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FACULTY OF COMPUTERS, INFORMATICS AND MICROELECTRONICS

DEPARTMENT OF SOFTWARE ENGINEERING AND AUTOMATION

Soil Composition Control

Final Report

Students: Gliga Daniela,

Gorcea Alexandrina,

Ernu Cătălina,

Grebennicova Ecaterina

Mentor: Andrei Bragarenco,
Ph.D., Technical University of Moldova

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Abstract

This report presents a comprehensive analysis and implementation strategy for a smart soil composition control system tailored to the agricultural context of Moldova. Given the region's reliance on farming and its challenges with soil degradation, inefficient fertilizer use, and climate variability, the proposed system integrates Internet of Things (IoT) technologies with advanced analytics and sensor networks to enable real-time monitoring of critical soil parameters such as moisture, pH, nutrient levels, and conductivity. By leveraging AI-driven decision-making, edge computing, and cloud platforms, the system enhances soil fertility management, reduces resource waste, and supports sustainable agriculture. This solution addresses the limitations of traditional soil monitoring practices by providing continuous, localized data and automated responses through actuators. The report details the architecture, components, communication technologies, and data analysis methods involved in the system, along with a comparative overview of existing soil monitoring solutions. The developed system aims to empower Moldovan farmers with actionable insights to improve productivity, mitigate environmental impact, and build resilience in the face of climate change.

Problem Overview

Soil quality is fundamental for achieving a successful harvest and maintaining sustainable agriculture. In the Republic of Moldova, a country where agriculture plays a vital role in economic stability and food security, around 21% of the workforce is employed in the sector, and many rural communities depend heavily on farming for their livelihoods. However, Moldova faces several pressing challenges, including progressive soil degradation, inefficient fertilizer use, and climate-induced fluctuations in soil conditions. These factors endangers both crop productivity and the long-term viability of farming practices.

This project aims to develop a smart soil composition control system that uses IoT-based sensors, AI-driven analytics, and automated alerts. By providing real-time monitoring and data-driven insights, the system will help farmers optimize soil health, reduce fertilizer waste, and enhance agricultural productivity, all of which are essential for promoting sustainable and resilient farming practices.

Soil Composition Control

Soil composition, a complex mixture of minerals, organic matter, water, and air, is a critical factor in ensuring soil health and fertility. The composition directly influences how soil supports plant life, water retention, and nutrient availability. The ideal balance of sand, silt, and clay particles determines the soil's texture, which in turn affects its ability to hold water and provide essential nutrients for plant growth. Organic matter, primarily derived from decomposed plant and animal matter, improves soil structure and supports beneficial microorganisms. Together with water and air, these components create the environment in which plants thrive.

Recent research has highlighted the importance of soil composition control, both for agricultural sustainability and environmental conservation. Scientists at the John Innes Centre in the UK, for instance, made a groundbreaking discovery that could significantly reduce the need for chemical fertilizers. They found a biological mechanism that enhances the attraction of plant roots to soil microbes, potentially cutting down on the use of nitrogen and phosphate fertilizers [1]. This advancement promises more sustainable farming practices and could help mitigate the environmental damage caused by excessive fertilizer use. Practically, there are numerous ways to manage soil composition for better plant growth. One of the simplest methods is adding organic materials like compost and aged manure to improve soil texture, nutrient content, and microbial activity. In areas with clay-heavy soils, amendments like expanded shale, greensand, and sphagnum peat moss can enhance aeration, root development, and water absorption, creating a more favorable environment for plant roots [2]. With the rise of technological advancements, new tools such as Artificial Intelligence (AI) are now being used to monitor and manage soil health more effectively. AI-driven systems are being employed to measure soil carbon sequestration, a key element in regenerative agriculture. These tools enable farmers to optimize soil management practices and track improvements in soil composition with greater accuracy [3].

By understanding and controlling soil composition, researchers and agricultural professionals are paving the way for more sustainable and efficient farming methods. The ongoing studies and innovations in this area promise not only to boost soil health but also to contribute to broader environmental goals such as carbon sequestration and reduced reliance on chemical fertilizers. As we continue to learn more about the delicate balance of soil components, the future of agriculture looks both promising and more sustainable.

Introduction to IoT for Soil Composition Control: A Comprehensive Analysis

Moldova's agricultural success has traditionally depended on its fertile chernozem soils, which cover approximately 70% of the country's agricultural land. However, decades of intensive cultivation, inefficient fertilizer application, and climate-induced variability have led to progressive soil degradation[4]. Recent studies indicate that improper nutrient management has reduced soil organic matter and disrupted key nutrient balances, ultimately affecting crop productivity. Modern IoT technologies offer a solution by providing real-time, continuous data on parameters such as moisture, pH, electrical conductivity, and nutrient levels. These insights enable precise adjustments in fertilizer use and irrigation, thereby safeguarding soil health and enhancing sustainability[5].

The conventional approach to soil composition monitoring in Moldova remains largely outdated, relying on infrequent soil tests conducted in laboratories. According to the National Bureau of Statistics, many farms lack access to real-time data, leading to suboptimal farming practices. For instance, excessive or insufficient fertilizer application results in either nutrient leaching or soil exhaustion, negatively impacting both environmental and economic sustainability. Furthermore, Moldova's exposure to climate change exacerbates these issues, with erratic precipitation patterns, extended droughts, and extreme weather events disrupting soil nutrient cycles. In contrast, IoT-based solutions provide continuous insights into soil conditions, allowing for precise interventions to maintain optimal nutrient balance and soil fertility. By deploying sensors that track real-time changes in soil properties, farmers can dynamically adjust irrigation schedules and fertilizer applications, mitigating the risks associated with unpredictable climate conditions. The ability to automate and optimize soil management practices through IoT solutions not only improves yield consistency but also reduces the environmental footprint of agricultural operations, making farming more resilient to changing climatic conditions.

IoT technology in soil composition control is built upon a network of sensors, cloud-based analytics, and AI-driven decision-making tools. Soil moisture sensors help prevent water stress by providing precise data on irrigation needs, while pH and electrical conductivity sensors monitor soil acidity and nutrient availability. Additionally, temperature sensors track thermal conditions, which influence microbial activity and nutrient mineralization. These sensors transmit data wirelessly using standards like LoRaWAN and ZigBee, ensuring efficient communication even in rural areas with limited connectivity. The collected data is processed in cloud-based platforms, where AI algorithms generate insights and recommendations for optimal soil management. Machine learning models can predict soil fertility trends and suggest tailored fertilization strategies, reducing costs and improving efficiency. However, the implementation of these systems comes with challenges, including sensor calibration, connectivity issues, and the initial cost barrier for small-scale farmers. Addressing these obstacles requires targeted investments, technical support programs, and policy incentives to encourage widespread adoption. Public-private partnerships and government subsidies can play a crucial role in making IoT-driven soil monitoring accessible to all farmers, ensuring the long-term sustainability of Moldova's agricultural landscape.

Despite its advantages, the adoption of IoT-based soil composition control systems is not without its limitations. The primary challenge lies in infrastructure constraints, particularly in remote agricultural regions where internet connectivity is inconsistent. Additionally, regular maintenance and calibration of sensors are essential to ensure the accuracy of collected data, which may require specialized knowledge and technical expertise. The initial investment in IoT infrastructure, including sensor installation and data integration platforms, may also deter smaller farms with limited financial resources. However, the long-term benefits of IoT adoption far outweigh these challenges. By reducing reliance on guesswork and providing actionable insights, IoT-driven soil monitoring enhances efficiency, conserves resources, and improves overall soil health. The return on investment (ROI) for IoT-based soil monitoring is typically realized within three to five years, making it a financially viable solution for forward-thinking farmers. As Moldova seeks to modernize its agricultural sector and enhance food security, the implementation of IoT-based soil composition control systems will be instrumental in ensuring a sustainable and resilient farming future. The synergy between technological innovation and traditional agricultural practices holds immense potential for transforming soil management, enabling Moldova's farmers to maximize yields while safeguarding the environment.

IoT device domain and edge computing (sensor /actuators / HW) on proposed

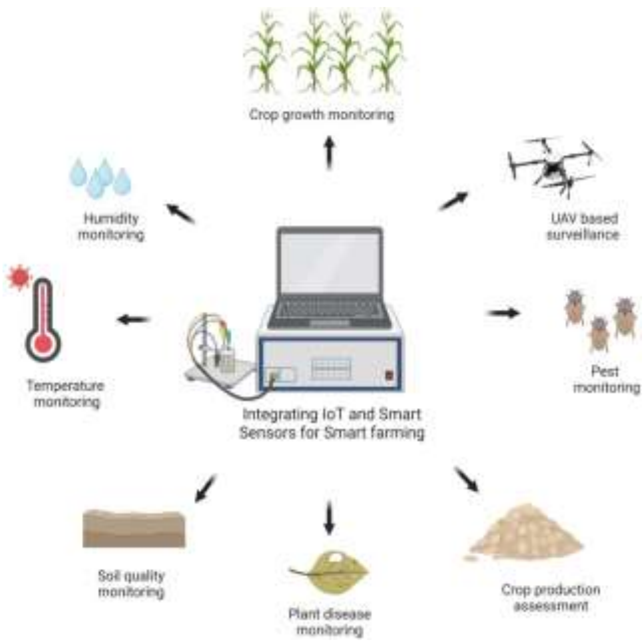
With the advancement of technologies, things became intelligent with the capabilities of self-communication between them. The Internet of Things (IoT) connected daily household things to the Internet and make them able to make decisions like the human mind. Sensors collect the real atmospheric data and with the help of Artificial Intelligence (AI) algorithms, analysis of data takes place so that devices behave more smartly. [6] In the agricultural domain, IoT, AI, and sensors are transforming traditional farming methods into data-driven precision agriculture systems. These technologies enable real-time monitoring and control of soil composition, ensuring optimal conditions for crop growth. By integrating smart soil sensors, farmers can receive detailed insights into critical soil parameters such as moisture levels, nutrient content, and pH balance, allowing for timely interventions that maximise productivity while reducing resource wastage. [7] Additionally, actuators such as automated irrigation valves, fertilizer dispensers, and pH regulators respond dynamically to sensor data, ensuring immediate adjustments for soil optimisation. Edge computing hardware, including microcontrollers (MCUs) and single-board computers (SBCs), processes data locally, reducing latency and enhancing decision-making without constant cloud dependency. The fusion of AI-driven analytics and IoT-enabled monitoring enhances decision-making, ensuring that soil remains fertile and well-maintained for sustainable agriculture.

