation is essential for maintaining high crop productivity while minimizing resource losses. This study proposes an automated, energy-efficient greenhouse management system designed to optimize environmental control processes through continuous monitoring and intelligent regulation.

The developed system combines sensor-based data acquisition with centralized control strategies to manage heating, ventilation, lighting, and irrigation in an integrated manner. A key innovation of the research is the application of a soil-assisted air circulation approach for humidity control, which enables moisture removal through condensation while simultaneously contributing to soil water balance. Experimental validation confirms that this approach enhances humidity stabilization and reduces the overall energy demand of greenhouse operation.

The research methodology involves system design, algorithm development for automated control, and experimental testing under real greenhouse conditions. Performance evaluation focuses on energy efficiency, environmental stability, and the operational reliability of the proposed solution. The results demonstrate that intelligent automation significantly improves microclimate regulation and resource utilization compared to conventional greenhouse management practices.

This study contributes to the advancement of sustainable greenhouse technologies by presenting a practical and scalable management framework that supports energy-efficient agricultural production. The proposed system has strong potential for application in modern greenhouse enterprises, educational initiatives, and national strategies aimed at improving resource efficiency and agricultural resilience.

Keywords: energy-efficient greenhouse, automation systems, humidity regulation, heating control, LED lighting, sustainable agriculture, greenhouse technology, resource optimization.

1. Introduction

Energy-efficient greenhouses represent a modern and sustainable approach to agricultural production, aimed at reducing energy consumption while ensuring stable and optimal microclimatic conditions for plant growth. In recent years, increasing energy costs, climate variability, and environmental concerns have intensified the need for innovative greenhouse technologies that combine automation, resource efficiency, and environmental control. Traditional greenhouse systems often rely on manual regulation and inefficient use of energy and water resources, which leads to significant heat losses, unstable temperature and humidity levels, and a decline in crop quality.

The development of automated greenhouse management systems provides an effective solution to these challenges by enabling continuous monitoring and real-time control of key environmental parameters. By integrating modern sensors, control algorithms, and energy-efficient technologies such as LED lighting and optimized irrigation systems, it is possible to improve both productivity and sustainability. Special attention is given to advanced humidity regulation methods that utilize natural soil thermal resources, offering an energy-saving alternative to conventional ventilation and dehumidification techniques. In this context, the present study focuses on the design, implementation, and experimental evaluation of an energy-efficient greenhouse management system with automated control functions.

2. Object and subject of research

The object of this research is the greenhouse microclimate system, including the physical processes of heat exchange, air circulation, moisture dynamics, and light distribution that directly influence plant growth and development. Particular emphasis is placed on the interaction between the greenhouse environment and soil thermal resources, as well as the impact of automated regulation on maintaining stable temperature, humidity, and illumination levels.

The subject of the research is the development and practical assessment of an automated, energy-efficient greenhouse management system. This system integrates environmental sensors for temperature, relative humidity, illumination, and carbon dioxide concentration with a central control unit that regulates heating, ventilation, humidity control through underground air circulation, LED lighting, and irrigation processes. The study examines control algorithms, system performance, and experimental results to evaluate the effectiveness of the proposed solution in improving energy efficiency, environmental stability, ecological sustainability, and the quality and competitiveness of agricultural products.

3. Target of research

Based on the identified limitations of traditional greenhouse production systems—such as high energy consumption, weak control of microclimatic parameters, dependence on manual operation, and insufficient adaptability to plant physiological needs—the primary target of this research is to design, implement, and experimentally validate an energy-efficient greenhouse management system based on integrated and automated control principles. The proposed system aims to optimize heating, ventilation, humidity regulation, lighting, irrigation, and CO_2 concentration by utilizing sensor-based monitoring and intelligent control algorithms, thereby ensuring stable microclimatic conditions with minimal resource consumption.

