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Sensor-based IoT nodes under development for the Green Digital Transformation for measuring soil quality parameter

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Abstract—**Green digitalization represents a modern concept that integrates digital technologies with the aim of enhancing sustainable development and promoting the rational use of natural resources. In the context of agriculture, it involves the application of intelligent IoT-based sensor systems and cloud infrastructure to optimize processes, reduce energy consumption, and protect the environment. Soil quality, as a fundamental resource of agricultural production, plays a crucial role in this process, as it directly affects the productivity and ecological stability of agroecosystems. In this paper, a cloud-oriented data acquisition system for soil quality monitoring has been developed, contributing to the goals of green digitalization through automation, energy efficiency, and the reduction of the need for manual sampling. The system is based on an Arduino microcontroller, an ESP8266 Node MCU Wi-Fi module, and a multifunctional RS485 4–20 mA soil sensor that measures temperature, moisture, pH value, and electrical conductivity. The collected data are automatically transferred to the Oracle Autonomous Database via REST Data Services (ORDS) and analyzed through the Oracle APEX application, providing remote access and real-time analysis. The proposed solution demonstrates how the integration of IoT technologies and cloud services can contribute to the development of green digital agriculture, enabling more precise resource management, reduced use of water and chemicals, and preservation of soil quality at the desired level. Such systems have significant potential for application in sustainable land management, environmental protection, and the achievement of green transition objectives.**

Keywords- Green digitalization, soil quality, IoT, cloud computing, sustainable agriculture, data acquisition system, Arduino

I. INTRODUCTION

In today's world, civilization faces the urgent necessity of finding long-term solutions to global ecological challenges that cannot be addressed or resolved without green digital transformation - a synergy of advanced digital technologies and sustainable principles aimed at promoting a circular economy. This concept involves the use of technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data analytics, and cloud computing to enhance efficiency, reduce resource consumption, and minimize the environmental footprint. In the context of agriculture and environmental protection, green digitalization enables the optimization of production processes, precise resource management, and decision-making based on real-time and accurately measured data [1][2][3].

Precise and continuous monitoring of environmental parameters has become a key prerequisite for sustainable management of natural resources. Digital technologies allow for the collection, analysis, and interpretation of data in real time, thereby improving transparency and efficiency in ecological and agricultural processes. Soil quality, as a fundamental resource for food production and ecosystem preservation, requires intelligent and integrated monitoring solutions that combine sensor systems, cloud infrastructure, and data analysis algorithms.

Soil quality is one of the essential factors for successful agricultural management and environmental protection. Monitoring its changes enables the identification of degradation, erosion, contamination, and loss of fertility, providing a foundation for planning protection and rehabilitation measures. Traditionally, soil quality assessment is carried out through laboratory analyses, which ensure high accuracy but require substantial resources in terms of time, cost, and human effort. The advancement of digital technologies has enabled the development of multifunctional sensor nodes integrated into data acquisition systems connected via communication networks, thereby achieving efficient, automated, and continuous monitoring of soil parameters.

These systems consist of both hardware and software components that work together to collect, process, and interpret data in real time. Typically, they include sensors, microcontrollers, communication modules (e.g., Wi-Fi, LoRa, RS485), and cloud platforms for data storage and visualization. The monitored parameters include pH value, temperature, soil moisture, electrical conductivity (EC), and the concentrations of key nutrients such as nitrogen, phosphorus, and potassium (NPK). Such systems enable informed decision-making regarding irrigation, fertilization, and crop protection, thereby directly contributing to greater efficiency and reduced negative environmental impact [4].

In addition to sensor based technologies, soil quality monitoring can also be implemented by combining other methods, including laboratory analyses, satellite imaging, Geographic Information Systems (GIS), and mathematical modeling [5][6][7]. The integration of data from these sources provides a comprehensive understanding of soil conditions and a better insight into their spatial and temporal dynamics. Such integrated approaches form the basis for developing the Soil Digital Twin concept, a virtual model that represents the soil's state in real time and enables predictive management of agroecosystems.

At the core of this research is a multiparameter RS485 4 – 20mA sensor, capable of simultaneously measuring temperature, moisture, electrical conductivity (EC), pH, and nutrient concentrations (NPK), (Fig.1.).