Soil composition control is essential for precision farming, enabling the continuous monitoring of environmental factors that influence crop growth. [8] Harsh environmental conditions and frequent pest infestations lead to agricultural losses. On a daily basis, agriculture is not a smooth-flowing business as it faces many challenges such as:

- Lack of irrigation facilities
- Lack of determining environmental conditions
- Weed management
- Lack of knowledge of crop disease
- Time period for pesticides [9]

To address these challenges, integrating advanced technologies such as smart sensors and IoT can significantly enhance agricultural production while minimising economic losses. These technologies provide real-time data on soil health, moisture levels, and climate conditions, enabling farmers to make informed decisions. [10] However, despite its significant benefits, soil composition control through IoT and smart sensors faces hurdles such as high implementation costs, data security concerns, and limited digital literacy among farmers. Overcoming these barriers requires economic policies to support technology adoption, robust data encryption methods for security, and digital education programs to empower farmers. The future of soil monitoring lies in continued advancements in AI, IoT, and cloud-based platforms, ensuring precision farming, increased crop yield, and sustainable agricultural practices.

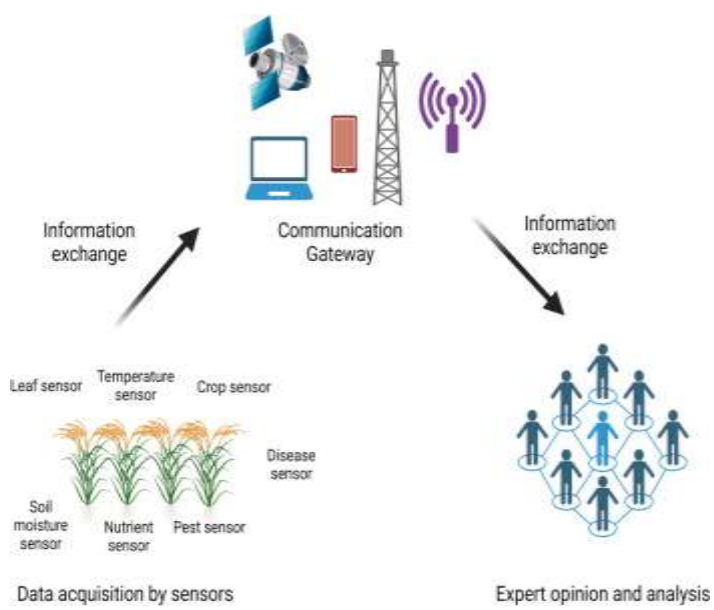
Studies have satisfactorily demonstrated the implications of integrated IoT-smart sensors in monitoring soil composition, including nitrogen content, moisture, humidity, and temperature, which are critical for crop growth. Some sensors specifically assess soil quality by determining nitrate levels and water content, providing essential data for optimizing soil conditions. Additionally, both active and passive sensors are employed in remote sensing to monitor various agricultural aspects such as weather forecasting, soil monitoring, landscape topology assessment, pest manifestation detection, and soil quality evaluation. [11] IoT-assisted smart sensors help farmers manage crops and vegetables over large areas in a short time, facilitating the understanding of when and how much pesticide and fertilizer should be applied. Excessive pesticide and fertilizer usage can lead to environmental contamination and health hazards, but IoT integration significantly reduces resource wastage while safeguarding farmers' revenues. Furthermore, smart sensors enhance agricultural productivity by enabling accurate diagnosis of crop diseases. By conducting continuous surveillance of environmental factors such as temperature, humidity, luminance, and soil moisture, IoT-enabled systems maximize crop yield while mitigating agricultural damage through real-time decision-making.



Applications of integrated IoT and smart sensors for precision farming

Agriculture depends on a wide range of smart sensors that enable real-time monitoring and analysis of soil, crops, and environmental conditions. These sensors play a crucial role in detecting soil deficiencies, optimizing irrigation, predicting pest infestations, and ensuring the proper use of fertilizers and pesticides. The integration of different types of sensors ensures precise, data-driven decision-making, ultimately leading to higher productivity, reduced waste, and improved sustainability in farming. **Acoustic-based sensors** detect and track pest populations and assist in harvesting by analyzing noise level variations in fields. [12] **Electromagnetic sensors** measure residual nitrate levels, organic matter concentrations, and transpiration rates by recording electromagnetic responses. [13] **Light Detection and Ranging (LIDAR)** technology is used for 3D modeling, soil erosion monitoring, land mapping, and soil type identification by analyzing the reflection of light pulses. **Optical sensors** evaluate soil texture, mineral composition, clay content, moisture, and color, while fluorescence-mediated optical sensors help detect fruit ripeness. [14] **Mechanical sensors** assess soil compaction and resistance using load cells and strain gauges, whereas **mass flow sensors** contribute to yield assessment by measuring grain flow through combine harvesters, integrating moisture content sensors and internal processing units. **FPGA-based sensors** measure soil moisture, humidity, and plant transpiration rates, supporting irrigation management with advanced digital circuits. **Electrochemical sensors** analyze soil pH and nutrient levels by detecting electrochemical gradients, while **eddy covariance-based sensors** monitor greenhouse gas emissions such as CO_2, methane, and water vapor across large agricultural areas. [15] **Airflow sensors** assess soil-air content, permeability, and moisture levels in both static and dynamic conditions.[16] **Ultrasonic ranging sensors** assist in pest detection, crop canopy monitoring, and weed identification by analyzing ultrasonic pulses. **Flexible and wearable sensors** track plant growth, temperature, and morphology using stretchable materials that can be directly attached to plants. **Battery-free and self-powered sensors**, powered by solar cells, measure environmental conditions like temperature and humidity and help monitor food quality without requiring batteries. [17]

To enhance performance, these smart sensors can be integrated with amplifiers, transducers, analog-to-digital converters, and analog filters, making them even more effective for real-time agricultural monitoring and precision farming applications. Their implementation significantly improves efficiency in irrigation, fertilization, and pest control, contributing to sustainable and technologically advanced agricultural practices.



Integration of IoT devices, farms, and human networks [18]

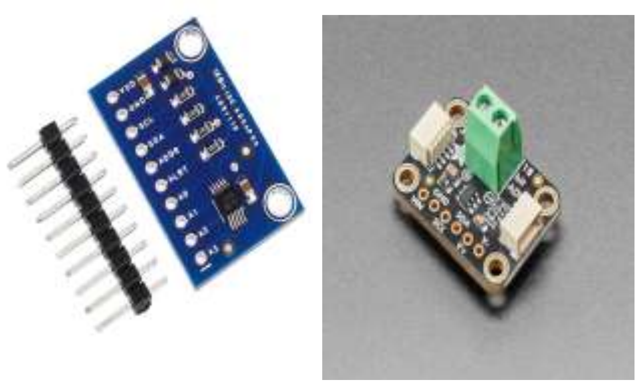
Smart Sensors Node Composition

Smart sensors are a cutting-edge technology capable of wireless communication from remote locations, detecting patterns and correlations in raw data and establishing cause-and-effect relationships among various factors affecting soil health. They are hardware devices that produce a measurable response to a change in a physical condition like temperature or pressure. Sensors measure physical data of the parameter to be monitored and have specific characteristics such as accuracy, sensitivity etc. The main components of a sensor node usually involve a **microcontroller**, **transceiver**, **external memory**, **power source** and one or more sensors.

Smart sensor node key components:

- **Physical transducer** – A transducer is a device that converts a signal in one form of energy to a signal in another. [19] Transducers are often employed at the boundaries of automation, measurement, and control systems, where electrical signals are converted to and from other physical quantities (energy, force, torque, light, motion, position, etc.). As key component of smart soil sensor the transducer is responsible for detecting physical or chemical properties of the soil and converting them into measurable electrical signals, such environmental conditions as moisture, temperature, pH, salinity, etc..

- **Analog-to-Digital Converter (ADC)** – Represent a system that converts an analog signal, such as a sound picked up by a microphone or light entering a digital camera, into a digital signal. An ADC may also provide an isolated measurement such as an electronic device that converts an analog input voltage or current to a digital number representing the magnitude of the voltage or current. [21] This data for various soil parameters can be processed by a microcontroller or transmitted to a cloud platform.

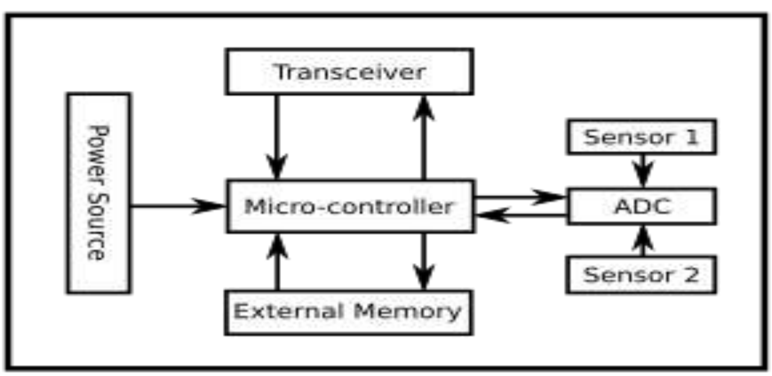


ADS1115 (16-bit ADC) & MCP3421 (18-bit ADC)

- **Microcontroller** – The controller performs tasks, processes the raw data from the sensing element, doing tasks like cleaning up the signal, filtering out noise, and changing the signals from analog to digital. It also helps run programs that analyze data, make decisions, and improve the system. [22]

Popular Microcontrollers (ESP32, Arduino)

- **Communication Link (Wi-Fi, ZigBee, LoRa, or NB-IoT)** – Communication links enable the seamless transfer of data from sensor nodes to central gateways and cloud platforms. These wireless communication technologies ensure that real-time data about soil properties—such as moisture, pH, temperature, conductivity, and nutrient levels—can be collected, transmitted, and analysed efficiently. Each protocol has its own specifications depending on the bandwidth, number of free channels, data rate, battery timing, price and other factors. [23]
- **Memory & Power Source** – External memories are used due to their cost and storage capacity. There are two categories of memory based on the purpose of storage are: user memory used for storing application related or personal data, and program memory used for programming the device. While the power unit supplies the power to all node components, which is a vital element of the sensor node. [24] Batteries, both rechargeable and non-rechargeable, are the main source of power supply for sensor nodes.



