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ANALYSIS OF THE EFFICIENCY OF WATERING INDOOR PLANTS IN A MULTI-AGENT SYSTEM BASED ON ENVIRONMENTAL PARAMETERS

The study presents the development and evaluation of an intelligent system for optimizing indoor plant irrigation based on a multi-agent architecture. The proposed system integrates real-time environmental data, including soil moisture, air temperature, light intensity, and humidity, with mathematical models of plant growth and condition assessment to enable adaptive and data-driven decision-making. A heuristic irrigation demand model was employed to estimate water requirements as a function of environmental conditions, while Monte Carlo simulations were used to identify optimal irrigation strategies and minimize deviations from target soil moisture levels under uncertainty. The multi-agent framework consists of sensor, data processing, prediction, parameter selection, decision, and control agents, each responsible for a specific stage of data acquisition, analysis, and actuation. Such a distributed structure allows agents to operate semi-independently while coordinating their actions to ensure efficient irrigation management. The prediction component utilizes regression-based models to estimate plant condition through an integrated index, enabling continuous monitoring of plant condition and environmental impact. The system was evaluated through simulation experiments involving multiple plant scenarios, demonstrating that adaptive control significantly improves plant condition indicators compared to conventional rule-based irrigation methods. In addition, the proposed approach achieved more efficient water utilization by dynamically adjusting irrigation volumes in response to environmental variability. The results confirm that the integration of stochastic optimization and multi-agent coordination enhances the robustness and flexibility of indoor irrigation systems. Furthermore, the proposed framework provides a scalable foundation for intelligent agricultural applications, supporting real-time operation and low computational cost. Future research will focus on extending the model by incorporating additional environmental parameters, improving agent autonomy, and integrating advanced machine learning techniques to further enhance prediction accuracy and decision-making efficiency.

Keywords: Monte Carlo simulation; indoor irrigation strategies; adaptive control; predictive modeling; smart data processing; Internet of Things.

Introduction / Вступ

The cultivation of indoor and controlled-environment plants has gained significant popularity in recent years, driven by growing interest in home gardening, urban farming, and sustainable agriculture. Despite this trend, maintaining favourable plant conditions remains a challenge for many users, as it requires continuous monitoring of environmental factors such as soil moisture, temperature, humidity, and light intensity. Traditional irrigation and care practices often rely on user experience or generic guidelines, which may not account for species-specific requirements or dynamic environmental changes. Recent advances in artificial intelligence, sensor technologies, and Internet of Things (IoT) devices provide an opportunity to develop intelligent, adaptive systems capable of assisting users in plant care. In particular, multi-agent systems (MAS) enable distributed decision-making, where agents can independently monitor

environmental parameters, estimate plant water needs, and coordinate actions to improve irrigation scheduling. Coupling MAS with computational modeling and Monte Carlo-based parameter sampling allows irrigation strategies to adapt dynamically to changing conditions, improving plant condition assessment while reducing unnecessary water use. This study focuses on the design and implementation of a MAS-based plant irrigation system that integrates real-time sensor data, predictive modeling of plant growth, and decision-making mechanisms to determine effective watering strategies based on soil moisture, temperature, humidity and light intensity. The proposed system aims to improve plant condition, enhance resource efficiency, and provide a scalable, adaptive solution for intelligent plant care in indoor environments.

At the same time, most of the available research focuses on specific aspects of irrigation automation, such as sensor monitoring or the use of adaptive control methods, while

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Цитування за ДСТУ: Мисюк Р. В., Кулик П. Р., Патинко А. М., Керод Т. І., Марчук Ю. Б. Аналіз ефективності поливу кімнатних рослин у мультиагентній системі на підставі параметрів середовища. Науковий вісник НЛТУ України. 2026, т. 36, № 2. С. 181–188.

Citation APA: Mysiuk, R. V., Kulyk, P. R., Patynko, A. M., Kerod, T. I., & Marchuk, Yu. B. (2026). Analysis of the efficiency of watering indoor plants in a multi-agent system based on environmental parameters. *Scientific Bulletin of UNFU*, 36(2), 181–188.

<https://doi.org/10.36930/40360220>

integrated approaches combining MAS, computational models, and adaptive decision-making approaches for irrigation management remain underexplored. The reason is the difficulty of integrating heterogeneous data sources, the need to simulate dynamic plant growth processes and coordinate decision-making between agents.

The study is motivated by the growing need to develop intelligent systems capable of adaptively managing irrigation strategies based on the analysis of environmental parameters, which requires a combination of sensor monitoring, plant condition assessment methods and decision-making mechanisms within MAS.

