International Conference on Computing, Artificial Intelligence and Information Systems
Hosted Online from Warsaw, Poland
Date: 11th May, 2026
Website: https://econferencia.com

DEVELOPMENT OF ENERGY-EFFICIENT AND SECURE IOT-BASED METHODS AND INFORMATION SYSTEMS FOR REAL-TIME MONITORING OF SMART AGROECOSYSTEMS IN THE NOOSPHERE

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Abstract

This study is aimed at developing a comprehensive information system for real-time monitoring of smart agroecosystems based on the noosphere concept, enhancing energy efficiency, and ensuring the security of IoT systems. The proposed system enables continuous measurement of environmental parameters, including soil moisture, water level, temperature, and mineralization, as well as visual monitoring through remote cameras, and data storage and processing on the Amazon Web Services (AWS) cloud platform.

To improve energy efficiency, specialized power management strategies were implemented, extending the autonomous operation time of the device by up to 10

additional days. To ensure information security, two-factor authentication (2FA) and protection mechanisms based on JSON Web Tokens (JWT) were introduced. The results of experimental studies demonstrated high accuracy of sensor measurements ($R^2 = 0.97$ for temperature and $R^2 = 0.89$ for humidity), confirming the system's reliability, energy efficiency, and practical effectiveness. The obtained results enable farmers to use resources more rationally, improve decision-making processes, and increase crop productivity.

Keywords. IoT, smart agriculture, monitoring system, energy efficiency, cloud technology, sensor networks, real-time monitoring, mobile application, precision farming

Introduction

At the global level, food security is one of the most pressing issues directly affecting the stability and well-being of human societies. In recent years, IoT-based monitoring systems used in water management and agriculture have achieved significant progress; however, they often face challenges related to high energy consumption, limited mobility, complex installation processes, and insufficient data protection measures.

According to the concept proposed by Vladimir Vernadsky, the noosphere represents a global system of interactions between human intelligence, technology, and nature. In this study, this concept is formalized into a mathematical model for hydrogeological systems and expressed as a closed-loop control system through the integration of IoT, Big Data, and Artificial Intelligence (AI). The research presents an improved IoT application focused on innovative processes. The proposed system integrates energy efficiency,

portability, and secure connectivity, providing farmers with enhanced capabilities for monitoring and managing the ecological state of crops. The system components include a remotely controlled camera and a sensor module for continuous monitoring of environmental parameters such as temperature, humidity, soil moisture, and others.

Review of International and National Literature

In recent years, the integration of the Internet of Things (IoT), Artificial Intelligence (AI), and Big Data technologies in monitoring and managing smart agroecosystems has become one of the main directions of global scientific research. According to the concept proposed by Neil Gershenfeld, "smart devices interconnected through systems enable real-time monitoring and control of the environment" [1]. Studies by Suraj Singh and Rajesh Kapoor demonstrate that IoT platforms play a crucial role in ensuring real-time monitoring in agriculture, improving resource efficiency, and increasing productivity [2]. Research conducted by Seyed Hossein Hejazi and colleagues developed effective methods for processing and forecasting agroecosystem parameters based on Big Data technologies [3].

At the same time, energy efficiency and security of IoT systems remain critical challenges. Ionut Dragomir and co-authors emphasized the necessity of developing secure communication protocols in IoT systems [4], while Kashif Naik and Paul Jenkins analyzed latency and security issues in Web of Things systems [5]. Modern studies widely apply real-time monitoring systems based on Amazon Web Services (AWS) cloud platforms and the MQTT protocol. However, existing research does not sufficiently address the comprehensive modeling and management of agroecosystems based on the noosphere concept,

particularly in terms of the interconnection between human, technology, and nature.

Uzbek scientists have conducted a number of studies in the fields of hydrogeological systems, water resource management, and environmental monitoring. In particular, J.Kh. Djumanov and co-authors proposed innovative methods for real-time monitoring of hydrogeological processes, demonstrating the application of modern sensor technologies [8]. Additionally, studies on the implementation and automation of remote monitoring in water distribution systems have substantiated the effectiveness of IoT devices [9].