The typical architecture of the sensor node [25]

The integration of a diverse range of smart sensors, such as DHT11, LDR, DS18B20, soil moisture sensors, and Noir cameras, along with single-board microcontrollers like Arduino, Raspberry Pi, and ESP8266, has revolutionized soil composition monitoring. These technologies, when combined with IoT-based networks and APIs, enable seamless real-time data collection and analysis. By leveraging these advanced tools, farmers and environmentalists can monitor critical soil parameters—such as moisture content, temperature fluctuations, and light exposure—with remarkable precision. This interconnected ensures efficient resource management, reducing water waste and optimising fertilisation. As IoT continues to evolve, the ability to predict soil trends, automate irrigation, and maintain soil health will become even more refined, paving the way for sustainable and technology-driven farming practices.

The Most Essential Soil Sensors for Composition Control

1. **Soil Moisture Sensor**
   Soil moisture sensors, also known as soil humidity sensors, measure water content in the soil to determine its moisture levels. These sensors can be buried for long-term use and are crucial for maintaining optimal soil hydration. [26] Based on their measurement principles, soil moisture sensors are divided into three main types:
   - **Capacitive Soil Moisture Sensors** – Use moisture-sensitive capacitors made of materials like metal oxides and high polymer polymers. The sensor measures capacitance changes caused by moisture absorption, converting this into an electrical signal for analysis.
   - **Resistive Soil Moisture Sensors** – Utilize moisture-sensitive resistors made of dielectric materials, semiconductors, or porous ceramics. The resistance changes when the material absorbs moisture, providing a direct measure of soil moisture.
   - I**on-Sensitive Soil Moisture Sensors (ISFET-based)** – Utilise semiconductor biosensors to measure ion concentrations in soil solutions, offering precise detection of dissolved ions related to soil moisture levels.

Soil Moisture & Conductivity Sensor

2. **Soil Temperature Sensor**
   Soil temperature is a key factor in plant growth, microbial activity, and biochemical soil processes. This sensor monitors heat variations in soil, affecting nutrient availability, soil

structure, and microbial life. The working principle of Soil Temperature Sensor is based on thermoelectric effect. It is mainly composed of thermistor and wire. The resistance value of the thermistor changes with the temperature, thus changing the current in the circuit. By measuring the current in the circuit, the temperature of the soil can be calculated. [27].

Soil Temperature Sensor

3. **Soil Conductivity Sensor**
   A soil electrical conductivity sensor is a device used to measure the electrical conductivity of soil and works on the basis of the electrical conductivity of the ions in the soil. It is an important technology in farmland management and water resource monitoring. Soil conductivity is a measure of the electrical conductivity of the soil, which reflects the amount of charged particles in the soil, and is mainly related to factors such as the humidity, temperature and salt content in the soil. It is often used to reflect the content of dissolved substances in the soil and the level of salinity. [28]
4. **Soil pH Sensor**
   Soil pH balance is essential for nutrient absorption and microbial activity. But unfortunately soil pH can affect nutrients available for plant growth. In highly acidic soil, aluminium and manganese can become more available and more toxic to plant while calcium, phosphorus, and magnesium are less available to the plant. In highly alkaline soil, phosphorus and most micronutrients become less available. [29]. The soil PH sensor is composed of a metal sensor and a functional value-switching device. As the core hardware system, the metal sensor is in direct contact with the soil during detection and uses the oxidation reaction in the chemical reaction to generate current. The magnitude of the current value will drive the different ph value unit data corresponding to the ammeter, and the value can be directly displayed to people through the host conversion, allowing precise real-time monitoring of soil acidity or alkalinity. [30]

Soil pH Sensor

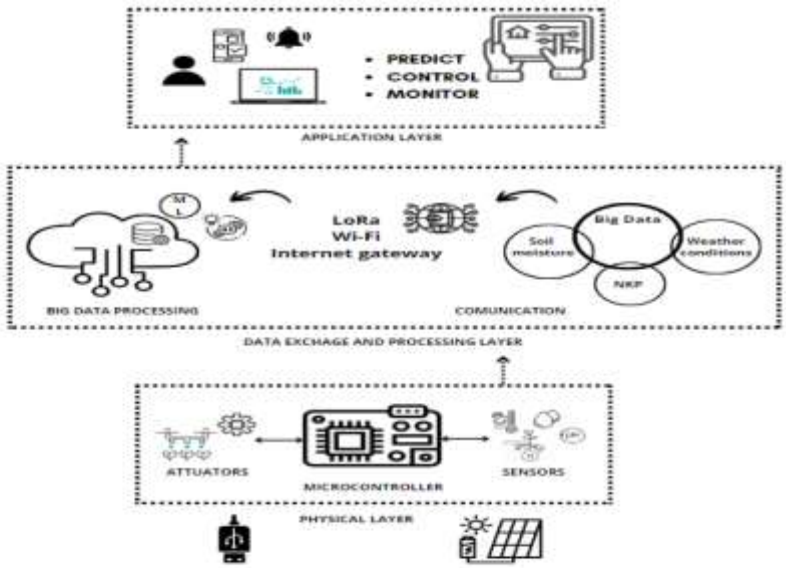
5. **Soil NPK Sensor**
   NPK sensors are essential tools in agriculture for measuring the levels of nitrogen (N), phosphorus (P), and potassium (K) in the soil. [31] Unlike chemical testing methods, these sensors use physical sensing techniques to detect and monitor soil nutrient levels over time. Continuous monitoring ensures that nutrient deficiencies are detected early, preventing soil depletion and optimising fertilisation practices.

Soil NPK Sensor

Soil Composition Monitoring System: How Sensors Collaborate in the Workflow

A Smart Soil Composition Monitoring System integrates multiple soil sensors, wireless communication technologies, and data processing platforms to provide real-time insights into soil conditions. By continuously collecting and analysing data, the system enables precise soil management, helping farmers, agronomists, and land managers optimise irrigation, fertilisation, and soil health management.

1. **Sensor Nodes: The Foundation of Data Collection:** Soil sensors nodes are designed to monitor soil parameters and measure a wide range of physical and chemical properties of the soil in real time from different locations within the field. [32] These sensors measure key parameters such as soil temperature, humidity, pH, conductivity, organic matter content, and microbial activity, providing important data for agricultural production, environmental protection, geological exploration, and other fields. Collected data is processed locally within the sensor module and then transmitted wirelessly to a central gateway.
2. **Data Logger/Gateway: Processing and Transmitting Data:** The data logger or gateway acts as a central hub that gathers data from multiple sensor nodes to the processing system that involves communication protocols and networks (Wifi, Bluetooth, Zigbee, MQTT etc.). [33] It processes raw data by filtering out inconsistencies and redundant values to ensure accurate readings and transmits real-time data to the cloud or local database for storage and further analysis.
3. **Cloud Platform or Local Server: Data Storage and Analysis:** Once the data reaches the cloud or a local server, it is processed using machine learning and advanced algorithms to identify relevant patterns and trends. [34] There, big data is stored, analysed, and processed, representing one of the most critical phases of the IoT system. This way raw data is transformed into useful, understandable, and easily accessible information for farmers. This process enables them to make informed decisions based on accurate data, which is refined into structured insights, allowing the system to analyse historical data, predict soil conditions, optimise irrigation schedules, and recommend precise fertilisation plans. [35] This ensures seamless access to real-time soil insights across multiple devices, including smartphones, tablets, and computers. For example, if soil moisture drops below a critical threshold, the system alerts the farmer to irrigate, while unbalanced pH levels trigger recommendations for soil amendments to maintain optimal soil health.
4. **User Interface (UI) & Dashboard: Real-Time Monitoring and Control:** The processed data, machine learning insights, and recommendations are presented through a user-friendly monitoring dashboard accessible via web or mobile interfaces. This dashboard offers real-time visualisations, alerts, and analytics, enabling farmers to make informed decisions remotely. [36] It could displays as well real-time soil conditions via graphs, heat maps, and tables with color-coded indicators which represent optimal, warning, or critical soil conditions. All these alerts can be sent via SMS, email, or push notifications when soil conditions require immediate action. This way users can track soil composition changes over days, weeks, or months and create some analysis over long-term patterns and soil health trends. With the appearance of AI the control has become easier as AI is powered to give insights about best irrigation schedules, optimal fertilisation plans, and soil improvement techniques.