Object of research – the process of caring for indoor and ornamental plants using intelligent systems, which includes monitoring environmental parameters, plant condition assessment and adaptive irrigation management.

Subject of research – methods and algorithms for adaptive irrigation houseplants decision-making based on sensor monitoring data using multi-agent systems, computational models and plant condition assessment methods.

The purpose of the research – develop and study a multi-agent system for adaptive irrigation houseplants management based on environmental parameters, which provides adaptive decision-making on irrigation by taking into account soil moisture, temperature, illumination and other factors to increase the efficiency of water resources use and maintain favorable plant conditions.

To achieve this *purpose*, the following main *research objectives* are identified:

- analyse modern approaches to plant care automation which will allow to determine their advantages and disadvantages, to justify the choice of effective management methods and to form requirements for the development of an intelligent irrigation system in a dynamic environment;
- develop computational models of plant condition and soil moisture dynamics, taking into account environmental parameters (temperature, lighting, humidity) in order to describe plant growth and water consumption processes and support irrigation-related decision-making;
- introduce an integrated plant condition indicator based on combined environmental and plant-related parameters to provide a comprehensive assessment of plant condition;
- develop a model for plant condition assessing based on environmental data analysis in order to identify deviations from suitable growing conditions and support adaptive care recommendations;
- design the architecture of a MAS for data collection, processing, and irrigation decision support to ensure distributed information processing, coordinated interaction of agents and effective formation of adaptive solutions in real time for plant watering management;
- conduct an experimental evaluation of the proposed system using selected plant species as case studies in order to assess the effectiveness of the developed models and decision-making methods.

Analysis of recent research and publications. The paper [6] investigates the impact of the presence of indoor plants on the productivity and psychological state of office workers. The authors conducted a field study in several organizations in the Netherlands and showed that the presence of plants in the work environment has a positive effect on the well-being, job satisfaction and concentration of employees, which confirms the relevance of developing indoor plant care systems.

The study [16] proposes an intelligent watering system for indoor plants that combines artificial neural networks

and fuzzy logic. The authors demonstrated that the use of hybrid artificial intelligence methods allows you to adaptively determine the required level of watering depending on the parameters of the environment and the condition of the plant. Unlike the study [24], which focused on hardware monitoring and physical and mathematical modeling of the soil water dynamics, this work uses an intelligent MAS with data analysis and Monte Carlo methods for adaptive irrigation management of indoor plants.

The paper [18] presents an intelligent automatic irrigation system based on Internet of Things technologies and fuzzy control logic. The authors showed that the use of soil moisture, temperature and other parameters sensors, combined with a fuzzy controller, ensures effective irrigation management and enhances water-use efficiency. The paper [12] considers a distributed document classification approach based on the integration of multi-agent systems and Bayesian methods. The proposed framework enables collaboration between intelligent agents, allowing them to exchange probabilistic information and improve classification accuracy in decentralized environments. The study demonstrates that such cooperation significantly enhances decision-making performance compared to isolated classification models, particularly in cases involving heterogeneous and distributed data sources.

The study [17] proposes a model of the indoor plant growing system based on the concept of Artificial Intelligence of Things (AIoT). The authors integrate sensor devices, network technologies, and artificial intelligence algorithms to monitor plant growth conditions, allowing for the automation of lighting, irrigation, and monitoring processes.

The paper [21] presents a semantic approach to modeling a smart indoor garden. The authors use semantic models and IoT technologies to describe the interaction between system components and provide more flexible management of plant care processes.

In the work [13] proposes the integration of Internet of Things (IoT) technologies and an agent-based approach to improve the efficiency of water use in collective irrigation systems. The authors showed that the use of agents allows you to coordinate the actions of the different components of the system and optimize the distribution of water resources.

The paper [5] presents a smart home model implemented on the basis of MAS. The authors demonstrate that the use of agents allows you to organize the interaction of different automation subsystems, providing flexibility and scalability of the control system.

The paper [4] provides an overview of modern approaches to multi-agent reinforcement learning. The authors analyze the main challenges and areas of application of such systems in various fields, including distributed control and autonomous intelligent systems.

The study [2] developed a system of recommendations for indoor plants for users based on individual preferences and environmental conditions. The authors showed that the use of data analysis algorithms allows you to form personalized recommendations for choosing plants for home cultivation.

The paper [11] presents a system for caring for indoor plants based on the Internet of Things. The authors proposed a system architecture that uses sensors to monitor environmental parameters and automatically control irrigation.

The paper [9] proposes a decision support system for urban agriculture based on the concept of a digital twin. The

authors demonstrate the possibility of modeling plant growing conditions and optimizing management processes based on data analysis.