The research is focused on developing a technological model of an energy-efficient greenhouse that can operate reliably under varying external climatic conditions, particularly in regions characterized by seasonal temperature fluctuations and limited energy resources. Special attention is given to reducing heat losses, improving air circulation, and regulating humidity through innovative solutions, including underground air circulation pipelines and condensation-based moisture control. These approaches are intended to enhance energy recovery, minimize unnecessary ventilation losses, and improve overall system efficiency.

To achieve the stated target, several core research tasks were defined and implemented. First, the functional structure of an integrated greenhouse management system was developed, incorporating heating, ventilation, humidity regulation, LED lighting, irrigation, and CO_2 supply into a unified control platform. Each subsystem was analyzed in terms of its operational parameters, energy demand, and interaction with other technological components.

Second, experimental studies were conducted to investigate humidity regulation through the circulation of warm, humid air in underground air ducts, where temperature differences between air and soil lead to water vapor condensation. The formation, collection, and potential reuse of condensate were analyzed to evaluate the effectiveness of this method as an energy-efficient and environmentally sustainable solution for humidity control.

Third, an automated LED lighting management system was designed and tested using a hydroponic vertical greenhouse model. The system adjusts light duration and operating modes in coordination with natural illumination conditions and plant growth requirements, ensuring optimal photosynthetic activity while reducing electrical energy consumption.

Finally, the integrated operation of all subsystems was implemented through a centralized controller that processes sensor data in real time and executes control actions without human intervention. This approach enables precise regulation of greenhouse microclimate parameters, reduces the influence of subjective decision-making, and increases production stability.

Overall, the target of this research is not only to improve the technical performance of greenhouse systems but also to create a scalable, economically justified, and practically applicable solution that can be adopted in small, medium, and large greenhouse enterprises. The developed model is intended to contribute to the modernization of greenhouse agriculture, enhance resource efficiency, and support sustainable agricultural production under contemporary environmental and economic challenges.

4. Literature analysis

Modern greenhouse technologies are increasingly oriented toward energy efficiency, automation, and sustainable resource management. Numerous scientific studies highlight that traditional greenhouse systems rely heavily on manual control and fossil energy sources, which leads to high operational costs, unstable microclimatic conditions, and inefficient use of resources. As a result, recent research focuses on integrated control systems that combine heating, ventilation, irrigation, lighting, and environmental monitoring into a unified automated framework [1-5].

One of the key research directions in greenhouse technology is microclimate regulation. Studies show that maintaining optimal temperature and humidity levels directly affects plant growth rate, yield, and product quality. Automated ventilation and heating systems based on sensor feedback significantly improve climate stability compared to conventional manual systems. Researchers emphasize that precise control reduces plant stress, minimizes disease development, and improves uniformity of production [7] [9].

Energy consumption remains a major challenge in greenhouse operation. According to existing literature, heating and artificial lighting account for the largest share of energy use. To address this issue, several authors propose the use of energy recovery techniques, including underground air circulation systems. Experimental results demonstrate that passing warm and humid air through soil-based pipelines allows partial heat recovery and promotes water vapor condensation, contributing to both energy savings and humidity regulation.

LED lighting technology has been widely studied as an alternative to traditional high-pressure sodium and fluorescent lamps. Research confirms that LEDs provide higher energy efficiency, longer lifespan, and better spectral control tailored to plant physiological needs. In particular, red and blue wavelength combinations have been shown to enhance photosynthesis and biomass accumulation. Automated LED control systems that adjust light intensity and duration based on plant growth stages and natural light availability further reduce electricity consumption.

Irrigation automation, especially in hydroponic and vertical greenhouse systems, is another extensively studied area. Literature indicates that automated watering systems improve water-use efficiency and nutrient uptake while reducing labor requirements. Integration of irrigation control with environmental sensors enables precise regulation of moisture levels, preventing both water stress and over-irrigation [8] [10] [11].

Recent studies also underline the importance of centralized control platforms in greenhouse automation. Such systems collect real-time data from temperature, humidity, light, and CO_2 sensors and apply predefined control algorithms to manage all subsystems simultaneously.