Figure 1. EC PH NPK Sensor

Owing to their robustness and ability to integrate into IoT networks, these sensors allow for detailed profiling of soil conditions and the creation of dense measurement networks. In this way, they form the foundational infrastructure for the green digital transformation of agriculture, a digitalized, sustainable, and energy-efficient approach to soil resource management.

The objective of this work is to research, implement, and evaluate a cloud-oriented data acquisition system for soil quality monitoring, developed in accordance with the principles of green digitalization. The system is based on an Arduino Uno microcontroller, an ESP8266 Node MCU Wi-Fi module, and a multi-parameter soil sensor. The collected data are transmitted to an Oracle Autonomous Database via Oracle REST Data Services (ORDS) and analyzed through the Oracle APEX application, (Fig.2.).

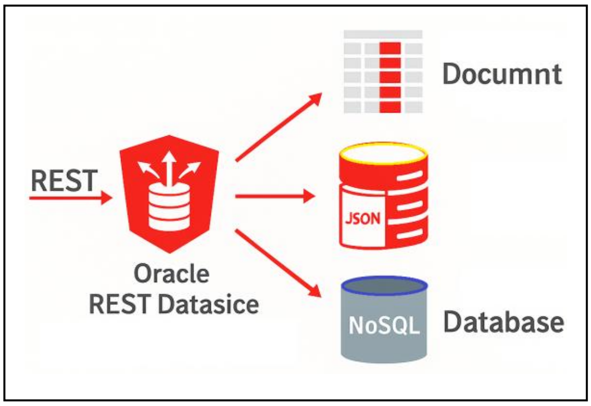

Figure 2. ORDS arhitecture

Additionally, the sensor node includes mobile hotspot connectivity, which enhances data accessibility and reduces the need for fixed infrastructure, allowing measurements to be performed directly in rural or remote areas. In this way, a flexible, affordable, and sustainable solution is achieved, contributing to the modernization of agriculture and the realization of the goals of green digital transformation.

II. GREEN DIGITAL TRANSFORMATION IN ARRICULTURE

The green digital transformation in agriculture represents the integration of ecological sustainability and advanced digital technologies with the goal of creating intelligent, resource-efficient, and climate-resilient production systems. This concept encompasses the use of Information and Communication Technologies (ICT), the Internet of Things (IoT), sensor networks, Artificial Intelligence (AI), and data analytics to optimize food production processes and ensure the protection of soil, water, and biodiversity. The essence of green digitalization lies not only in the modernization of agriculture but also in achieving a sustainable balance between productivity and the preservation of natural resources.

Within this approach, sensor networks form the fundamental layer of the digital infrastructure for smart and sustainable agriculture. They enable the continuous collection of data on soil conditions, atmospheric parameters, and crop status, creating a foundation for data-driven decision-making based on actual and quantifiable measurements. Sensor networks consist of interconnected sensor nodes that communicate via wired (RS485, Modbus) or wireless protocols (Wi-Fi, LoRa), and their architecture can be adapted depending on the size and topology of the agricultural area.

A. *Sensor Networks in Green Transformation*

Sensor networks in agriculture make it possible to digitally map agroecosystems and create dynamic databases on soil conditions. The collected data serves as input for precision agriculture systems, which optimize irrigation, treatment, fertilization, and soil management processes. In this way, they make a direct contribution to the green transition through:

- Reduced resource consumption – precise monitoring of soil moisture and electrical conductivity enables the rational use of water and fertilizers.
- Increased energy efficiency – automation and wireless data transfer reduce the need for physical sampling and transportation.
- Reduction of environmental footprint – optimization of agrochemical interventions reduces soil and groundwater pollution.
- Improved productivity and system resilience – continuous monitoring enables timely response to stress conditions (such as drought, salinity, or acidity).

B. *Measuring soil quality parameters*

The soil quality parameters monitored through sensor networks form the basis for assessing the fertility and sustainability of agroecosystems. The key parameters include:

- Soil temperature, which affects the rate of chemical reactions, microbial activity, and root growth.
- Soil moisture, which determines water availability for plants and irrigation efficiency.
- Electrical conductivity (EC), which indicates soil salinity and the presence of dissolved salts.
- pH value, as an indicator of soil acidity or alkalinity, directly influencing the availability of nutrients.
- NPK content (Nitrogen, Phosphorus, Potassium), which defines the nutrient value and fertility of the soil (Fig.3.).