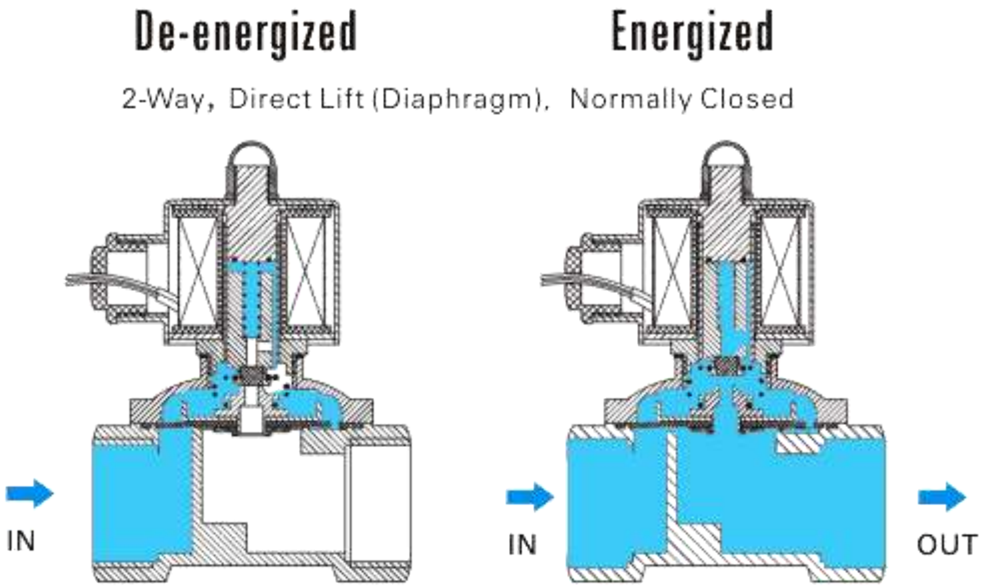
Schematic diagram of the IoT monitoring sensor system [37]

Actuators

In soil composition control systems, actuators play an important role in automating responses based on real-time sensor data. These devices convert electrical signals into physical actions, enabling automated irrigation, fertilization, aeration, and other soil management tasks. The choice of actuator depends on the specific soil control function and system requirements. For instance, with the use of specialized sensors, including machine vision, laser-based devices, and inertial devices, actuators (hydraulic cylinders, linear and rotary motors, etc.) play an essential role in enabling the agricultural robots to execute different tasks via the help of electronic devices (embedded computers, industrial computers, and programmable logic controller) [38]

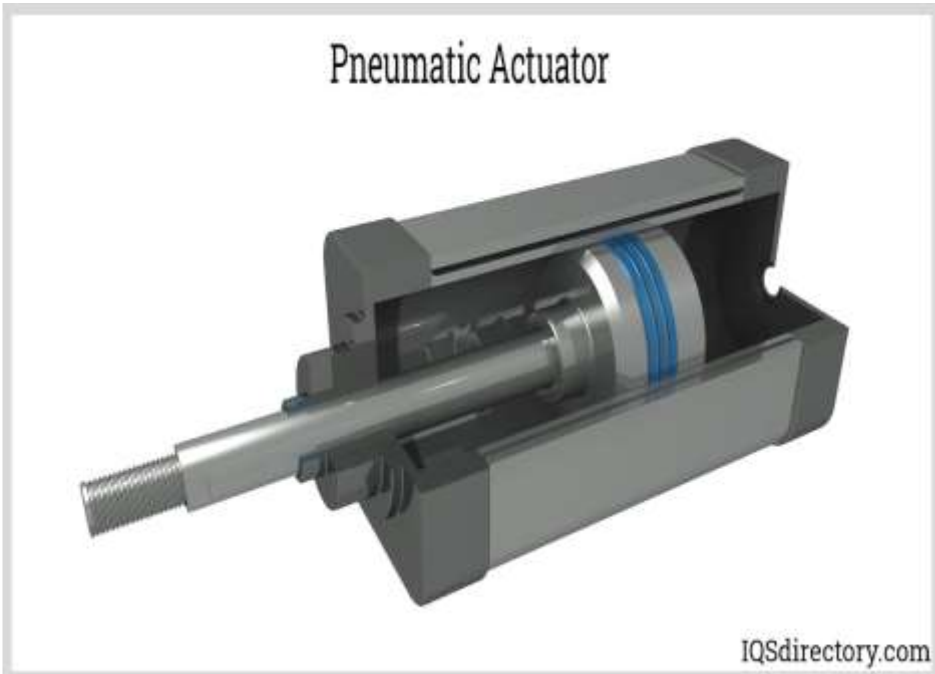
Types of actuators:

1. **Solenoid Valves (For Automated Irrigation Systems):** A solenoid valve is an electromechanical device used to control the flow of a liquid or gas. It is comprised of two features: a solenoid and a valve. [39] Solenoid valves are the most frequently used control elements in fluidics. Their tasks are to shut off, release, dose, distribute or mix fluids.

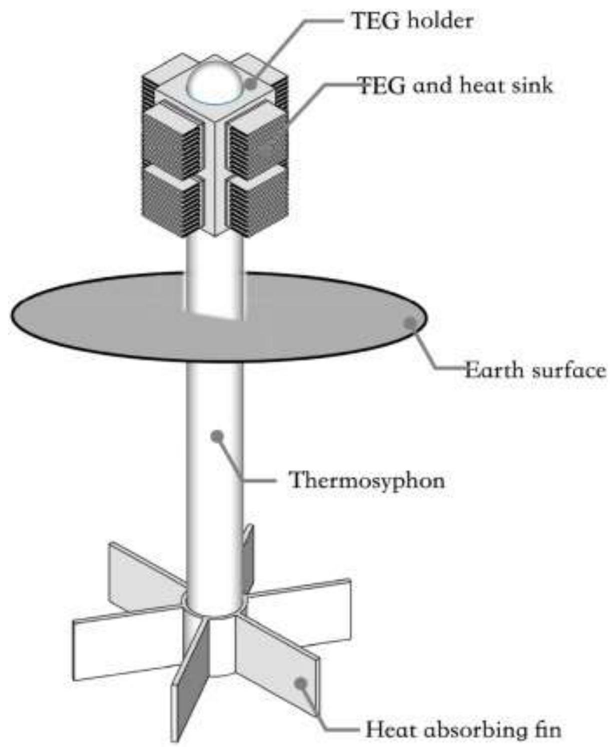


2. **Peristaltic & Dosing Pumps (For Fertilization & pH Control):** It deliver precise amounts of liquid fertiliser, pH balancers, or soil conditioners into irrigation lines. As sensors monitor soil nutrient levels (NPK) and pH, and when imbalances are detected, the pump activates to inject the required amount of solution into the soil.
3. **Linear Actuators & Servo Motors (For Mechanical Soil Aeration & Smart Farming Equipment):** Linear actuators and servo motors are electromechanical devices that enable precise movement and positioning in smart agricultural machinery. They are used for soil aeration, automated plowing, greenhouse automation, and robotic farming equipment. These actuators convert electrical energy into linear or rotary motion, making them essential for automated soil management. [40]
4. **Smart Sprinklers & Mist Nozzles (For Precision Irrigation & Humidity Control):** Smart sprinklers and mist nozzles automate irrigation and humidity control in fields, orchards, and greenhouses. These devices ensure that crops receive the right amount of water based on real-time soil moisture levels, weather conditions, and plant water requirements. Smart sprinklers use electromagnetic valves or piezoelectric actuators to control the pressure, direction, and duration of water release depending on soil moisture, temperature, and wind conditions. They prevent overwatering, reduce water waste, and optimize crop health.
5. **Pneumatic & Hydraulic Actuators (For Heavy-Duty Agricultural Machinery):** A pneumatic actuator converts air pressure energy into mechanical energy such as linear work, ash transfer, and shaking. Pneumatic actuators include pneumatic motors and shaking pneumatic actuators, which form a pneumatic control system with air tanks, air compressors, or vacuum pumps, as well as control valves and control circuits .[41] Based on sensor feedback from soil compaction and texture analysis, these actuators adjust the depth of plowing, speed of planting machines, or the operation of automated harvesters. While hydraulic valve actuators convert a fluid pressure supply

into a motion. A valve actuator is a hydraulic actuator mounted on a valve that, in response to a signal, automatically moves the valve to the desired position using a outside power source. [42]



6. **Thermoelectric Actuators (For Soil Temperature Regulation):** Thermoelectric actuators are devices that utilize temperature differences to generate movement or control mechanical systems. They operate based on the thermoelectric effect, particularly the Peltier effect, where electrical current is used to create a temperature gradient, resulting in either heating or cooling. These actuators are widely used in automated climate control, temperature-sensitive applications, and precision farming, where soil temperature plays a crucial role in plant growth and soil health.



Actuators transform soil composition monitoring into an automated control system by responding to real-time sensor data. Whether it's solenoid valves controlling irrigation, dosing pumps managing soil nutrients, or linear actuators adjusting farming tools, these devices enable precision agriculture and resource-efficient farming.

IoT Communication Technologies for Soil Composition Control

Soil composition monitoring is a critical aspect of modern precision agriculture, enabling farmers and agronomists to optimize resource usage and improve crop yields. To achieve this, a reliable communication infrastructure is necessary to transmit soil data from distributed sensors to centralized systems for analysis. Various Internet of Things (IoT) communication protocols can be employed, each with its own strengths and weaknesses. In modern agriculture, IoT-based soil monitoring systems have been successfully implemented in smart farms to track moisture levels, pH, and nutrient composition. For example, large-scale farms use LoRaWAN to collect real-time data from soil sensors across vast areas, improving irrigation efficiency. Similarly, ZigBee networks are deployed in greenhouses to monitor soil parameters in confined environments, ensuring optimal growing conditions for crops.

Comparison of IoT Communication Technologies

To facilitate an easier understanding of the different IoT communication technologies for soil composition control, the table below compares them based on key criteria:

Table 1.1 Comparison of different IoT communication technologies

Technology	Range	Power Consumption	Data Rate	Network Type	Cost	Best Use Case
ZigBee	Short (10-100m)	Low	Moderate	Mesh	Low	Small-scale soil monitoring in confined areas
LoRaWAN	Long (up to 15km)	Very Low	Low	Star	Moderate	Large agricultural fields with dispersed sensors
NB-IoT	Long (nationwide)	Low	Low	Cellular	High (subscription)	Areas with strong cellular coverage, underground applications
Wi-Fi	Short (up to 100m)	High	High	Star	Low	Greenhouses, small farms with existing network infrastructure
Bluetooth	Very Short (10m)	Very Low	Low	Point-to-Point	Low	Short-range communication between nearby sensors

This table 1.1 compares different IoT communication technologies based on several key criteria: range that shows the maximum distance over which data can be transmitted. This is crucial for determining the suitability of a technology for different field sizes. Another criteria is power consumption that describes the energy efficiency of a protocol, which impacts battery life and operational costs.Data rate is another important criteria that shows the speed at which data is transmitted, influencing real-time monitoring capabilities.Network type presents the topology used to connect devices, which affects scalability and reliability of system. Cost is another criteria that describes the relative cost of implementing and maintaining the technology, including hardware and subscription fees. The column Best Use Case contains information about the most appropriate application scenario based on the protocol's strengths.Based on data from table 1.1 above we can conclude that for large agricultural fields, LoRa/LoRaWAN is the preferred choice due to its long range, low power consumption, and cost-effectiveness. NB-IoT can be considered in areas with strong cellular coverage and budget allowance for network subscriptions. ZigBee and WiFi are useful for small, confined environments where a mesh network can be effectively utilized. To develop the MVP of our project we will use WiFi.