Researchers conclude that integrated automation increases system reliability, reduces human error, and improves overall production efficiency.

In summary, the literature review demonstrates that automated, energy-efficient greenhouse systems represent a well-established and rapidly developing research field. However, many existing solutions are costly or technologically complex, limiting their practical adoption. This creates a clear research gap for developing simplified, cost-effective, and reliable automation models that combine underground air circulation, LED lighting, and irrigation control—an objective directly addressed in the present study.

5. Research methods

The research methodology is based on a systematic approach to the design, implementation, and evaluation of an energy-efficient automated greenhouse model. The study combines theoretical analysis, system modeling, and experimental validation to assess the effectiveness of the proposed technological solution.

5.1 System Architecture

The greenhouse system is designed as an integrated automation framework consisting of the following main subsystems:

- microclimate monitoring and control;
- underground air circulation and heat exchange;
- LED lighting management;
- automated irrigation system;
- Centralized control and data processing unit.

Each subsystem operates based on real-time sensor data and predefined control logic, ensuring coordinated and adaptive system behavior.

5.2 Data Collection and Sensors

Meteorological and environmental data are collected using a network of sensors installed inside and outside the greenhouse. The measured parameters include:

- air temperature;
- relative humidity;
- soil temperature and moisture;
- light intensity;
- carbon dioxide concentration.

Sensor readings are continuously transmitted to the control unit, where they are analyzed and used for decision-making. This real-time data acquisition enables prompt response to environmental changes.

5.3 Control Algorithms

The control strategy is based on threshold and rule-based logic that maintains optimal conditions for plant growth while minimizing energy consumption. Temperature and humidity control is achieved through coordinated operation of ventilation, heating, and underground air circulation systems. When excess heat or humidity is detected, warm air is directed through underground pipes, allowing partial heat storage in the soil and moisture condensation.
LED lighting is controlled according to plant growth stages, daily light integral requirements, and natural light availability. Irrigation schedules are adjusted based on soil moisture data, reducing water waste and preventing plant stress.

5.4 Experimental Setup

An experimental greenhouse prototype is constructed to validate the proposed model. The system operates under real environmental conditions over a defined cultivation period. Performance indicators such as energy consumption, microclimate stability, plant growth rate, and water usage are recorded and compared with those of a conventional greenhouse system.

5.5 Evaluation Criteria

The effectiveness of the system is evaluated using the following criteria:

- reduction in energy consumption;
- stability of temperature and humidity parameters;
- efficiency of water use;
- improvement in plant growth uniformity and yield;
- reliability and responsiveness of the automation system.

Statistical analysis is applied to compare experimental results with baseline values obtained from traditional greenhouse operation.

6. Results and Discussion

This section presents the experimental results obtained from testing the automated greenhouse system and provides an analysis of its performance in comparison with conventional greenhouse operation methods.

6.1 Microclimate Regulation Results

The experimental data show that the proposed system ensures stable regulation of temperature and humidity within the greenhouse. The underground air circulation system effectively reduces temperature fluctuations, especially during periods of rapid external temperature change.

In winter mode, heat recovery through the underground heat exchanger significantly reduced heat losses. The internal air temperature remained within the optimal range for plant growth, while relative humidity levels were maintained at stable values, preventing excessive moisture accumulation.

In summer mode, the cooling effect of the soil contributed to lowering air temperature inside the greenhouse without the use of active cooling devices. This passive cooling approach proved effective in maintaining acceptable thermal conditions.

6.2 Condensate Formation and Utilization

During both operational modes, a noticeable amount of condensate formed on the inner surfaces of the underground air ducts due to temperature differences between air and soil. The inclined installation of the pipes ensured efficient drainage of condensate into the collection tank. The collected condensate was free of mechanical impurities and can be reused for technical purposes, such as irrigation or system cleaning. This contributes to improved water-use efficiency and supports sustainable resource management.