The study [1] considers an approach to creating a smart indoor gardening system that integrates automation, sensor technologies and data analysis algorithms to control plant growth and optimize their development conditions.

The paper [3] proposes an automatic system of watering plants for small gardens, which is based on the use of soil moisture sensors and microcontrollers. The authors showed that automating the irrigation process can increase the efficiency of plant care and reduce water consumption.

In the work [19], an automated system of self-watering plants has been developed, integrating sensors and IoT technologies for monitoring soil condition and controlling water supply. The authors demonstrated the effectiveness of the proposed solution for maintaining optimal conditions for growing indoor plants.

Regarding Monte Carlo method implementation in system the proposed irrigation control system in [7] integrated with it to generate synthetic training data by simulating diverse environmental and irrigation scenarios, enabling robust training of the RBF-SVM model.

Thus, the above works consider in sufficient detail the issues of automation of plant care, the use of IoT technologies, artificial intelligence and multi-agent systems to control watering processes and monitor the condition of plants. Research covers the development of intelligent irrigation systems, recommendation systems, smart gardening models, and multi-agent control system architectures.

At the same time, most of the existing work focuses on certain aspects of automation, the use of sensors, artificial intelligence algorithms or IoT infrastructure. The issue of integrating the multi-agent approach with methods of data mining and adaptive decision-making models for the inte-

rated management of indoor plant care systems remains insufficiently studied, which determines the relevance of further research in this direction.

Materials and methods of research. The paper uses the methods of data mining, regression modeling and the Monte Carlo method to determine the adaptive irrigation strategies. The study applied multi-agent system design and IoT-based data collection to automate plant care and minimize resources, evaluating the adaptive irrigation method against fixed-frequency watering in terms of soil moisture and plant condition assessment.

Research results and their discussion / Результати дослідження та їх обговорення

Implementation of the intelligent plant care system.

The study implemented an intelligent chatbot-based system that models plant condition and optimizes irrigation schedules based on environmental parameters, including air temperature and humidity, soil moisture, and light intensity. Environmental data (Figure 1) were collected hourly over a 30-hour observation period in a controlled indoor space of 11 m². Consequently, the system enabled continuous monitoring and basic automated irrigation without requiring complex predictive algorithms. Environmental conditions reflect typical indoor (apartment) dynamics, characterized by relatively stable temperature and humidity profiles and an estimated daily lighting cycle of 300 to 700 lux. The temperature shows slight daily variations, remaining in a comfortable range, while the humidity changes gradually with a limited amplitude. The key trend observed in the model is the inertia of soil moisture dynamics. Unlike environmental variables, soil moisture slowly decreases over time, indicating that the drying process is not instantaneous, but cumulative.

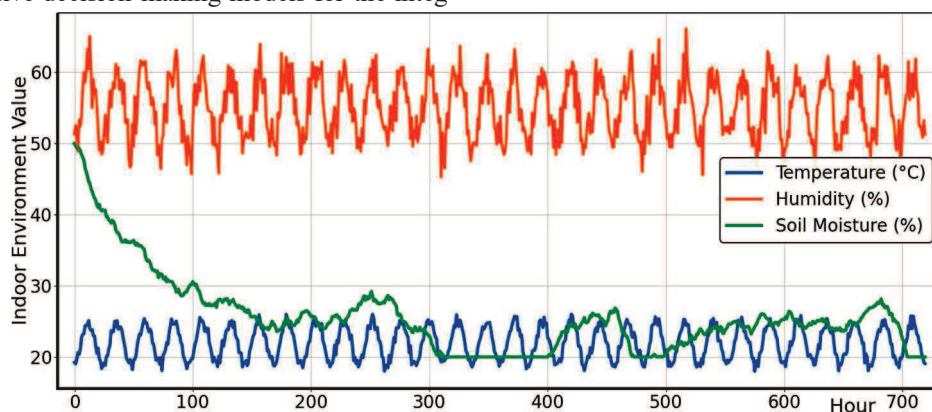


Fig. 1. Collected and normalized values of environment data for 30 days / Зібрані та нормалізовані значення даних про навколишнє середовище протягом 30 днів

Development of a plant watering indicator. To assess irrigation requirements, a weighted linear model was applied, incorporating soil moisture, air temperature, light intensity, and relative humidity. Each factor was assigned α , β , γ , δ coefficients to compute an aggregated irrigation demand as a function of deviations from predefined thresholds. Specifically, lower soil moisture increases irrigation demand, higher temperatures and light intensity contribute to increased evaporation, while elevated air humidity reduces water requirements. Unlike binary control approaches, the model produces a continuous irrigation output, where the amount of water is dynamically adjusted within predefined bounds. Irrigation is applied at specific time intervals, and the computed value is limited by a maximum allowable irrigation

rate. A Monte Carlo simulation procedure was employed to select appropriate parameter values. Multiple random combinations of coefficients were evaluated, and the best-performing configuration was selected by balancing plant condition and water consumption. This approach enables adaptive irrigation control that responds to environmental dynamics. However, its main limitation lies in the use of a linear approximation, which may not fully capture complex nonlinear interactions between environmental factors such as temperature, light intensity, evaporation processes, and plant condition dynamics.