In recent years, scientific research on the application of artificial intelligence and information technologies across various sectors has expanded in the country. In particular, there are developments related to the analysis and forecasting of complex systems based on neural networks and mathematical modeling [20], [21]. However, existing studies have not sufficiently integrated real-time monitoring of smart agroecosystems, the development of energy-efficient IoT architectures, and the provision of cybersecurity as a unified system. In particular, the formation of information infrastructure and the development of intelligent control systems based on the noosphere approach remain insufficiently explored from a scientific perspective.

Main Part

To reduce energy consumption, specialized energy management strategies were implemented. Unlike conventional solutions, the developed system utilizes the Amazon Web Services (AWS) cloud platform for reliable data storage and processing. In addition, comprehensive security mechanisms—two-factor authentication (2FA) and JSON Web Token (JWT) technologies—were applied,

ensuring critical protection measures that are often overlooked in existing agricultural IoT systems [4, 7].

Users can access this monitoring system through a specially developed Android application, enabling fast and convenient use of crop-related data via mobile devices. The system's effectiveness was confirmed through experimental studies. Evaluation results demonstrated high sensor reliability, with strong correlations between measured and reference values [8, 9] ($R^2 = 0.979$ for temperature and $R^2 = 0.875$ for humidity).

Furthermore, the implemented energy management strategies ensured efficient battery utilization, extending the device's operational lifetime to up to 10 days on a single charge. This result represents a significant improvement compared to existing systems that typically require daily recharging. In addition, the two-stage security mechanism based on 2FA and JWT provided reliable protection of sensitive agricultural data against unauthorized access [8, 11].

In the noosphere context, the lack of real-time data on plant growth processes and environmental conditions limits farmers' ability to make data-driven decisions and respond promptly to changes in the growth environment. As a result, inefficient resource usage—such as over-irrigation or insufficient fertilization—occurs, leading not only to reduced crop yields but also to environmental degradation.

The interaction model between human intelligence, technology, and nature can be represented as follows [8]:

$N=\langle M, T, I, A, K\rangle$

where:

- MMM (Environment) – natural environment (soil, water, atmosphere);
- TTT (Technology) – technological infrastructure (IoT, AI, GIS);

- III (Human) – human activities (decision-making, management);
- AAA (Information) – data flows (sensors, Big Data);
- KKK (Control/Observation) – control and feedback mechanisms.

The functional equation of the noosphere model, representing system dynamics, depends on temporal and spatial parameters as follows [9, 15]:

$X(t+1)=F\{X(t), U(t), D(t)\}$

where:

- $X(t)X(t)X(t)$ – system state (e.g., water level, quality);
- $U(t)U(t)U(t)$ – control decisions;
- $D(t)D(t)D(t)$ – data flow;
- FFF – noospheric transformation function.

The formalization of the intelligent core is expressed as:

$AI=\alpha \cdot ML(D)+\beta \cdot FL(E)AI =$

where:

- ML – machine learning (prediction);
- FL – fuzzy logic (handling uncertainty);
- $\alpha+\beta=1$

The closed-loop control model of the noosphere is defined as:

$L:S\rightarrow D\rightarrow AI\rightarrow U\rightarrow G$

This represents the evaluation system:

Sensor → Data → Analysis → Decision → Environmental Impact → New State → Monitoring

Thus, the noosphere concept was formalized into a mathematical model for hydrogeological systems and represented as a closed-loop control system through the integration of IoT, Big Data, and AI technologies.

In this study, the noosphere concept was transformed from a classical philosophical notion into a formal information-mathematical model for monitoring plant conditions in hydrogeological and agroecosystems in real time. Based on real-time data, a self-adaptive intelligent system was developed.

Therefore, advanced technologies are essential for accurate and real-time monitoring of plant growth processes and their surrounding environmental conditions. Such solutions enable farmers to optimize agricultural practices, use resources efficiently, and sustainably increase crop productivity.

To address challenges in water management and agriculture, the adoption of the Internet of Things (IoT) has gained significant attention over the past decade. IoT-based monitoring systems have brought transformative changes to agriculture by enabling farmers to collect real-time data on key environmental parameters necessary for optimal plant growth, such as temperature, humidity, and soil moisture.

These systems ensure continuous monitoring by utilizing various sensors and wireless communication technologies, providing valuable insights into crop health and productivity. When processed using modern Artificial Intelligence (AI) and Machine Learning (ML) methods, this data allows farmers to optimize resource utilization, resulting in increased agricultural productivity and sustainable development.