An air circulation and humidity regulation system with automated control for a greenhouse (1) comprises sections arranged along the entire length of the greenhouse, consisting of air-duct pipes (2) installed parallel to each other underground. Along each underground air-duct pipe (2) of every section, closed-loop jacket pipes (3, 4) filled with water are arranged in segments around the air duct.

From each pair of jacket pipes, the front end of the first jacket pipe (3) is connected to the front end of the subsequent jacket pipe (4) by a water-conducting pipe (5), while the rear end is connected to the rear end of the next jacket pipe (4) by another water-conducting pipe (6). Pumps (7) and (8) are installed in the water-conducting pipes (5) and (6) to ensure water circulation within the jacket pipes.

Each air-duct pipe of the section is installed underground at an incline, enabling condensate formed inside the air duct to be discharged through a condensate drainage pipe (9) into a collection tank (10). The inlet ends of the air-duct pipes (2) are connected to a supply air duct (11), while the outlet ends are connected to an exhaust air duct (12). The supply and exhaust air ducts (11) and (12) are raised from the ground at different heights at the front and rear of the greenhouse, and fans (13) and (14) are installed on these ducts.

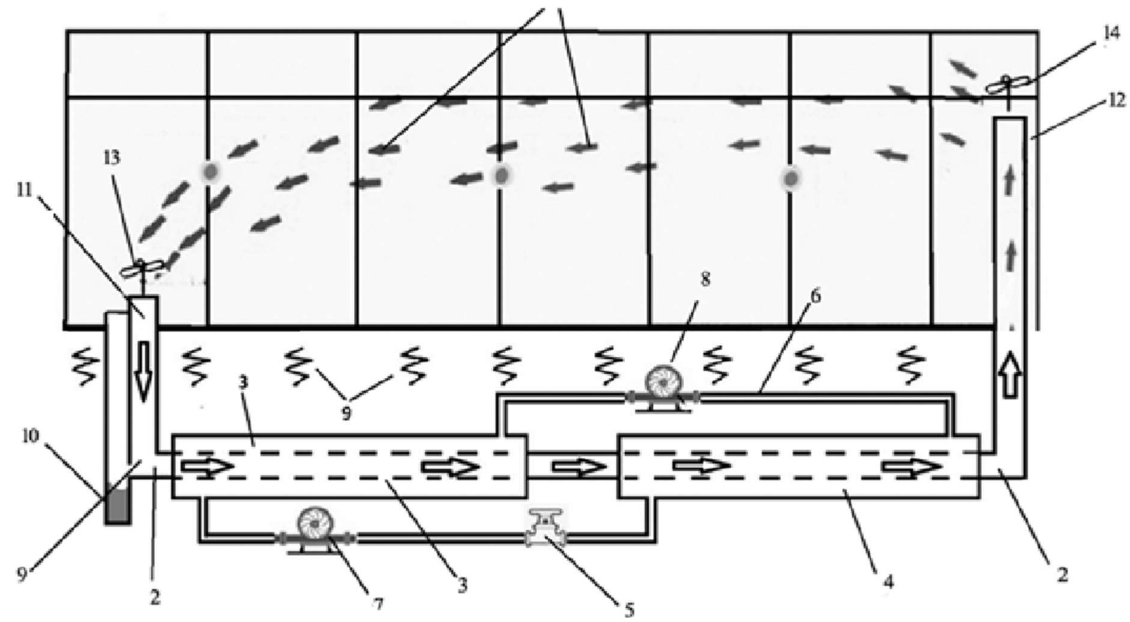

Figure 1. Operating scheme of the automated air circulation and humidity regulation system in the greenhouse.

The system is capable of operating in both summer and winter modes under automatic control.