Monte Carlo-based selection of watering strategies.

The Monte Carlo method was applied to determine suitable irrigation intervals and weighting coefficients for the aggre-

gated plant condition index. Weight coefficients (α , β , γ , δ) were randomly generated and normalized, and each combination was evaluated for system performance (Figure 2).

The configuration of coefficients for the rule-based irrigation strategy that best balanced plant condition and water use was approximately $\alpha \approx 0.100$, $\beta \approx 0.048$, $\gamma \approx 0.967$ and $\delta \approx 0.124$. These results indicate that soil moisture and temperature have the greatest influence on irrigation require-

ments, whereas air humidity has minimal impact. Performing 5,000 Monte Carlo simulations required approximately 1.22 seconds, demonstrating the efficiency of this method for rapid parameter evaluation. The Monte Carlo analysis (Figure 3) using wide ranges of weights for soil moisture ($\alpha = 0.1$ – 1.5), temperature ($\beta = 0$ – 1.0), light ($\gamma = 0.01$ – 0.15) and humidity ($\delta = 0.1$ – 1.5) showed that the best balance between plant condition and water use.

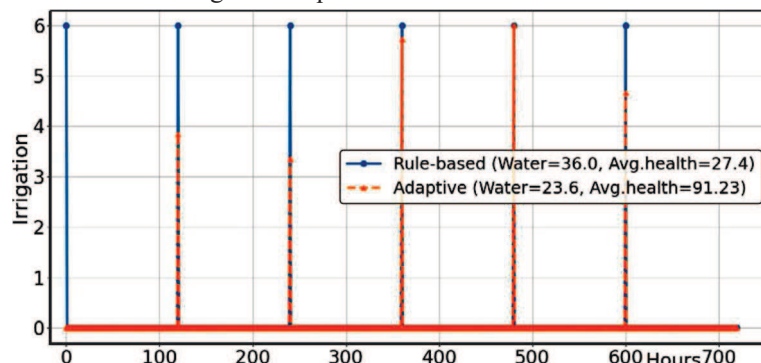


Fig. 2. The calculated values of watering the plant based on rule 1 time per 10 days / Обчислені значення поливу рослини, виходячи з правила 1 раз на 10 днів

The combined plant condition index is quantified as the average plant condition, integrating deviations from suitable soil moisture, thermal stress, and light exposure, reduced by 20 % of the total applied water, thereby balancing physiological factors with efficient irrigation.

Each point in the plot represents a randomly sampled combination of parameters evaluated during the Monte Carlo analysis. The parameter γ and δ are not shown explicitly due to dimensional limitations, although they were included in the calculations and influenced the resulting score values. In this context, the score reflects irrigation intensity, represented by irrigation intensity rather than plant condition directly.

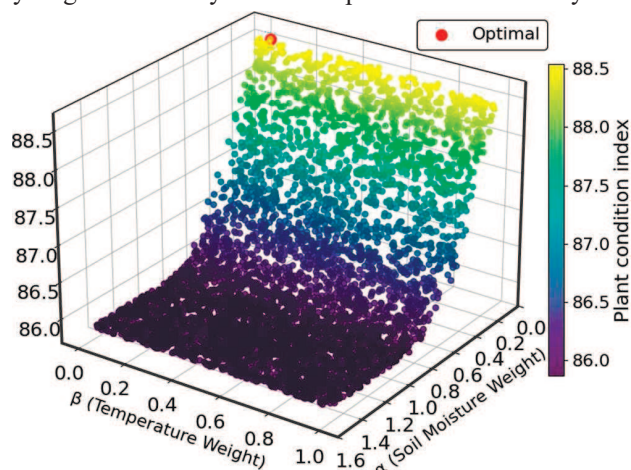


Fig. 3. Dynamics of Monte Carlo simulation for α , β and plant condition index / Динаміка оптимізації за методом Монте-Карло для α , β та індексу стану рослини

Comparative evaluation of irrigation strategies. Two irrigation strategies were evaluated in terms of plant condition and water consumption:

The rule-based strategy provides predictable water behavior but does not adapt to variations in indoor environmental conditions, leading to periods of either under- or over-watering. For example, irrigation may be triggered on predefined days using a fixed water amount, regardless of current soil moisture or environmental conditions. While easy to implement, this approach does not consider soil moisture, temperature, light, or humidity, which can lead to

overwatering or under-watering and inefficient water use. Its main advantage is simplicity, but it lacks adaptability and precision.