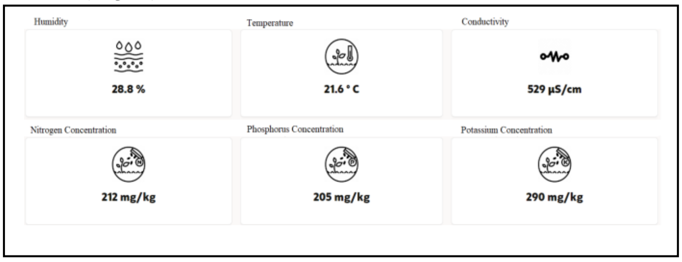

Figure 3. NPK Cloud aplication

Multi-parameter sensors, such as the RS485 4–20 mA sensor, are cost-effective and efficient devices widely available on the market. They enable the simultaneous measurement of multiple soil parameters and serve as the core components of sensor node networks. When integrated with microcontrollers (e.g., Arduino Uno) and communication modules (e.g., ESP8266 Node MCU), these sensors form intelligent IoT nodes that transmit real-time data to cloud platforms.

Cloud infrastructure (e.g., Oracle Autonomous Database and the APEX platform) provide centralized storage, visualization, and analysis of the collected data. In this way, a closed-loop digital management system is established — from real-time measurement and analysis to decision-making and automated actions (e.g., irrigation system activation),(Fig.4.).

C. *Contribution to the green digital transition*

The application of sensor networks in soil quality monitoring represents a tangible contribution to achieving the goals of the green digital transition in agriculture. Such systems:

- Enhance transparency and accountability in resource use.
- Enable a data-driven approach to planning and decision-making.
- Contribute to the decarbonization of agriculture through energy optimization and emission reduction.
- Create a foundation for a circular agricultural economy, by providing feedback on soil health and production efficiency.

The combination of sensor networks, cloud technologies, and intelligent analytics forms a key pillar of the digital transformation of agroecosystems. This establishes the foundation for developing smart, self-regulating systems that contribute to long-term sustainability, food security, and the preservation of natural resources.

Green digitalization in agriculture, based on real-time soil quality data, thus represents a bridge between technological advancement and environmental responsibility, paving the way toward a sustainable and climate-resilient future of agricultural production.

III. SENSOR NODE IN THE GREEN TRANSFORMATION

The green digital transformation represents the fusion of digital innovation and sustainable development principles aimed at reducing the negative human impact on the environment and optimizing the use of natural resources. The application of knowledge and technology derived from advanced digital solutions such as the Internet of Things (IoT), cloud computing, Big Data analytics, and Artificial Intelligence (AI) plays a crucial role in achieving this transformation.

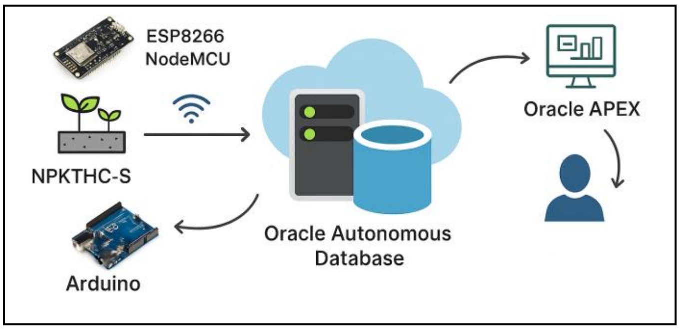

Figure 4. Architecture of a cloud-oriented data acquisition system

These technologies enable real-time data collection and analysis, forming the basis for data-driven decision-making supported by precise information. In this context, sensor networks represent the core of digitalized agriculture, as they allow for the measurement and control of numerous environmental and soil parameters directly related to sustainable food production.

Sensor nodes integrated into agricultural sensor networks constitute decentralized systems composed of interconnected units that autonomously collect data from the environment. These data typically include parameters such as temperature, soil and air humidity, electrical conductivity, pH level, and nutrient concentrations. Monitoring these parameters allows for the creation of digital agroecosystem models that enable optimal resource management, (Fig.5.).