Communication Protocols for IoT

Efficient data transmission in IoT systems requires appropriate communication protocols. One of the most widely used messaging protocols is **MQTT (Message Queuing Telemetry Transport)**, which is lightweight and optimized for low-bandwidth networks. It ensures reliable message delivery even in constrained environments, making it ideal for soil monitoring applications. Compared to other messaging protocols like **CoAP (Constrained Application Protocol)**, MQTT provides better reliability due to its publish-subscribe architecture, while CoAP is more suited for direct device-to-device communication.

By integrating IoT sensors with edge computing, modern soil composition monitoring systems can provide farmers with real-time insights, enabling optimized resource management and improved agricultural sustainability.

Data Base, Data analysis and Cloud Computing (back End)

1. Database Management for Soil Composition

Data management is one of the most important stages of data analysis and plays a critical role in ensuring data quality and reliability. Raw data often contains many imperfections and inconsistencies, making analysis difficult. These issues include inconsistent formats or structures, out-of-range values, missing data points, noisy data, and excess information. Thus, a variety of processing techniques have been extensively used such as data normalization, filtering, and handling of missing values [43].

Data normalization is a crucial pre-processing stage that involves organizing data into a uniform format to eliminate redundancy and inconsistencies, facilitating efficient storage and analysis. Many methods have been proposed such as Z-score normalization, min-max normalization, median absolute deviation, pareto scaling. Data filtering involves the process of selecting and extracting relevant data from large datasets based on predefined criteria, enhancing data accuracy and reducing noise. Numerous methods have been developed such as the ensemble filter and iterative portioning filter. Finally, handling missing values is another critical aspect, where strategies such as imputation or removal are employed to mitigate the impact of incomplete data on analysis outcomes. Some of the most widely used strategies to deal with missing values are deleting an instance, using a prediction model, replacing with the mean, and replacing with a global constant. In both the agricultural and smart water sectors, historical data and sensor measurements collected over time serve as a valuable resource in various applications, including prediction and decision-making. However, the collected datasets (historical data and sensor data) frequently suffer from incompleteness, noise, and inconsistency due to factors such as sensor inaccuracies, environmental variability and seasonality, network miscommunication and human error. The effective handling of missing values, data filtering, and normalization holds paramount importance, and decision-making. Once the data has been preprocessed and cleaned, it is then stored in the database.

Types of Databases Used

Relational databases, such as PostgreSQL and MySQL, are commonly utilized for structured data storage, offering transactional integrity and sophisticated querying capabilities. PostgreSQL with its PostGIS extension, which also may serve as a geospatial database, enables efficient querying of geospatial soil properties while supporting complex spatial analyses and time-series data processing. Singh et al. together with some other scientists explores in their paper "Spatial Crop Monitoring System for India using Direct-Broadcast Remote Sensing Data and Open Source Web-GIS Technologies" the use of PostgreSQL with PostGIS for managing and analyzing geospatial data in precision agriculture. It speaks how remote sensing data with an open-source Web-GIS framework is easily used for monitoring soil health, crop conditions, and land use patterns in India [44]. MySQL is a commonly used relational database for mid-scale deployments, ensuring strong data integrity. Recent improvements in JSON support have made it suitable for managing semi-structured soil data. According to a study made by Chonnam National University, MySQL can handle semi-structured soil data using JSON format for efficient agricultural big data analytics. This paper discusses MySQL's role in integrating weather services, geospatial soil data, and structured databases. [45]

NoSQL databases, such as MongoDB and Cassandra, excel in handling unstructured or semi-structured data, providing scalability and flexibility for modern applications. MongoDB is a document-oriented database, ideal for heterogeneous soil data collected from multiple sensor types. Its geospatial indexing capabilities allow for queries within specific field boundaries. According to [46], MongoDB supports storing and querying geospatial data. Another NoSQL database which may be used in this scope is Cassandra, a column-oriented database, optimized for time-series sensor data and offers high write throughput, making it ideal for continuous soil monitoring deployments. [46]

Time-series databases like InfluxDB cater to the specific needs of time-stamped data storage and analytics, facilitating real-time monitoring and trend analysis . Additionally, object storage solutions like Amazon Simple Storage Service (S3) and Google Cloud Storage offer scalable and durable storage for large volumes of unstructured data, ideal for archival and backup purposes. Moreover, one widely used tool for analyzing large databases is Elasticsearch serving as a search engine that provides a way to organize data, making it easily accessible .

2. Data Analysis Techniques

Analysis of soil nutrients can aid farmers and soil analysts to get higher yield of the crops by making prior arrangements [47]. Over the years, the application of various advanced techniques such as machine learning (ML), geographic information systems (GIS), and statistical methods has significantly improved our ability to assess, predict, and understand soil properties. These methods allow for more precise monitoring, predictive analysis, and spatially informed decision-making, providing essential insights into soil health, nutrient distribution, and land use management.

Machine Learning & AI for Soil Analysis

Machine learning and artificial intelligence (AI) have revolutionized soil composition monitoring by offering tools to analyze large, complex datasets and extract valuable insights. According to a study made by Department of Civil Engineering, Turkey [48] which describes use of machine learning techniques in soil classification, the following techniques were highlighted.

Supervised learning such as **regression** models, including linear and non-linear regression, have been used to predict soil properties such as pH, organic matter, and nutrient content based on observed environmental conditions. For instance, models like Random Forests and Gradient Boosting can enhance the prediction accuracy by learning complex relationships between soil parameters and external factors like rainfall, temperature, and crop history. On the other hand, classification models such as Support Vector Machines (SVM) and Decision Trees can categorize soil samples into different types, such as sandy, loamy, or nutrient-rich. These models use historical data to learn patterns that can later be applied to new, unseen soil samples. Furthermore, neural networks, particularly deep learning models, offer the ability to uncover intricate, non-linear relationships in the data. This is especially beneficial when working with large datasets that might include time series data or complex interactions among multiple variables. For example, recurrent neural networks (RNNs) can predict soil health based on time-dependent factors like moisture content or organic matter over extended periods.

Unsupervised learning techniques also provide substantial benefits for soil monitoring, especially when the dataset lacks predefined labels. According to [49] Clustering algorithms like K-means, DBSCAN, and hierarchical clustering can be used to group soil samples with similar properties. This helps identify areas of a field that share similar characteristics, allowing for targeted management practices like precision irrigation or fertilization. Dimensionality reduction methods such as Principal Component Analysis (PCA) can reduce the complexity of datasets by identifying the most significant features influencing soil health, making it easier to visualize and interpret large amounts of data.

Deep Learning techniques offers image classification for soil mapping using satellite data. Such an example may be Convolutional Neural Networks (CNNs) [50] which identifies soil texture, moisture level and contamination patterns.

GIS-Based Soil Mapping

GIS-based methods have become indispensable in soil monitoring, offering powerful tools for spatial analysis and visualization. One such technique, Kriging, is a geostatistical method used to predict soil properties at locations where no direct measurements have been made. By leveraging spatial autocorrelation, Kriging can provide highly accurate estimates of parameters like pH or nutrient content in areas with sparse data. Another common spatial analysis method is spatial interpolation, which creates continuous maps from discrete soil samples

The integration of GIS with soil monitoring also enhances land-use planning and decision-making. By mapping soil properties and environmental factors, GIS helps identify areas at risk of erosion, nutrient loss, or degradation. It can also help manage soil variability across large landscapes by facilitating precision agriculture. Zoning tools within GIS can identify regions that require specific management practices, such as where to apply lime to adjust soil pH or where to focus irrigation efforts based on soil moisture levels. Furthermore, soil erosion and risk mapping can be combined with terrain analysis, which uses factors like slope and rainfall data to predict areas prone to erosion or nutrient runoff, thus enabling better risk mitigation strategies.[51]

An example of such a database is Google Earth Engine (GEE). It processes petabytes of geospatial data with JavaScript or Python APIs for large-scale soil mapping.

Statistical Methods for Soil Health Assessment

Statistical methods are essential for assessing soil health, as they provide quantitative insights into the relationships between soil properties and crop yields. By analyzing soil attributes, researchers can develop predictive models to enhance agricultural productivity.[52]

For example, **regression** analysis is a fundamental statistical tool used to predict crop yields based on various soil health indicators. Through regression models, studies have demonstrated that soil health scores, derived from attributes such as soil texture, organic matter, and moisture content, can correlate well with wheat yields. In some instances, multiplicative response functions have been found to be more sensitive and accurate than simpler regression models, emphasizing the importance of considering multiple, interacting factors when predicting crop performance.

In addition to regression analysis, **correlation** analysis is another essential statistical method that helps identify the strength and direction of relationships between individual soil properties and crop yields. Research has shown that focusing on the soil attributes that exhibit the most severe stress and have relatively lower rating values can significantly improve the predictability of wheat yields. By identifying these key factors, soil management efforts can be more targeted, addressing specific limitations that are hindering crop productivity.

Furthermore, soil **quality indexing** has emerged as a valuable method for integrating multiple soil parameters into a single metric that reflects the overall health of the soil. These statistical methods, through their ability to quantify and analyze the relationships between soil properties and crop yields, are indispensable for enhancing soil management practices and optimizing agricultural productivity.[53]

3. Cloud Computing Trends

Integrating cloud computing into IoT-based soil composition control systems offers scalable data storage, real-time analytics, and remote monitoring capabilities, enhancing precision agriculture practices.

Cloud platforms today are equipped with AI models capable of processing large volumes of soil data gathered from IoT sensors deployed in the field. By utilizing AI-powered cloud analytics, these platforms can provide real-time analysis of critical soil parameters such as moisture levels, nutrient content, and temperature. This integration facilitates predictive insights that help farmers and stakeholders make informed decisions, ensuring that soil health is managed proactively and efficiently. For instance, AI models can identify soil stress indicators and recommend timely interventions to optimize soil composition, thereby enhancing agricultural productivity [54].