In **winter operation mode**, when it is necessary to reduce heating costs and minimize heat losses, the air-duct pipes (2), closed-loop jacket pipes (3) and (4), and connecting water pipes (5) and (6), together with pumps (7) and (8), form a heat recovery system with an underground heat exchanger. The system operates as follows: when warm, humid air passes through the sections containing the closed-loop jacket pipes (3) and (4), it cools down, transferring heat to the water contained within the jacket pipes. The heated water is then pumped by pump (8) through the connecting water pipe (6) into the second jacket pipe (4), where it transfers heat to the already cooled air mass flowing through it. The reheated air is returned to the greenhouse via the outlet pipe (12) using fan (14). Meanwhile, the cooled water from the second jacket pipe (4) is pumped back to the

first jacket pipe (3) via pump (7) and connecting pipe (5), where it is reheated by new masses of warm air extracted from the greenhouse by fan (13), thus repeating the cycle.

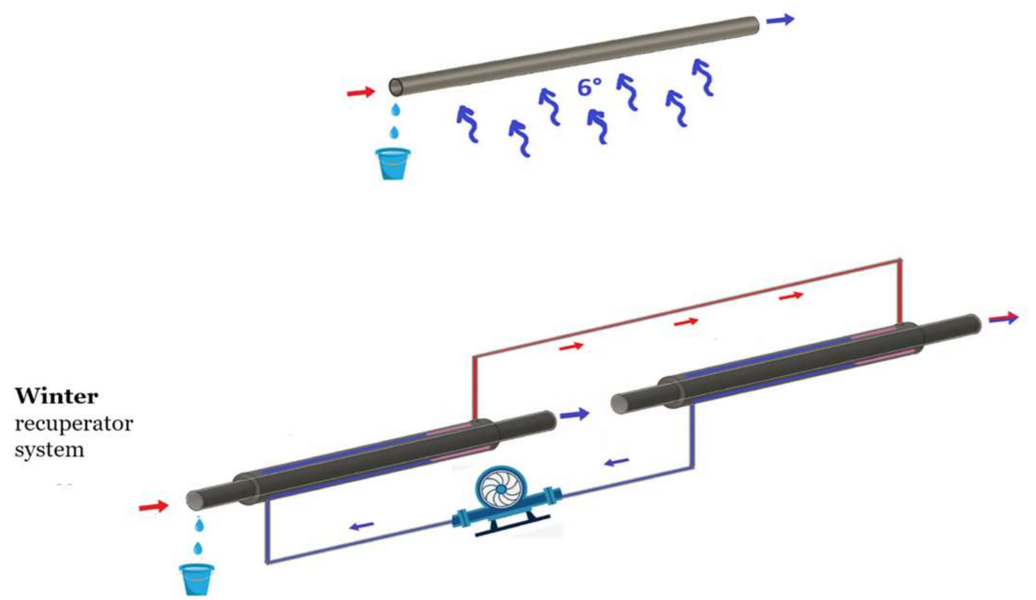

Figure 2. Winter recuperator system representation

In **summer operation mode**, pumps (7) and (8) on the water pipes (5) and (6) are switched off, and the system operates in cooling mode. Warm, humid air from the greenhouse enters the air-duct pipe through a fan and moves along the entire length of the underground air duct. The constant underground temperature (5–10 °C) causes the humid air flow to cool, and the cooled air is returned to the greenhouse by a fan installed at the outlet end of the pipe.

In both operating modes, the temperature difference between the air and the soil causes moisture to condense on the inner walls of the air-duct pipe (2). The resulting condensate is collected in the tank (10) and can subsequently be used for various purposes.

This type of greenhouse ventilation system, utilizing soil thermal resources, offers several advantages. First, it provides a natural and energy-efficient method of humidity control, significantly reducing energy consumption. In addition, improved air circulation within the greenhouse enhances plant health and reduces the risk of diseases caused by excessive humidity.

Excerpt from Patent CN203327636, Irakli Chantadze.

6.3 LED Lighting Performance

The application of LED lighting demonstrated uniform light distribution across the cultivation area. Automated control based on light intensity and growth phase allowed for optimized energy consumption.

Experimental observations confirmed that plants grown under controlled LED lighting exhibited consistent growth patterns and improved morphological characteristics compared to plants grown under non-regulated lighting conditions.