In contrast, the adaptive Optimized strategy dynamically adjusts irrigation according to the current environmental conditions, aiming to maintain suitable soil moisture while minimizing water use. This approach is the most efficient, as it adapts watering to actual plant needs, preventing both under- and overwatering. Its main limitation is higher complexity and the requirement for environmental data and parameter selection.

Environmental parameter analysis. The study examined soil moisture dependence on temperature and relative humidity in the indoor environment. The analysis revealed how simultaneous changes in environmental parameters affect soil moisture, providing guidance for identifying critical conditions that require irrigation and for real-time irrigation decision-making. Furthermore, regression models were evaluated to predict water consumption over the next 30 hours. Linear Regression perfectly reproduced the observed trends ($MAE \approx 0$, $R^2 = 1.0$).

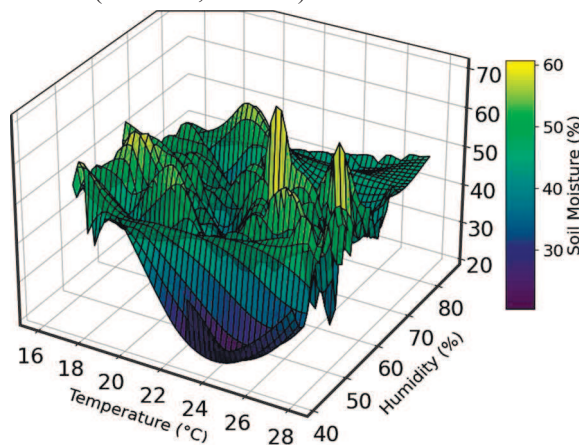


Fig. 4. 3D surface of soil moisture, temperature and humidity / 3D-модель вологості ґрунту, температури та вологості повітря

Random Forest ($R^2 \approx 0.88$, $MAE \approx 1.08$) and Gradient Boosting ($R^2 \approx 0.84$, $MAE \approx 1.23$) provided robust predictions but with slightly higher error. Support Vector Regression (SVR) performed worse ($R^2 \approx 0.33$, $MAE \approx 3.06$), failing

to fully capture trends with sparse experimental data. These results indicate that linear and ensemble methods are the most reliable for forecasting water demand and planning automated irrigation. The soil moisture decreases with increasing temperature and decreasing relative humidity, highlighting critical irrigation points as shown in Figure 4.

Designing the architecture of a MAS. The study collected environmental parameters that influence plant condition, including soil moisture, air temperature, relative humidity, and light intensity. These parameters were obtained using IoT-enabled sensors integrated into a monitoring system (Figure 5). Specifically, soil moisture was measured with an LM393 sensor, temperature and relative humidity with a DHT22 sensor, and illuminance with a BH1750 light sensor. The Sensor Agent, implemented on an ESP32 microcontroller, performed periodic polling of all sensors, converted analog signals to digital values, and generated a structured dataset. Moreover, the agent applied basic filtering to remove noise and erroneous readings caused by sensor instability or electrical interference, ensuring high-quality input for downstream processing.

A heuristic linear irrigation demand model was developed based on commonly used environmental factors affecting evapotranspiration, including soil moisture, temperature, light intensity, and air humidity.

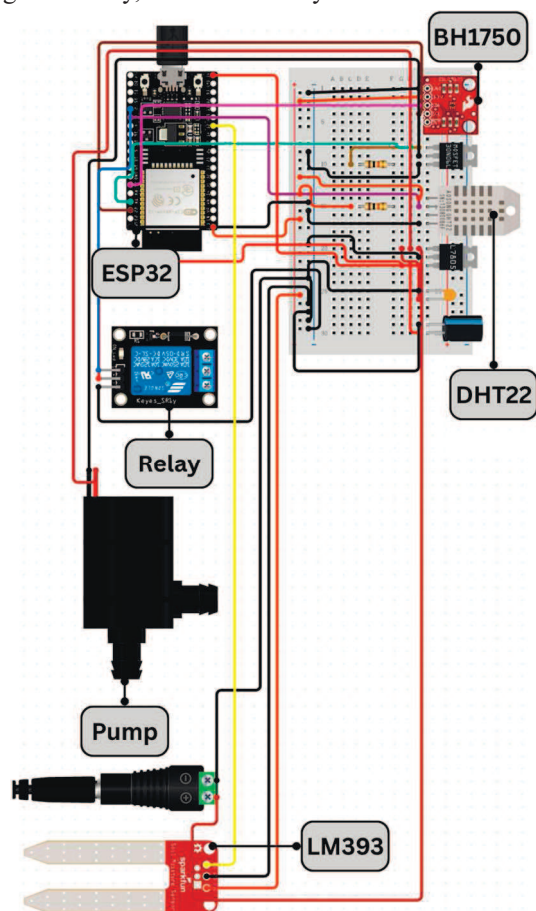


Fig. 5. Hardware diagram Sensor Agent / Схема апаратного забезпечення Sensor Agent