The application of sensor networks within the framework of green digitalization enables:

- Rational use of water and fertilizers through precision irrigation and nutrient delivery systems.
- Reduction in the use of chemical agents and greenhouse gas emissions.
- Preservation of soil structure and biodiversity.
- Increased energy efficiency through the automation of measurement and data transmission processes.

By integrating sensor nodes with cloud infrastructure, a system is achieved that operates without the need for constant human presence in the field, thus reducing both operational costs and emissions associated with transportation and sampling.

A. Architecture of the IoT sensor node

As part of this research, an IoT sensor node was developed to enable real-time soil quality monitoring and data transmission. The node was designed to combine ease of use, energy efficiency, and modularity, making it suitable for applications in smart and sustainable agricultural systems [8][9][10].

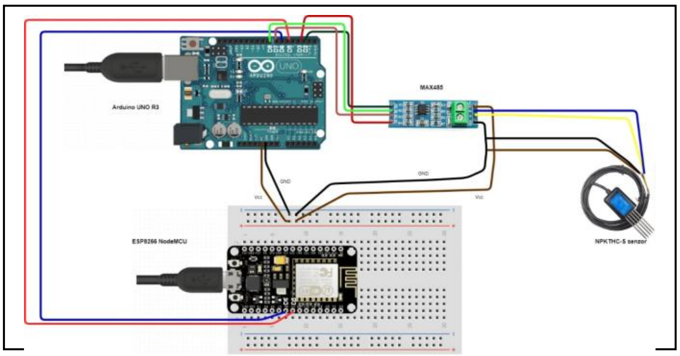

Figure 5. Sensors node

The structure of the node consists of the following components:

- NPKTHC-S multi-parameter sensor, which measures temperature, humidity, electrical conductivity (EC), pH value, and nutrient concentrations (nitrogen, phosphorus, and potassium – NPK).
- Arduino UNO R3 microcontroller, which manages communication with the sensor via an RS-485 connection and the MODBUS RTU protocol, using a MAX485 interface.
- ESP8266 Node MCU module, which enables wireless data transmission via Wi-Fi to the cloud service.
- REST API service and Oracle Autonomous Database, which handle the reception, processing, and storage of data on the cloud platform.

The operation of the sensor node can be divided into four phases:

- Data acquisition – the sensor collects measurement data and transmits them to the Arduino microcontroller in hexadecimal format.
- Data processing – the Arduino converts the received values into decimal format, groups them into a JSON object, and forwards them to the Node MCU module.
- Wireless transmission – the ESP8266 establishes a Wi-Fi connection and sends the data via the HTTP POST method to the REST API service hosted on the Oracle Autonomous Database.
- Analysis and visualization – the cloud platform enables data analysis and visualization through the Oracle APEX application, providing charts and reports accessible from any device with internet connectivity.

This architecture allows for autonomous and continuous monitoring of soil quality parameters, which represents a key contribution to the digitalization of agriculture. The system operates without the need for manual sampling, and data is available in real time, enabling quick responses to changing soil conditions.

B. Environmental and energy aspects of the IoT node

One of the key characteristics of the developed system is its energy efficiency. All node components operate at low voltage (5 V), and overall power consumption is minimal, allowing for long-term operation and potential integration with renewable energy sources such as solar panels. In this way, the system aligns with the principles of green infrastructure, enabling digitalization without additional energy burden.

The contribution to green digitalization is also reflected in:

- Reducing the need for physical sampling, thereby minimizing fuel consumption and CO_2 emissions.
- Minimizing water and chemical use through accurate insight into soil parameters.
- Long-term protection of soil and biodiversity through continuous monitoring of pH and EC values, which indicate salinization or degradation trends.

By deploying such nodes, it is possible to form a network of sensor units covering different agricultural zones. This creates a digital soil ecosystem, enabling production optimization based on real data and supporting the principles of precision and sustainable agriculture.