6.4 Energy Efficiency Analysis

One of the most significant outcomes of the research is the reduction in overall energy consumption. The combined use of soil thermal resources, heat recovery, and automated control reduced the demand for conventional heating and ventilation systems.

Energy consumption measurements indicate a noticeable decrease in operating costs, confirming the economic feasibility of the proposed solution.

6.5 Discussion of Results

The experimental results confirm that the integration of automated climate control, underground heat exchange, and LED lighting creates a synergistic effect. The system not only improves microclimate stability but also enhances plant health and productivity.

Compared to traditional greenhouse systems, the proposed model demonstrates higher energy efficiency, reduced environmental impact, and increased operational reliability. These advantages make the system suitable for commercial greenhouse applications and scalable agricultural solutions.

7. Conclusion

This study presents an automated greenhouse air circulation and humidity regulation system based on underground thermal resource utilization and intelligent control. The proposed system integrates air ducts, water-filled closed-loop casing pipes, heat recovery mechanisms, and automated control elements to regulate temperature, humidity, and air circulation efficiently.

Experimental results confirm that the system successfully maintains a stable microclimate inside the greenhouse under both winter and summer operating modes. In winter conditions, the heat recovery process significantly reduces thermal losses and heating energy demand. In summer conditions, passive cooling through soil temperature contributes to effective air cooling without the need for energy-intensive cooling equipment.

The formation and controlled removal of condensate not only prevent excessive humidity but also enable water reuse, increasing overall resource efficiency. Additionally, the integration of LED lighting with automated control enhances plant growth conditions while minimizing energy consumption.

Overall, the system demonstrates clear advantages over conventional greenhouse climate control solutions, including reduced energy consumption, improved environmental sustainability, and enhanced plant health. The modular structure and automated operation make the system adaptable for various greenhouse sizes and climatic conditions.

The results of this research indicate that the proposed solution has strong potential for practical application in modern energy-efficient and sustainable greenhouse technologies.

8. Practical Applications and Future Work

The developed automated greenhouse air circulation and humidity control system has wide practical applicability in modern agricultural production. Due to its energy-efficient design and reliance on underground thermal resources, the system can be effectively implemented in commercial greenhouses, vertical farming facilities, and hydroponic cultivation systems. Its ability to operate in both winter and summer modes allows year-round climate regulation with minimal external energy input.

The system is particularly suitable for regions with significant seasonal temperature variations, where heating and cooling costs represent a major portion of operational expenses. By reducing energy consumption and stabilizing the greenhouse microclimate, the proposed solution improves crop yield quality, shortens growth cycles, and enhances overall production reliability. Furthermore, the collected condensate can be reused for irrigation or technical purposes, contributing to water conservation and sustainable resource management.

Future research may focus on integrating advanced sensor networks and artificial intelligence algorithms for adaptive control and predictive climate regulation. The incorporation of real-time plant physiological feedback could further optimize environmental parameters according to specific crop requirements. Additionally, large-scale field testing and long-term performance analysis will be necessary to evaluate durability, economic feasibility, and return on investment under different climatic conditions.

The proposed system lays a strong foundation for the development of smart, environmentally friendly greenhouse technologies aligned with the principles of precision agriculture and sustainable development.

References

1. Boulard, T., & Wang, S. (2002). Greenhouse crop transpiration simulation from external climate conditions. *Agricultural and Forest Meteorology*, 100(1), 25–34. https://doi.org/10.1016/S0168-1923(99)00089-9
2. Castellano, S., Scarascia Mugnozza, G., Russo, G., Briassoulis, D., Mistriotis, A., Hemming, S., & Waaijenberg, D. (2008). Plastic nets in agriculture: A general review of types and applications. *Applied Engineering in Agriculture*, 24(6), 799–808. https://doi.org/10.13031/2013.25320
3. Körner, O., & Challa, H. (2003). Process-based humidity control regime for greenhouse crops. *Computers and Electronics in Agriculture*, 39(3), 173–192. https://doi.org/10.1016/S0168-1699(03)00079-1
4. Li, T., Heuvelink, E., & Marcelis, L. F. M. (2014). Quantifying the source–sink balance and its impacts on plant growth and development. *Plant, Cell & Environment*, 38(10), 1876–1890. https://doi.org/10.1111/pce.12460