Raw sensor data were processed sequentially through the multi-agent architecture. The Data Processing Agent normalized and averaged measurements over predefined intervals, while detecting and mitigating anomalies. Consequently, the cleaned dataset was delivered to the Plant Model Agent, which computed an aggregated plant condition index as a weighted sum of normalized environmental para-

eters, including soil moisture, illumination, and relative humidity. This index served as a quantitative representation of plant status and provided the foundation for decision-making in irrigation management. The modeling framework was implemented using Python and scientific computing libraries, which facilitated reproducibility and rigorous numerical analysis.

MAS comprised six functional agents (Figure 6): sensor, data processing, prediction, parameter selection, decision, and control agents. The sensor agent collected environmental data, including soil moisture, temperature, and lighting conditions. These data were then processed by the data processing agent, which handled data collection and preparation. The prediction agent applied a regression model to estimate plant condition based on the processed data. The parameter selection agent subsequently applied a Monte Carlo-based procedure to evaluate irrigation parameter configurations under the current environmental conditions.

The adaptive irrigation strategy implemented in this study follows threshold-based principles [15], where irrigation is triggered when soil moisture falls below 35 %, water supply increases when temperature exceeds 25 °C, and additional factors such as light and relative humidity modulate the irrigation intensity. At the same time, it incorporates a stress-oriented approach [23] by combining multiple environmental parameters into a single plant stress indicator, reflecting the overall effect of soil moisture, temperature, light, and humidity on plant condition.

Based on these results, the decision agent generated irrigation recommendations for the plant. Finally, the control agent executed the irrigation process by starting or stopping the water pump depending on the detected soil dryness. For example, when soil moisture dropped below an acceptable level, the system activated the pump to deliver the required amount of water.

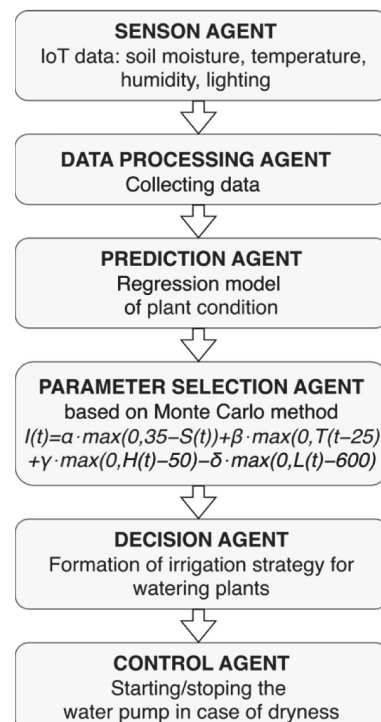


Fig. 6. Scheme of operation of the proposed multi-agent irrigation system for indoor plants / Схема роботи запропонованої мультиагентної системи зрошення кімнатних рослин

The experimental methodology involved computational simulations comparing the three irrigation strategies. Key

performance metrics included plant condition index, water consumption, and resource efficiency. Moreover, sensitivity analyses were conducted to identify potential sources of error, including sensor drift, measurement noise, and stochastic variability in Monte Carlo scenarios. The results provide a reproducible framework for validating the proposed approach and enable replication of the study by independent researchers.

Multi-criteria evaluation and efficiency analysis. A comprehensive evaluation framework assessed both plant condition and water consumption. The integrated plant condition index was computed using normalized sensor data (temperature, humidity, light, and soil moisture) with corresponding weight coefficients. Water use was normalized relative to the maximum across all strategies, and efficiency was quantified as the ratio of average plant condition to normalized water use. A weighted multi-criteria function accounted for the relative importance of plant condition and water consumption, allowing flexible prioritization depending on operational objectives.

This approach objectively identifies the most effective irrigation strategy and highlights trade-offs between water consumption and plant condition.

Discussion of research results. In studies [6, 11, 19], the authors point out a significant dependence of the effectiveness of monitoring systems on the quality of sensor data, since measurement errors or instability of sensors can significantly affect the prediction results.