Furthermore, integrating edge computing with cloud services significantly reduces the latency in soil monitoring systems. By processing data at the sensor nodes themselves, edge computing enables immediate analysis, allowing for real-time adjustments in irrigation, fertilization, and other soil management practices. The cloud infrastructure, on the other hand, serves as a central repository for historical data analysis, enabling farmers to gain deeper insights into long-term soil health trends. This combination of edge-to-cloud integration is crucial for creating a responsive and adaptive soil monitoring system that can quickly react to changing conditions.[55]

Existing Soil Monitoring Software

OneSoil: Smart Farming Through Satellite Monitoring[56]

OneSoil is an advanced agricultural software that leverages satellite monitoring and precision farming technologies to help farmers optimize their crop management. The platform enables users to track plant development remotely, analyze vegetation health using the NDVI (Normalized Difference Vegetation Index), and detect problem areas in fields without requiring physical inspection. With just a single click, farmers can define field boundaries, which are automatically identified through satellite imagery, making setup seamless and efficient. Beyond basic monitoring, OneSoil provides comprehensive analytical tools, including growing degree-days, accumulated precipitation charts, and real-time weather forecasts to assist in decision-making. The software facilitates scouting by allowing users to create notes and attach photos while inspecting fields. By sorting and coloring fields according to different data types, farmers can easily interpret the information and take timely actions. OneSoil also aids in planning agricultural activities, such as identifying the optimal time for spraying based on weather conditions.

QuickTrials: Streamlining Agronomic Field Trial Management[57]

QuickTrials is a leading Software-as-a-Service (SaaS) platform designed to facilitate the planning, execution, monitoring, and analysis of agronomic field trials. The platform aims to accelerate agricultural innovation by providing a structured, real-time data collection system that reduces the time and effort required to conduct field trials. By integrating mobile and web applications, QuickTrials enables researchers and trial managers to track data remotely, ensuring that results are available almost instantly rather than months after harvest. The software is highly flexible, allowing trials to be set up using global templates and managed from a centralized data warehouse. Field staff can collect data on mobile devices, which is then uploaded and immediately available for analysis. This process eliminates the need for manual data aggregation, reducing errors and allowing trial coordinators to validate data in real-time. Observations are mapped and color-coded by field staff, enabling users to visualize data in a dynamic and interactive manner. The system supports a wide range of trial types, including seed variety trials, agrochemical testing, biotechnology research, and climate-smart agriculture initiatives..

FarmLab: Precision Soil and Farm Data Management[58]

FarmLab is an Australian-based software platform designed to streamline soil, plant, and water sample collection while providing powerful data management and analysis tools for farmers and agronomists. The platform integrates with leading environmental testing laboratories and farm management systems, ensuring that soil data is easily accessible, shareable, and compliant with the National Farmers Federation Farm Data Code. With FarmLab's mobile and web applications, users can efficiently collect and track soil samples, upload historical soil test results, and visualize soil changes over time. The software also supports collaboration by allowing farmers, agronomists, and clients to share farm data, enabling more informed decision-making in precision agriculture. By simplifying sample collection, centralizing farm data, and supporting sustainability initiatives, FarmLab empowers farmers and agronomists to make data-driven decisions that enhance productivity and environmental stewardship.

Agworld: Streamlined Farm Management & Soil Sampling[59]

Agworld is an advanced farm management and soil sampling software designed to help agricultural professionals streamline their operations and improve efficiency. The platform integrates precision agriculture, soil health analysis, budgeting, and planning into one comprehensive system, allowing farmers and agronomists to make data-driven decisions that enhance productivity and profitability. With its cloud-based infrastructure and mobile accessibility, Agworld ensures that farm data is always available, whether in the office or out in the field. A key strength of Agworld is its ability to facilitate effortless data migration. Farmers can easily transfer essential field data, soil sampling results, and customer prescription formulas from legacy software, ensuring a smooth transition without data loss. The platform also provides a fast and efficient soil sampling workflow, allowing users to move seamlessly from sample collection to actionable insights and prescription writing. This streamlined process supports bulk recommendations, helping agronomists and farmers optimize soil health and maximize crop yield with minimal effort.

xFarm: Field Management[60]

xFarm is a comprehensive digital farm management platform that allows farmers to efficiently monitor and optimize their agricultural operations. With a user-friendly interface, xFarm provides a complete overview of a farm's fields, crops, and machinery, making it easier than ever to digitize agricultural management. By integrating field mapping, soil characteristic analysis, and geolocated notes, the platform enables users to make informed decisions that improve productivity and sustainability. One of xFarm's standout features is its field tracing and customization options. Farmers can quickly add their fields, organize them into groups, and input detailed characteristics, ensuring a highly personalized management experience. The platform supports importing field data in multiple formats, allowing users to seamlessly transition from other systems. Once integrated, users can monitor field activity, track crop history, and even plan long-term crop rotations to enhance soil health and optimize nutrient management. With modules for telemetry, agrometeorology, and crop planning, xFarm provides a highly adaptable system that supports the evolving needs of modern agriculture.

Soil Monitoring Software (SMS): Protecting Soil in a Changing Climate[61]

Soil Monitoring Software (SMS) is an innovative tool developed through the SoilPro project to address the challenges of soil degradation, particularly in Mediterranean ecosystems. As soil faces increasing vulnerability from both human activities and natural processes, such as droughts and floods, SMS provides a means to monitor and assess the condition of soil across different landscapes. By leveraging historical data and cutting-edge technologies like GIS and remote sensing, SMS helps local authorities understand the extent of soil degradation and identify at-risk areas before they become severe problems. This early detection allows policymakers to implement low-cost solutions and strategies for soil restoration and protection. The platform's modular architecture includes a data handling module, a data repository, soil management monitoring modules, and a mapping module, all designed to be accessible through a web-based interface. SMS handles two primary types of data: raw grid data, often in raster format, and georeferenced map images. The system also supports the upload of punctual data from direct measurements or historical datasets, which can be used to create maps that highlight areas at risk of soil degradation due to climate and human pressures. The tool's focus on data-driven decision-making allows stakeholders to define and implement targeted adaptation and protection actions that combat the effects of climate change and prevent soil erosion, helping ensure the longevity and sustainability of agricultural lands.

Crop Management Software for Sustainable Farming | Intellias[62]

Intellias has partnered with a multinational agricultural corporation to create a platform-based crop management software aimed at promoting sustainable farming practices and compliance with stringent European Union environmental regulations. The goal of this product is to help farmers and commercial teams assess environmental and regulatory risks efficiently, offering insights on field vulnerabilities, proactive solutions for resource depletion, and strategies for effective market positioning.The collaboration led to the establishment of an Innovation Lab in Ukraine, where Intellias engineers developed a comprehensive crop management solution. The product development process is marked by extensive user research, iterative design sprints, and rapid prototyping, ensuring that only validated, effective ideas make it to delivery. The resulting software suite includes two major systems designed to address soil health and sustainable farming practices.

The first system focuses on Risk Self-Assessment and Soil Health Management. This web-based application helps farmers evaluate field conditions and potential environmental risks, such as soil erosion, groundwater contamination, and land degradation. It provides immediate, simplified risk evaluations and offers tailored recommendations for suitable products and practices to mitigate these risks and avoid environmental harm. The software uses an algorithm to assess the impact of active ingredients on specific soil and crop types, generating detailed PDF reports with actionable insights.

The second system, the Sustainability Toolbox for Sales Strategy and Crop Planning, encourages sustainable farming practices, such as vertical farming, and ensures compliance with agricultural policies. It allows crop protection product manufacturers to evaluate the environmental impact of their chemicals and provides tools for planning sales strategies. The crop planning software includes heat maps that visualize vulnerabilities related to soil runoff, leaching, and proximity risks across European countries, providing valuable data for both farmers and sales teams.

AgroCares: Precision Farming Based on Real-Time Nutrient Intelligence[63]

AgroCares offers innovative precision farming solutions designed to help agribusinesses optimize productivity while reducing resource use. With the world's population steadily growing, food production must double to meet the increasing demand, and AgroCares addresses this challenge with technology that helps farm managers treat their fields, animals, and resources like never before. Their cutting-edge data solutions empower farmers to achieve new levels of efficiency, delivering real-time nutrient intelligence for managing soil, feed, and crops.

The company's products provide a comprehensive approach to soil fertility management, allowing farmers to monitor and analyze their soil conditions throughout the growing season. These insights are made available through an online portal, ensuring that farm managers, even those in remote areas, can access critical data at any time. In addition to soil management, AgroCares offers rapid, affordable testing of feed quality, enabling farmers to gain control over raw materials and feeding programs. The ability to measure nutrients in leaf tissue further supports crop management, helping farmers make informed decisions about fertilization and harvesting. Through these technological advancements, AgroCares is driving sustainable farming practices and making significant strides toward meeting the world's growing food needs.

Agronomy Software: Revolutionizing Soil Health and Plant Monitoring in Farm Management[64]

Agronomy software is transforming modern farm management by providing advanced tools to monitor soil health and plant conditions, all while improving operational efficiency. Through features like crop monitoring, fertilizer management, and soil analysis, this software empowers farmers to make data-driven decisions that optimize yields and sustain soil fertility. By integrating agronomy software with farm management systems, a more comprehensive view of farm operations is achieved, allowing real-time monitoring of soil moisture, crop health, and resource management. The integration enhances soil health management by providing in-depth analysis of key parameters such as pH levels and nutrient content, facilitating effective fertilization techniques and sustainable farming practices. The software also aids in detecting nutrient deficiencies and potential issues like pest infestations or disease outbreaks, enabling farmers to act swiftly and minimize crop loss. The seamless coordination between agronomy and farm management software leads to better resource allocation, labor management, and more efficient farm operations, ensuring higher productivity and sustainability.

Our Project

While existing solutions like OneSoil, QuickTrials, FarmLab, Agworld, and xFarm offer valuable tools for precision agriculture, they primarily focus on satellite-based monitoring, field management, and agronomic trials. These platforms provide insights into crop health, soil characteristics, and farm operations, but they often rely on periodic data collection, remote sensing, or manual input, which may not capture rapid soil condition changes in real-time.