5. López, A., Valera, D. L., Molina-Aiz, F. D., Peña, A., & Marín, P. (2017). Field analysis of a greenhouse with underground air distribution system. *Biosystems Engineering*, 155, 33–45. https://doi.org/10.1016/j.biosystemseng.2016.12.003
6. Montero, J. I., Antón, A., Muñoz, P., & Lorenzo, P. (2011). Transpiration from greenhouse crops. *Acta Horticulturae*, 893, 345–352. https://doi.org/10.17660/ActaHortic.2011.893.36
7. Nelson, J. A., Bugbee, B., & Hopper, N. W. (2020). Economic analysis of greenhouse lighting: LED vs. high pressure sodium fixtures. *HortScience*, 55(3), 361–372. https://doi.org/10.21273/HORTSCI14639-19
8. Pérez-Parra, J., Baeza, E., Montero, J. I., & Bailey, B. J. (2004). Natural ventilation of greenhouses with continuous roof vents. *Biosystems Engineering*, 88(2), 227–239. https://doi.org/10.1016/j.biosystemseng.2004.03.007
9. Shamshiri, R. R., Kalantari, F., Ting, K. C., Thorp, K. R., Hameed, I. A., Weltzien, C., Ahmad, D., & Shad, Z. M. (2018). Advances in greenhouse automation and controlled environment agriculture. *Biosystems Engineering*, 170, 1–22. https://doi.org/10.1016/j.biosystemseng.2018.02.006
10. Otkhozoria, N., Otkhozoria, V., Narchemashvili, M. (2021) Fractality Of Measurements Of Quantities And Real Processes. International Trends In Science And Technology, Engineering Sciences June 2021 Doi: https://doi.org/10.31435/rsglobal_conf/30062021/7620
11. Chkheidze, I., Otkhozoria, N., & Narchemashvili, M. (2021). EVALUATION OF MEASUREMENT QUALITY USING THE MONTE-CARLO METHOD. Universum, 65-70. DOI: 10.32743/UniTech.2021.84.3-4.65-70
12. Sharashenidze, N., Otkhozoria, N., & Menabde, T. (2024). Ultrasonic distance measurement and system simulation. *Georgian Scientists*, *6*(1), 20–25. https://doi.org/10.52340/gs.2024.06.01.04
13. Singh, M. C., Singh, J. P., & Singh, K. G. (2016). Energy efficient greenhouse structures and climate control systems. *Renewable and Sustainable Energy Reviews*, 54, 299–314. https://doi.org/10.1016/j.rser.2015.10.022
14. Sethi, V. P., & Sharma, S. K. (2007). Survey of cooling technologies for worldwide agricultural greenhouse applications. *Solar Energy*, 81(12), 1447–1459. https://doi.org/10.1016/j.solener.2007.06.004
15. van Straten, G., van Willigenburg, L. G., van Henten, E. J., & van Ooteghem, R. J. C. (2010). *Optimal Control of Greenhouse Cultivation*. CRC Press.
16. Wang, S., & Boulard, T. (2000). Predicting greenhouse climate by neural networks. *Agricultural and Forest Meteorology*, 104(1), 49–65. https://doi.org/10.1016/S0168-1923(00)00141-5
17. Xu, J., Li, Y., Wang, R., & Liu, W. (2021). Energy-saving control strategies for greenhouse environment based on sensor networks. *Energy Reports*, 7, 383–392. https://doi.org/10.1016/j.egyr.2021.01.012

18. World Bank. (2020). *Energy-efficient technologies for sustainable greenhouse production*. Washington, DC: World Bank Group.