In the papers [4, 7], the researchers also note the high computational complexity of stochastic optimization methods, in particular Monte Carlo method, which limits their application in real time.

In the works [16, 17, 18], the authors emphasize the problem of insufficient adaptability of models due to the use of fixed parameters that do not take into account the variability of the environment and the characteristics of different plant species.

In the studies [1, 21] also note the limitations of the factors taken into account, which may reduce the accuracy of assessing the condition of plants due to ignoring additional parameters such as nutrient levels or ventilation.

In the papers [4, 5, 12], the authors draw attention to the complexity of coordination in MAS, where the inconsistency of agent interaction can lead to suboptimal decisions.

The study [7] highlights the dependence of machine learning models on the quality and volume of training data, which limits their effectiveness in the new environment. A robust ML classifier, specifically the Radial Basis Function - Support Vector Machine (RBF-SVM) was trained on synthetic data generated through the Monte-Carlo (MC) technique, which was then used to specify a set of irrigation rules implemented in the irrigation controller. The synthetic data were derived from observations collected from irrigation plots at the Texas A&M University Turfgrass Laboratory in Texas, United States, with Soil Wetting Efficiency Index (SWEI) serving as the target variable. When tested against a commercially available irrigation controller, the ML-based controller significantly reduced runoff by an average of 74 % while maintaining high Green Cover (GC) in turfgrass, achieving an accuracy of 87 %.

The papers [11, 19] also note the need for technical training of the user for setting up and maintaining the system, which reduces its practical availability. For papers [11] describes a system for caring for houseplants based on the

Internet of Things. The authors believe that pollution is a concern worldwide, and pollution levels inside buildings (homes or workplaces) can be higher than outdoors. To alleviate this problem and improve air quality, ornamental plants can be used. This paper presents the application of Internet of Things (IoT) technologies to develop a system called P4L, an acronym for "Plants for Life". The objective of P4L is the automated care of potted plants to improve air quality and make the indoor environments of a building healthier. This IoT-based system (IoTS) has been developed through low-cost Arduino-compatible components. In addition, the Test-Driven Development Methodology for IoT-based Systems (TDDM4IoTS) has been used to guide P4L development. In fact, this article shows the result of the application of this methodology (phase by phase), with the help of the Test-Driven Development Tool for IoT-based Systems (TDDT4IoTS), which supports the aforementioned methodology, to develop P4L. To validate the methodology, we conducted a survey among developers that have used it, the results of which show that it is efficient and covers all aspects of IoTS development.

In studies [10, 14, 20], the authors analyzed more complex dynamic approaches and simulation modeling for adaptive irrigation control, highlighting their potential in decision-making. In contrast, the present model approximates irrigation need as a weighted combination of deviations from thresholds, inspired by the principles of evapotranspiration estimation and rule-based management [10]. This approach, compared to the Penman-Monteith equation [14] and Model Predictive Management [20], offers computational efficiency, interpretability, and straightforward parameterization, making it suitable for stochastic optimization and real-time decision-making without extensive data requirements.

In studies [8, 22], the authors investigated advanced sensing technologies and cloud-based IoT systems for monitoring plant condition in both indoor and outdoor farming, emphasizing real-time data acquisition and remote management capabilities.

Summarizing the above, the existing approaches are either limited in taking into account factors or characterized by insufficient adaptability and high computational complexity. Thus, the study confirms the feasibility of developing the proposed MAS with an adaptive approach to irrigation management, which, unlike existing solutions, provides comprehensive accounting of environmental parameters, flexibility of setting and demonstrated by a reduction in water consumption from 36.0 to 23.6 conventional units ($\approx 34.4\%$) while simultaneously increasing the average plant condition index from 27.4 to 91.23 (more than 3.3 times) compared to the rule-based approach.

So, based on the results of the work performed, it is possible to formulate the following scientific novelty and practical significance of the research results.

Scientific novelty of the obtained research results – for the first time, an adaptive method for irrigation management based on a multi-agent approach using the Monte Carlo method was developed, which, in contrast to existing solutions, provides integration of environmental parameters, modeling of plant condition and forecasting of effective care scenarios, which minimizes deviations from the optimal level of soil moisture and increases the efficiency of water use.

Practical significance of the research results – the results of the study can be used to develop and implement intelligent multi-agent systems for automated control of irri-

gation management based on the analysis of environmental parameters, in particular in smart irrigation systems, monitoring the condition of plants in greenhouse and home conditions, as well as in precision farming tasks in order to increase the efficiency of water resources use and provide suitable parameters for maintaining plant condition.