In contrast, our project introduces a smart soil composition control system that leverages IoT-based sensors and AI-driven analytics to provide continuous, real-time soil monitoring at the field level. Unlike satellite-based approaches that offer macro-level insights, our system gathers precise, localized data directly from the soil, allowing farmers to immediately detect and respond to critical changes in nutrient levels, moisture, and other essential parameters. Additionally, automated alerts and AI-driven recommendations help optimize fertilizer use, reducing waste and environmental impact.

By integrating real-time IoT sensing with AI-powered analytics, our system bridges the gap between broad-scale monitoring solutions and hands-on soil management, offering farmers a proactive rather than reactive approach to soil health. This innovation is crucial for Moldova, where soil degradation and inefficient fertilizer use threaten long-term agricultural sustainability. Our solution empowers farmers with actionable, data-driven insights that enhance productivity, conserve resources, and promote sustainable farming practices, making it a transformative addition to the current agricultural technology landscape.

Potential Use Cases and Benefits in Moldova:

One of the primary benefits of these systems is **soil nutrient monitoring**. IoT sensors can continuously measure soil parameters like nitrogen, phosphorus, potassium, pH levels, moisture content, and temperature. This real-time data enables precise nutrient management, ensuring optimal conditions for crop growth. For instance, a study published in the *International Research Journal of Engineering and Technology* (IRJET) highlights how real-time monitoring facilitates timely interventions to maintain soil fertility. This is particularly relevant for Moldova, where nutrient depletion due to intensive farming practices is a recurring issue. By adopting such systems, Moldovan farmers can reduce the overuse of fertilizers, improve yields, and enhance long-term soil health.[84]

Another significant application is **crop recommendation**. Machine learning algorithms integrated with IoT systems can analyze soil composition data to recommend the most suitable crops for specific conditions. This approach minimizes risks associated with poor crop selection and maximizes yield potential. A study published in *MDPI Computers* outlines an IoT-enabled soil nutrient analysis model that uses machine learning to optimize crop selection based on soil health data. For Moldova, where diverse microclimates and soil types exist, such technology could help farmers make informed decisions about crop rotation and diversification. This would not only improve productivity but also reduce the risk of crop failure due to unsuitable planting.[85]

Fertilizer optimization is another critical use case. Real-time data from IoT sensors allows for targeted fertilizer application, reducing waste and environmental impact while cutting costs. Fertilizer misuse is a common issue in Moldova, leading to both economic losses and environmental degradation. The *International Journal of Engineering Research & Technology* discusses a smart fertilizer monitoring system that leverages IoT and machine learning to optimize fertilizer use. By adopting these systems, Moldovan farmers can achieve cost savings while minimizing nutrient runoff into water bodies—a critical concern for maintaining the health of rivers like the Dniester.[86]

Efficient **irrigation management** is also crucial in Moldova, where water resources are increasingly under pressure due to climate change. IoT-based soil moisture sensors provide real-time data that can optimize irrigation schedules, ensuring crops receive adequate hydration without wasting water. Research in the *International Research Journal of Modernization in Engineering Technology and Science* (IRJMETS) describes an IoT-enabled system that enhances irrigation efficiency by automating water delivery based on soil moisture levels. This technology could be particularly beneficial for Moldova's southern regions, which are prone to droughts. By conserving water resources and improving crop resilience, such systems would support sustainable agricultural practices. [87]

Lastly, monitoring soil conditions with IoT devices aids in **early disease detection**. Deviations in soil pH or moisture levels often signal conditions favorable for disease outbreaks. The *International Journal of Creative Research Thoughts* (IJCRT) discusses a smart agriculture system that uses IoT for early disease detection through soil nutrient analysis. For Moldovan farmers, this capability could reduce crop losses by enabling proactive measures such as adjusting irrigation or applying targeted treatments before diseases spread. [88]

Existing Business Cases and References for Moldova:

- **Climate-Smart Agriculture in Moldova**

The climate-smart agriculture (CSA) concept reflects an ambition to improve the integration of agriculture development and climate responsiveness. [89] It highlights technologies and approaches such as conservation agriculture, precision irrigation, and protective systems to improve soil fertility, reduce erosion, and increase yields. Drip irrigation systems, conservation agriculture techniques (no-till, strip-till), and organic mulching rely on soil moisture sensors and remote sensing technologies to monitor soil conditions, optimise water use, and improve soil health.

- **Modern soil testing laboratory in Ungheni**

This project focuses on enhancing soil health and agricultural sustainability in Moldova by promoting the use of organic fertilisersOrganic fertilisers are a lifesaver for degraded and chemically polluted soils, as they remediate and restore the humus layer, increase resistance to draught, improve the quality of harvest, stimulate the plants' growth and development. [90] With support from the EU4Moldova program a grant of 30,000 EUR, it establishes a modern soil analysis laboratory, enabling scientific assessment of soil conditions and the production of high-quality organic fertilisers. The high-performance soil testing laboratory utilises digital sensors and analytical equipment to measure pH levels, ion concentrations, and organic matter content, enabling precise soil composition analysis and optimised fertiliser production.

Existing Business Cases and References:

- **The Monitoring System of Soil PH Factor Using IoT-Webserver-Android and Machine Learning (Indonesia)**

This is a research that aims to make and implement an IoT-Webserver-Android and Machine Learning-based soil PH factor monitoring tool system. The system is created of multiple sensors data acquisition subsystem, consisting of sensors for soil PH-Moisture, Temperature-Humidity, and Sunlight. The sensors are connected to the Arduino Uno microcontroller for serial communication with the ESP 8266 microcontroller for the Wi-Fi module. The monitoring subsystem is done with the local web application, which contains a MySQL database and a local web page. Monitoring subsystem uses the Android application, which includes a real-time Firebase database and the application for real-time and mobile data display. [91] This way the project represents an advanced soil monitoring system that integrates IoT and machine learning to provide real-time insights into soil health, enabling farmers to optimize fertilizer use and crop selection, improving agricultural productivity.

- **Smart Soil Monitoring Application (Rwanda)**

It is a project Smart Soil Monitoring Application proposed for monitoring soil composition to facilitate farmers and policy makers in deciding the type of crops and fertilizer needed in different regions in Rwanda. Proposed Smart Soil Monitoring Application consists of a pH sensor, moisture sensor and DHT11 controlled by a nodeMCU. pH sensor for collecting pH data, moisture sensor to sense presence of water in soiland and DHT11 for collecting data about humidity and temperature. [92] So it is clear that the project utilizes IoT sensors connected to a microcontroller unit to measure soil parameters such as pH, moisture, humidity, and temperature, with data transmitted to the cloud for analysis and remote access. This project represents an innovative approach to precision agriculture by integrating IoT-based soil monitoring with cloud computing and mobile applications.

- **Precision Irrigation Management in Michigan (USA)**

This project represents a smart irrigation system that leverages IoT technology to optimize water usage in agriculture. The project employs IoT-based soil moisture sensors that measure and transmit the data to a cloud-based platform for real-time irrigation recommendations. A LOCOMOS system can continuously measure soil moisture levels at multiple depths, leaf wetness duration, air temperature, relative humidity, and precipitation. The data were then sent to a LOCOMOS IoT website ([93]) to display the recommended irrigation timing and amount, the location of the sensor system, the raw sensor data, and the switch to turn irrigation on and off. [94] By continuously monitoring soil moisture and providing precise irrigation recommendations, it helps farmers reduce water consumption while maintaining high crop yields.

Table of Stakeholders with Interests and Influence:

Stakeholder	Interest in the Project	Level of Influence
Farmers in Moldova	Primary users of IoT soil monitoring to improve crop yields and optimize water usage. Interested in cost-effective and user-friendly solutions.	**High** – Their adoption determines project success.
Agricultural and Environmental Agencies in Moldova	Concerned with sustainable agriculture, food security, and environmental protection. May provide funding and regulatory support.	**High** – They create policies and funding opportunities that shape project implementation.
Agronomists	Provide expertise on soil health and help interpret data for effective decision-making. Support farmers in implementation.	**High** – They guide farmers on best practices for soil monitoring.

Technology Providers & IoT Solution Developers	Responsible for developing and maintaining the IoT system, ensuring its efficiency and reliability.	**High** – Their expertise determines the system's functionality and success.
Agricultural Entrepreneurs & Business Owners	Invest in agricultural technology to increase productivity and profitability. They drive commercial adoption.	**Medium** – Their financial backing can boost adoption and scalability.
Agricultural Cooperatives & Associations	Support farmers in accessing new technologies and training. Encourage adoption at a larger scale.	**Medium** – Can drive collective adoption among farmers.
Landscape Managers & Public Green Space Administrators	Use soil monitoring for public parks and urban agriculture.	**Low** – Secondary use case but can showcase benefits to a wider audience.
Hobby Gardeners & Small-Scale Growers	May use IoT soil monitoring for personal gardening and small farms.	**Low** – Niche users with limited impact on large-scale agricultural adoption.

Stakeholders Interview Clonclusions

The stakeholder interviews and survey results provide a comprehensive view of the current landscape and future needs of soil health monitoring in agriculture, especially within regions like Moldova where farming is both economically vital and environmentally vulnerable. A common theme emerging from the interviews is the challenge of maintaining soil fertility over time. Farmers often experience strong yields during the first planting cycle due to high levels of nutrients like potassium and sodium, but without proper replenishment, the soil becomes depleted, resulting in reduced productivity in subsequent years. While crop rotation and land resting strategies are sometimes employed, these methods are time-consuming and not always feasible, particularly for large-scale or intensive farming operations.

Monitoring soil health presents additional difficulties, primarily due to the high cost and logistical burden of laboratory testing. Although lab tests are accurate, they are expensive and impractical for frequent use. Consequently, farmers often rely on limited data from sensors that measure only a few key parameters such as moisture or basic nutrient levels. Differences in soil type further complicate matters, as properties like acidity, granularity, and water retention vary greatly and influence which crops can be grown successfully. Furthermore, water availability and temperature fluctuations, particularly in open fields, make maintaining optimal moisture levels a persistent struggle.