C. Architecture of a Cloud oriented data acquisition system

The cloud-oriented data acquisition system for soil quality monitoring represents an integration of IoT devices, communication modules, and cloud services into a unified solution. The core of the system consists of sensor-based IoT nodes that measure parameters such as soil temperature, moisture, and electrical conductivity. These data are collected by a microcontroller unit) and transmitted via a WiFi communication module to the Oracle Autonomous Database hosted in the cloud.

The stored data are processed and visualized through the Oracle Application Express (APEX) platform, while Oracle REST Data Services provides a RESTful interface enabling communication between the sensor layer and the cloud infrastructure. This design ensures efficient data flow, real-time access, and seamless integration between edge and cloud components.

The proposed architecture provides several key advantages:

- Centralized data storage and real-time processing within a cloud environment,
- System scalability that allows the addition of multiple sensor nodes without architectural modifications,
- Automated analysis and visualization of collected soil parameters through the APEX application, and
- Enhanced data security and reliability enabled by Oracle's managed cloud infrastructure.

By integrating Internet of Things technologies with cloud computing, the system enables digital transformation in the field of soil quality assessment and sustainable resource management.

D. Oracle APEX

Oracle Application Express is a free, web-based development platform designed exclusively for use with the Oracle Database. It represents one of the most popular low-code application development environments, enabling the rapid creation of secure, scalable, and feature-rich business applications.

Oracle APEX is fully adaptable for mobile devices and can be deployed either as an on-premises installation or as a cloud-based service. The platform supports multilingual applications and provides seamless integration with modern web technologies such as HTML, CSS, JavaScript, and jQuery, allowing the development of interactive and visually appealing user interfaces.

With built-in support for source code versioning and change tracking, Oracle APEX is well-suited for collaborative software development and continuous integration environments. Its flexibility, security, and integration capabilities make it a robust tool for building enterprise-grade applications within the Oracle ecosystem.

In the proposed cloud-oriented data acquisition system, Oracle APEX serves as the primary front-end interface for the visualization and management of measurement data stored in the Oracle Autonomous Database. By leveraging its declarative development model, customized dashboards, analytical charts, and data-entry forms can be created with minimal coding effort. Integration with Oracle REST Data Services (ORDS) ensures real-time communication between the web application and the database through RESTful APIs, enabling continuous monitoring and analysis of sensor data collected from distributed IoT nodes. This combination of APEX, ORDS, and Oracle Autonomous Database establishes a unified, secure, and scalable environment for data-driven applications in smart agriculture and environmental monitoring.

E. Oracle REST data services

Oracle REST Data Services (ORDS) is a tool that enables developers to create RESTful web services over data stored in the Oracle Database using the SQL programming language. REST (Representational State Transfer) is an architectural style that provides access to data and functionality through unique resource identifiers (URIs).

ORDS is built on Java EE technology and allows seamless interaction with the database without the need for additional programming languages. RESTful web services rely on the HTTP protocol and standard methods such as GET, POST, PUT, and DELETE. The communication model is stateless, meaning that each client request must contain all the information necessary for the server to understand and process it.

Data are most exchanged in JSON (JavaScript Object Notation) format, while XML and CSV formats are also supported. ORDS includes built-in functionality for metadata management, enabling the creation and maintenance of RESTful services through APIs without requiring explicit SQL query development.

By simplifying database access and integrating seamlessly with Oracle Application Express (APEX) and Oracle Autonomous Database, ORDS plays a crucial role in modern Oracle-based cloud systems. It allows efficient data exchange between client applications and the database layer, facilitating the implementation of scalable and flexible web-based data acquisition and visualization systems.

IV. ANALYIS OF MESURED SOIL PARAMETER DATA

This analysis represents a comprehensive evaluation of changes in the physical and chemical parameters of soil after the addition of liquid fertilizer EZ NPK 7-3.5-5 under controlled conditions. The aim of the study is to determine the fertilizer's impact on key soil characteristics, including moisture, temperature, electrical conductivity, and the concentrations of the main nutrients: nitrogen, phosphorus, and potassium. Measurements were carried out using the NPKTHC-S sensor system, while data were collected and analyzed through the NPK Cloud platform (Fig.6.), whose interactive report and statistical features allow detailed monitoring of changes over time intervals.