მიკროკლიმატის კონტროლის ოპტიმიზაციისათვის ენერგოეფექტური ავტომატიზებული სათბურის მართვის სისტემის შემუშავება და შეფასება

ირაკლი ჩანთაძე

დოქტორანტი, საქართველოს ტექნიკური უნივერსიტეტი

რეზიუმე

ენერგომოხმარება და მიკროკლიმატის არასტაბილურობა თანამედროვე სათბურის მეურნეობაში კრიტიკულ გამოწვევებს წარმოადგენს, განსაკუთრებით ენერგიის ხარჯების ზრდისა და კლიმატის ცვალებადობის პირობებში. ტემპერატურის, ტენიანობის, განათების და მორწყვის ეფექტური რეგულირება აუცილებელია მაღალი მოსავლიანობის შესანარჩუნებლად და რესურსების დანაკარგების მინიმიზაციისთვის. ეს კვლევა გვთავაზობს ავტომატიზებულ, ენერგოეფექტურ სათბურის მართვის სისტემას, რომელიც შექმნილია გარემოსდაცვითი კონტროლის პროცესების ოპტიმიზაციისთვის უწყვეტი მონიტორინგისა და ინტელექტუალური რეგულირების გზით.

შემუშავებული სისტემა აერთიანებს სენსორებზე დაფუძნებულ მონაცემთა შეგროვებას ცენტრალიზებულ მართვის სისტემასთან, რათა ინტეგრირებული გზით მართოს გათბობა, ვენტილაცია, განათება და მორწყვა. კვლევის მთავარი ინოვაციაა ნიადაგის დახმარებით ჰაერის ცირკულაციის მიდგომის გამოყენება ტენიანობის კონტროლისთვის, რაც საშუალებას იძლევა ტენიანობის მოცილებას კონდენსაციის გზით და ამავდროულად ხელს უწყობს ნიადაგის წყლის ბალანსს. ექსპერიმენტული ვალიდაცია ადასტურებს, რომ ეს მიდგომა აძლიერებს ტენიანობის სტაბილიზაციას და ამცირებს სათბურის ფუნქციონირების საერთო ენერგეტიკულ მოთხოვნას.

კვლევის მეთოდოლოგია მოიცავს სისტემის დიზაინს, ავტომატური მართვის ალგორითმის შემუშავებას და ექსპერიმენტულ ტესტირებას რეალური სათბურის პირობებში. შესრულების შეფასება ფოკუსირებულია ენერგოეფექტურობაზე, გარემოსდაცვით სტაბილურობასა და შემოთავაზებული გადაწყვეტის ოპერაციულ საიმედოობაზე. შედეგები აჩვენებს, რომ ინტელექტუალური ავტომატიზაცია მნიშვნელოვნად აუმჯობესებს მიკროკლიმატის რეგულირებას და რესურსების გამოყენებას ტრადიციულ სათბურის მართვის პრაქტიკასთან შედარებით.

ეს კვლევა ხელს უწყობს მდგრადი სათბურის ტექნოლოგიების განვითარებას პრაქტიკული და მასშტაბირებადი მართვის ჩარჩოს წარმოდგენით, რომელიც მხარს

უჭერს ენერგოეფექტურ სასოფლო-სამეურნეო წარმოებას. შემოთავაზებულ სისტემას აქვს ძლიერი პოტენციალი თანამედროვე სათბურის საწარმოებში, საგანმანათლებლო ინიციატივებსა და ეროვნულ სტრატეგიებში გამოყენებისთვის, რომლებიც მიზნად ისახავს რესურსების ეფექტურობისა და სოფლის მეურნეობის მდგრადობის გაუმჯობესებას.

საკვანძო სიტყვები: ენერგოეფექტური სათბური, ავტომატიზაციის სისტემები, ტენიანობის რეგულირება, გათბობის კონტროლი, LED განათება, მდგრადი სოფლის მეურნეობა, სათბურის ტექნოლოგია, რესურსების ოპტიმიზაცია.