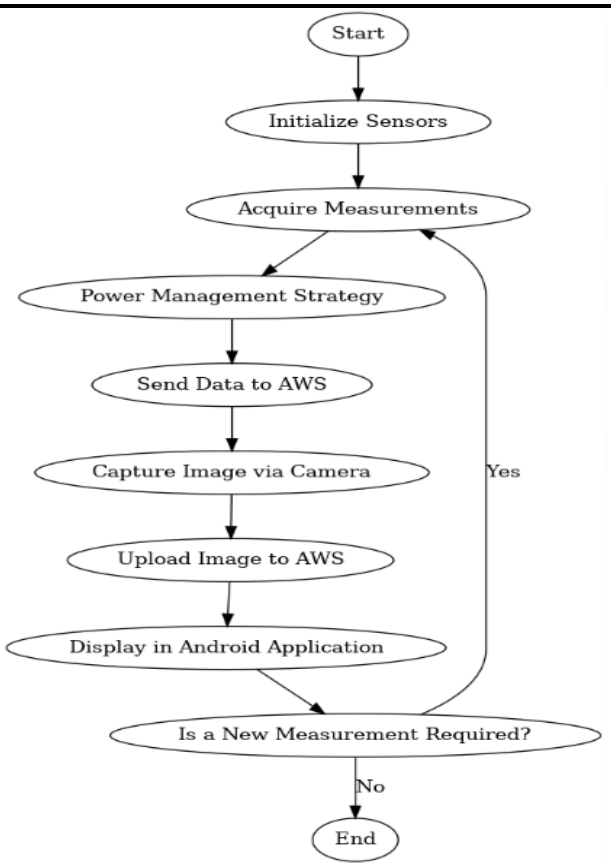

Figure 1. Block diagram of the IoT monitoring algorithm.

This article presents an innovative IoT application developed for monitoring plants in agriculture. The primary objective of the system is to assist farmers in monitoring and controlling the environmental conditions essential for optimal plant growth.

The proposed solution features a power management configuration designed to minimize energy consumption and periodically measures various environmental parameters. The collected data is securely transmitted to the Amazon Web

Services (AWS) cloud platform for subsequent storage and analysis. Additionally, images of the plants are captured via a remote camera and uploaded to the cloud. Users can monitor and verify this data through a specially developed Android application on their mobile devices.

To ensure system security, mechanisms for protecting access to sensor data have been implemented. The application utilizes Two-Factor Authentication (2FA) and JSON Web Token (JWT) based authentication. 2FA provides a high level of security by requiring an additional verification step alongside the standard username and password. Meanwhile, JWT enhances security by assigning expiration periods to tokens, thereby mitigating risks associated with token reuse.