A. Analysis of Changes in Soil Parameters

The results of the initial measurements showed that the soil was extremely dry, with low nutrient content and low electrical conductivity. Soil moisture was only 10.3%, while the nitrogen, phosphorus, and potassium values were 12 mg/kg, 4 mg/kg, and 62 mg/kg, respectively. After the addition of 50 ml of the liquid fertilizer solution, the moisture increased to 28.8%, indicating improved soil hydration and a greater capacity for water retention. At the same time, the soil temperature slightly decreased from 22.7°C to 21.6°C, which can be attributed to the thermal cooling effect caused by the addition of the solution.

The most pronounced changes were observed in electrical conductivity and nutrient concentrations. Electrical conductivity rose from 114 µS/cm to 529 µS/cm, directly reflecting the increased concentration of dissolved ions in the soil. The concentrations of nitrogen, phosphorus, and potassium increased sharply, reaching 212 mg/kg, 205 mg/kg, and 290 mg/kg, respectively, after fertilizer application. These results confirm that the soil immediately absorbed the nutrients from the fertilizer.

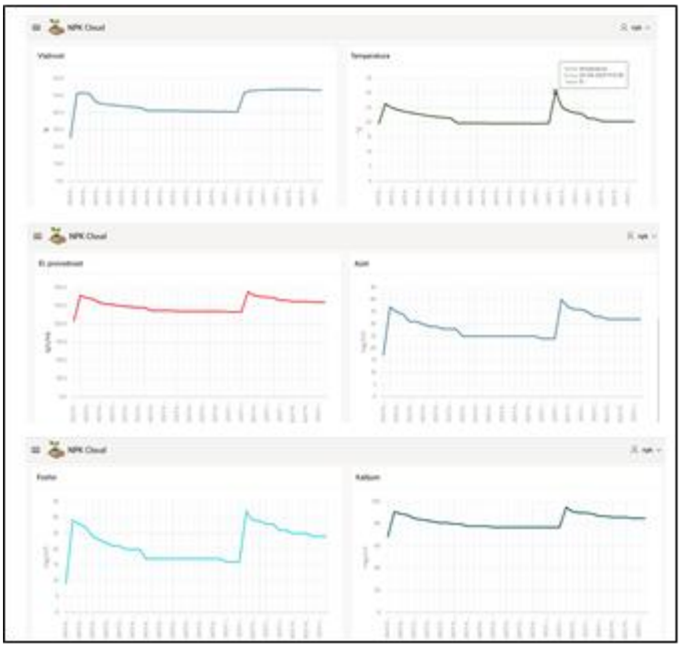

Figure 6. Display of graphs with parameters: a) moisture and temperature, b) electrical conductivity and nitrogen, c) phosphorus and potassium.

Further analysis using the NPK Cloud interactive report revealed specific trends in the behavior of each parameter. Moisture showed a steady increase, while temperature returned to equilibrium after the initial drop. Electrical conductivity and nutrient concentrations followed an exponential change pattern after an initial sharp rise, the values gradually decreased. This pattern indicates a diffusion and dilution process of the fertilizer within the soil, where nutrients gradually distribute and adsorb onto soil particles. Additionally, microbiological processes and chemical reactions contribute to the transformation and loss of some nutrients, especially nitrogen.

The Oracle Interactive Grid Report enabled the use of advanced data filtering and grouping functions by day, allowing the calculation of average parameter values and visualization of long-term trends. This functionality was further confirmed through graphical representations in the Excel report, where changes in nutrient concentrations and electrical conductivity over time were clearly visible.

B. Visual Data Analysis

Based on additional analyses and generated graphs, clear relationships between physical and chemical soil parameters were identified. The graph showing the relationship between pH and electrical conductivity indicates an inverse correlation: an increase in electrical conductivity leads to a decrease in pH, meaning that a higher concentration of dissolved salts and nutrients causes soil acidification. This result confirms well-known agronomic principles stating that high conductivity signals an increased level of mineral ions in the soil solution, which consequently lowers pH (Fig.7.).

A three-dimensional graph showing pH as a function of moisture and temperature demonstrated that pH increases with rising moisture and temperature (Fig.8.). Wetter and warmer soils tend to become slightly more alkaline, while dry and cold soils are more acidic. This finding suggests that the physical conditions of the soil directly influence its chemical balance.