Conclusion / Висновки

Developed and studied a multi-agent system for adaptive irrigation houseplants management based on environmental parameters, which provides adaptive decision-making on irrigation by taking into account soil moisture, temperature, illumination and other factors to increase the efficiency of water resources use and maintain favorable plant conditions. Based on the results of the research the following main conclusions can be drawn.

1. Modern approaches to automation of plant care have been analyzed and their advantages and disadvantages have been identified, which has made it possible to substantiate the feasibility of using adaptive control methods and to form requirements for an adaptive irrigation system in a dynamic environment.
2. Computational models of plant condition and soil moisture dynamics have been developed, taking into account temperature, lighting, and humidity, which provide an adequate description of growth and water consumption processes and create the basis for real-time decision-making.
3. The plant condition index has been introduced as an integral indicator that takes into account the cumulative influence of environmental parameters and allows to increase the accuracy of assessing the condition of plants and the validity of irrigation decisions.
4. A model for assessing the state of the plant based on the analysis of environmental data has been developed, which provides timely detection of deviations from suitable conditions, prediction changes in the state and the formation of adaptive recommendations for irrigation management.
5. A multi-agent system architecture has been developed that provides distributed data processing, consistent agent interaction, and the formation of adaptive real-time solutions for irrigation control.
6. A multi-agent system architecture has been developed that provides distributed data processing, consistent agent interaction, and the formation of adaptive real-time solutions for irrigation control.
7. Experimental modeling of different irrigation modes was carried out, and the results showed that the adaptive approach reduced water use by approximately 34.4 % while simultaneously increasing the average plant condition index by more than 3.3 times compared to the rule-based method.
8. The effectiveness of the proposed system for automated care of indoor and ornamental plants with the ability to scale additional agents and sensors has been established.

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АНАЛІЗ ЕФЕКТИВНОСТІ ПОЛИВУ КІМНАТНИХ РОСЛИН У МУЛЬТИАГЕНТНІЙ СИСТЕМІ НА ПІДСТАВІ ПАРАМЕТРІВ СЕРЕДОВИЩА

Встановлено актуальність розроблення інтелектуальних систем для оптимізації режимів поливу кімнатних рослин за динамічних умов закритого середовища, де параметри мікроклімату змінюються у часі та істотно впливають на стан рослин. Для вирішення цього завдання застосовано мультіагентну архітектуру системи, яка інтегрує сенсорні дані про вологість ґрунту, температуру, освітленість і вологість повітря з математичними моделями росту рослин і прогностичними алгоритмами. Додатково використано метод Монте-Карло для пошуку оптимальних сценаріїв поливу за умов невизначеності та варіативності зовнішніх факторів. Виявлено, що мультіагентна система забезпечує ефективне розподілене оброблення даних, підвищує адаптивність управління та дає змогу враховувати індивідуальні, зокрема – видоспецифічні потреби рослин. Охарактеризовано закономірності впливу температури, вологості ґрунту, освітлення та вологості повітря на інтегральний показник стану рослин, що дає змогу комплексно оцінювати ефективність різних режимів поливу. Запропоновано підхід до формування керівних впливів на основі зваженої оцінки відхилень параметрів середовища від оптимальних значень та їх взаємного впливу. Оцінено вплив координації агентів на точність прийняття рішень і раціональність використання водних ресурсів; встановлено підвищення середнього показника стану рослин порівняно із традиційними методами поливу. Показано, що застосування прогностичних моделей та алгоритмів оптимізації параметрів середовища дає змогу формувати персоналізовані рекомендації для користувача, забезпечувати стабільність рівня вологості ґрунту та своєчасну реакцію системи на зміну умов середовища. Ефективність роботи системи підтверджено шляхом експериментального моделювання режимів поливу для кількох типів рослин, що демонструє її практичну придатність. Перспективним напрямом подальших етапів дослідження є розширення системи за рахунок додаткових параметрів середовища, підвищення автономності агентів, а також інтеграція сучасних методів машинного навчання для підвищення точності прогнозування стану рослин та якості прийняття рішень. Інтеграція сучасних методів машинного навчання (ML) та глибокого навчання (DL), таких як згорткові нейронні мережі (CNN), випадковий ліс та метод опорних векторів (SVM) – зробила революцію в прогнозуванні стану рослин, перевівши сільське господарство від реактивного до проактивного управління на основі даних. Аналізуючи величезні набори даних з давачів Інтернету речей, супутникових знімків та дронів, ці методи підвищують точність прогнозування врожайності, раннє виявлення хвороб та управління ресурсами.

Ключові слова: моделювання за методом Монте-Карло; стратегії кімнатного зрошення рослин; адаптивне керування; прогностичне моделювання; інтелектуальне оброблення даних; Інтернет речей.