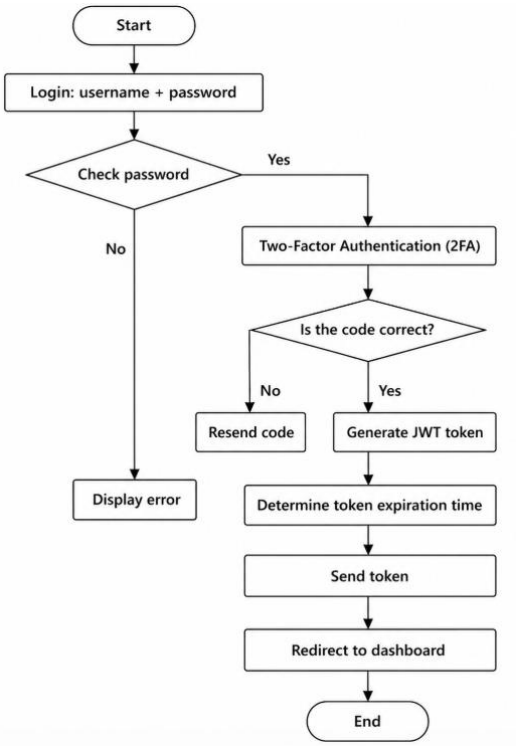

Figure 2. Authentication algorithm flowchart

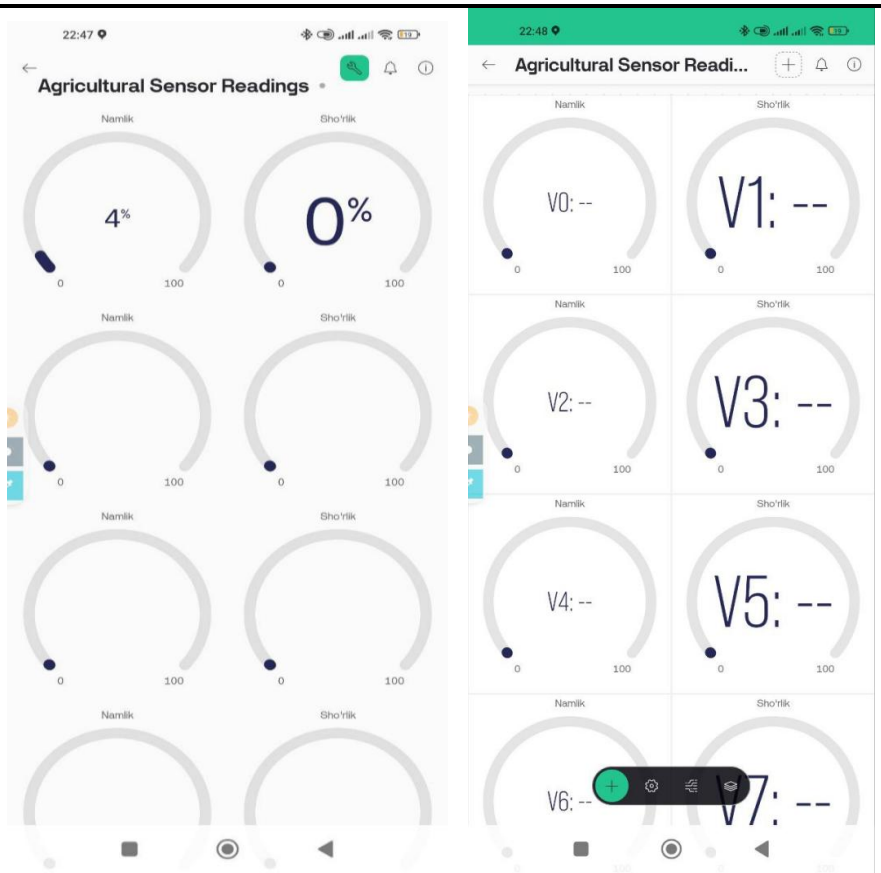

Figure 3. Interface of the soil moisture and water level measuring device

To evaluate the system's effectiveness, it was tested on garlic plants in two containers placed on the roof of a building at Okayama University. The experiments demonstrated that the developed IoT-based monitoring system provides high-precision sensor readings, ensures longer battery life due to energy efficiency, and guarantees secure access exclusively for authorized users.

CONCLUSION

In this work, a new scientific approach for monitoring smart agro-ecosystems was developed based on the noosphere concept. It implements an IoT-supported plant monitoring system to address water and agricultural management issues. The interface of our mobile application is as follows, with the flexibility to be modified as needed; this requires no programming skills from the user. The device serves to measure soil moisture and water levels and transmit this data remotely. To integrate our device with this software, the following code was implemented:

1. Initially, the necessary libraries for working with the Blynk platform were imported, and an auth variable was created to perform authentication with the web application. In this code, the ssid and pass variables store the connection credentials for the Wi-Fi router or modem.

```
#include <WiFi.h>           // WiFi library for Blynk
#include <BlynkSimpleEsp32.h> // Blynk library for ESP32

// Blynk credentials
char auth[] =                                  '; // Replace with Blynk Auth Token
char ssid[] =          ;    // Replace with your WiFi SSID
char pass[] =           ;// Replace with your WiFi password
```

2) Variables have been declared for the required data.

```
// Received sensor values
String receivedMessage = "";
int receivedMoisture = 0;
int receivedSalt = 0;
```

3) The systems starts the web application and connects it to the device.

```
// Initialize Blynk
Serial.println("Connecting to Blynk...");
Blynk.begin(auth, ssid, pass);
Serial.println("Blynk connected!");

delay(1000);
```

4) It received data from the devices and transmitted the data to the web application.

5) In this approach, the web application transmits the measured values to a Virtual Pin, where the associated data stream continuously updates the widgets in the application interface. The key advantage of this device is its ability to transmit all collected data to the web application using Wi-Fi–based wireless communication protocols.

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