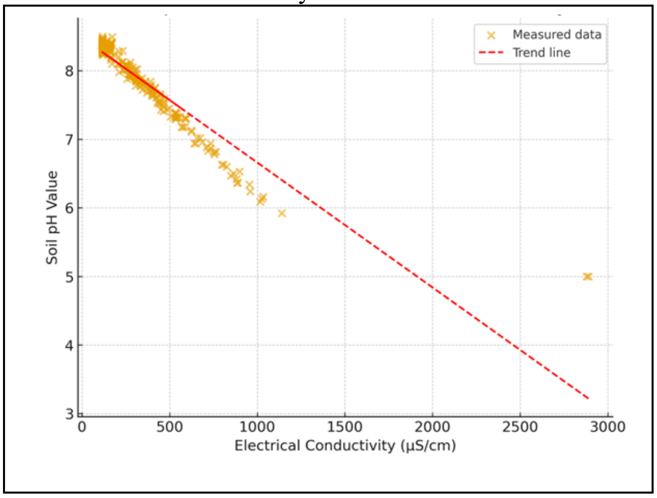

Figure 7. Soil pH as a function of electrical conductivity

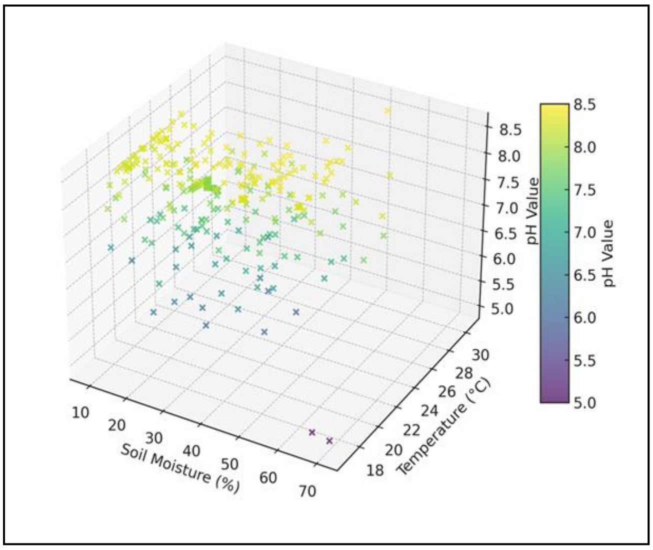

Figure 8. Soil pH as a function of moisture and temperature

The correlation map of parameters confirms these relationships: electrical conductivity, nitrogen, phosphorus, and potassium are highly positively correlated, while pH is strongly negatively correlated with these parameters.

V. Conclusion

The analysis of the measured data shows that the addition of liquid fertilizer EZ NPK 7-3.5-5 has an immediate and significant impact on the physics-chemical properties of the soil, with changes in moisture, conductivity, and nutrient concentrations indicating a rapid response of the soil to the addition of dissolved nutrients. The NPK Cloud system proved to be a reliable tool for real-time data collection and visual analysis, while the Oracle Interactive Grid Report enabled detailed evaluation of trends and statistical processing of measurements. The correlation between pH values, conductivity, and nutrient concentrations confirms that the chemical balance of the soil depends on the degree of mineralization and moisture, further emphasizing the importance of precise soil condition monitoring.

The introduction of Grin digital technologies and sensor-based IoT nodes opens new possibilities for efficient and automated measurement, monitoring, and management of soil quality parameters. Integration of these systems with cloud-based analytical platforms enables real-time data collection, processing, and transformation into practical recommendations for optimizing irrigation and fertilization. This approach significantly enhances the digitalization of agriculture, increases productivity and sustainability, and contributes to the reduction of resource overuse and environmental impact.

Future research should focus on the long-term monitoring of liquid fertilizer effects on different soil types, as well as on the development of intelligent systems based on artificial intelligence and big data analytics that allow precise control and prediction of soil conditions. The synergy of EZ NPK fertilizer, IoT sensor networks, and Grin digital cloud analytics represents a key step toward the development of modern digital agriculture, enabling higher yields, efficient resource utilization, and the transition toward precision, intelligent, and sustainable agricultural production of the future.

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