Technology and automation are increasingly seen as essential tools for improving soil health management. Automated systems can provide real-time data and enable timely interventions, reducing dependence on manual inspections. Mobile applications are especially valuable for field workers who need quick access to data and the ability to record observations on-site, while web platforms support farm managers in making strategic decisions through detailed analysis and historical data tracking. Despite this potential, many farmers remain hesitant to adopt these systems due to concerns about cost, complexity, and infrastructure limitations.

The survey results reinforce the themes raised in the interviews. Many respondents continue to use manual observation or do not monitor soil health at all. Only a small percentage utilize laboratory testing or IoT-based systems, highlighting a significant technology gap. The most important soil parameters identified by respondents include organic matter content, pH level, nutrient profiles, and moisture content—all directly linked to crop health and yield. However, there is limited demand for continuous real-time updates, with most users preferring daily or weekly data refresh rates.

Cost is clearly the primary barrier to adoption, followed by the complexity of using such systems and connectivity issues in rural areas. Respondents also emphasized the importance of wireless functionality, ease of integration, and user-friendly design. While technical features like historical data tracking and automation are appreciated, they are considered secondary to practical concerns such as affordability and ease of implementation. Trust and familiarity with new technologies remain low, and building this trust through education, demonstration, and clear benefits is seen as key to encouraging adoption.

In conclusion, both the interviews and survey responses point to an urgent need for affordable, user-friendly, and scalable soil monitoring systems. These systems should balance technological sophistication with practical usability and offer step-by-step pathways for farmers to gradually integrate advanced features as their confidence grows. Successful solutions must provide actionable insights, require minimal technical expertise, and be adaptable to diverse environmental and infrastructural conditions. As Moldova and similar regions strive for more sustainable and productive agriculture, these findings underscore the importance of bridging the gap between innovation and accessibility in the field of soil health management.

Soil Health Monitoring Stakeholder Requirements

Category	Requirement	User Story	Job Story	MoSCoW Category	Explanation

Affordability	The solution should be cost-effective and accessible to farmers.	As a farmer, I want the system to be affordable so that I can adopt it without significantly increasing my expenses.	When evaluating soil monitoring solutions, I want to ensure the system is affordable so I can justify the investment.	Must Have	High cost could be a major barrier to adoption. Without affordability, the solution will have limited reach.
Ease of Use	The system should be easy to install, operate, and maintain without requiring technical skills.	As an agronomist, I want a user-friendly interface so that I can quickly interpret soil data without extensive training.	When using the system in the field, I want a simple interface so I can get quick and clear insights without delays.	Must Have	If the system is too complex, users will struggle to adopt and use it efficiently.
Soil Composition Monitoring	The system must measure key soil parameters such as moisture, pH, electroconductivity, and nutrient levels.	As a farm manager, I want to track soil nutrients in real-time so that I can adjust fertilization plans accordingly.	When managing crop health, I want to monitor soil composition accurately so I can optimize growth conditions.	Must Have	Core functionality for soil monitoring and decision-making.
Real-Time Data Updates	The system should provide real-time monitoring and timely updates on soil health.	As an agronomist, I want to receive soil health updates frequently so that I can plan necessary interventions in time.	When monitoring soil health, I want real-time insights so I can react to changes before they impact crop yields.	Must Have	Delayed data could lead to crop failure or poor soil management.

Automation & IoT Integration	The system should integrate with wireless sensor networks and provide AI-driven insights.	As a greenhouse owner, I want the system to automatically adjust irrigation and fertilization based on soil data.	When optimizing farm operations, I want automated alerts and adjustments so I can reduce manual work.	Should Have	Enhances efficiency, but manual monitoring is still possible.
Scalability	The system should be adaptable for different farm sizes and monitoring needs.	As a researcher, I want to analyze soil data from multiple locations to study regional differences.	When expanding my farm, I want the system to scale with my operations so I don't have to switch solutions.	Should Have	Useful for long-term usability, but not essential for initial deployment.
Remote Access & Mobile Compatibility	Users should be able to access soil data from a mobile app and web platform.	As a field technician, I want to check soil health data on my mobile phone while working in the field.	When monitoring soil remotely, I want mobile access so I can stay updated without needing to visit the farm.	Must Have	Essential for usability, especially in large farms or remote areas.
Water Management Support	The system should help manage soil moisture efficiently and measure at different depths.	As a farmer, I want the system to notify me when soil moisture is too low so I can adjust irrigation.	When optimizing water usage, I want accurate soil moisture readings so I can conserve water and reduce costs.	Must Have	Prevents overwatering or drought conditions that can damage crops.

Predictive Maintenance & Alerts	The system should provide early warnings about soil degradation and nutrient depletion.	As a farm owner, I want early warnings about soil nutrient depletion so I can take corrective action in advance.	When monitoring soil conditions, I want predictive alerts so I can prevent crop failures.	Should Have	Helps with long-term soil health but isn’t immediately critical.
Environment al Sustainability	The system should promote sustainable soil management by reducing chemical overuse.	As an organic farmer, I want to minimize excessive chemical use by tailoring fertilizer application based on data.	When planning fertilization, I want precise recommendatio ns so I can minimize environmental impact.	Should Have	Important for long-term benefits, but not a core requirement for system functionality.
Data Privacy & Security	The system should ensure encryption, secure storage, and controlled access.	As a farm operator, I want my soil data to be private and secure.	When using the system, I want confidence that my data won’t be exposed to unauthorized parties.	Must Have	Data protection is critical for trust and regulatory compliance.
Multi-Language Support	The system should support multiple languages for usability.	As a non-English-speaking farmer, I want to use the system in my native language.	When accessing soil data, I want information presented in a language I understand.	Should Have	Enhances usability for a wider audience but isn’t essential for core functionality.

Integration with Farm Systems	The system should integrate with existing farm management software.	As a farm manager, I want soil data to sync with my farm software.	When managing my farm digitally, I want soil data seamlessly integrated.	Should Have	Useful for advanced users but not necessary for initial use.
Customizable Alerts	Users should be able to set specific alert thresholds for soil parameters.	As a technician, I want to receive alerts for abnormal soil conditions.	When monitoring soil health, I want to configure alerts to match my specific needs.	Should Have	Enhances user experience but not a fundamental requirement.
Soil Health Reports	The system should generate detailed reports on soil conditions.	As a researcher, I want to analyze downloadable soil reports.	When reviewing farm data, I want structured soil reports for decision-making.	Should Have	Important for analytics but not necessary for real-time monitoring.
User Roles & Permissions	The system should provide role-based access control.	As a farm manager, I want to assign different levels of access to my team.	When managing soil data, I want to control who can edit or view specific information.	Should Have	Helps with security, but not essential for single-user farms.
Mobile App Notifications	Users should receive notifications on soil health changes via mobile.	As a farmer, I want to be alerted to significant soil changes.	When monitoring soil remotely, I want instant mobile notifications.	Should Have	Increases responsiveness but is not mandatory.

GPS Integration	The system should tag soil data with precise GPS locations.	As a researcher, I want location-specific soil data for regional analysis.	When mapping soil health, I want GPS tagging for precise monitoring.	Won't Have	Adds complexity and cost; not a primary need for soil monitoring.
Offline Data Collection	The system should store data offline when connectivity is lost.	As a field worker, I want data to sync when internet access is restored.	When using the system in remote areas, I want it to work without internet.	Must Have	Essential for farms in remote areas with poor connectivity.
Adaptive Learning & AI Insights	The system should improve recommendations based on user data.	As a researcher, I want AI-driven insights for better soil care.	When analyzing soil, I want AI recommendations to evolve over time.	Won't Have	AI insights are beneficial but not a necessity for basic soil monitoring.
Power Efficiency	The system should support energy-efficient operations.	As a farm owner, I want solar-powered sensors for sustainability.	When deploying sensors, I want energy efficiency to reduce maintenance costs.	Should Have	Helps with sustainability but isn't essential for functionality.
Soil Parameter Customization	Users should define and track additional soil metrics.	As a scientist, I want to monitor specific soil elements beyond standard parameters.	When studying soil, I want flexibility in choosing which parameters to track.	Should Have	Customization is useful for researchers and advanced users but not mandatory for basic functionality.

Historical Data & Analytics	The system should store and analyze past data trends.	As an agronomist, I want access to historical soil data for better predictions.	When managing crops, I want to compare soil data from previous seasons.	Should Have	Valuable for long-term planning but not critical for real-time monitoring.

System Requirements

Based on stakeholder requirements analysis we have developed the following system requirements:

Affordability is addressed through requirements that ensure the total cost of ownership is competitive, offer tiered subscription models for different budgets, and prioritize low maintenance costs through durable hardware and automated software updates.

Ease of Use emphasizes user-friendliness by requiring tool-free sensor installation, intuitive web and mobile interfaces following usability heuristics, onboarding tutorials and tooltips, guided tours for first-time users, clear operational indicators, and step-by-step maintenance instructions within the app.

Soil Composition Monitoring outlines essential measurement functions, such as detecting moisture at various depths, accurately recording pH, electroconductivity, and nutrient levels of Nitrogen, Phosphorus, and Potassium. It also supports customizable measurement frequency.

Real-Time Data Updates ensure timely information through fast data transmission, regular dashboard refreshes, and synchronization after connectivity loss.

Automation & IoT Integration mandates the use of wireless communication protocols like LoRaWAN, API availability for third-party systems, and AI-driven recommendations for fertilization, irrigation scheduling, and alert rule configurations.

Scalability ensures the system handles between 1 and 1000 sensors efficiently, supports sensor grouping, and maintains a horizontally scalable architecture.

Remote Access & Mobile Compatibility includes requirements for cross-browser web access, native mobile apps, offline access to synchronized data, and responsive UI across devices.

Water Management Support is achieved through moisture trend visualization, customizable moisture thresholds, and alerts for threshold breaches.

Predictive Maintenance & Alerts cover early warnings for nutrient depletion, battery and connectivity status alerts, and rule-based degradation detection.

Environmental Sustainability includes recommendations minimizing chemical inputs and tracking applied treatments.

Data Privacy & Security focuses on encrypting data at rest and in transit, strong password policies, role-based access control, and access logging.

Multi-Language Support enables multilingual UI and user-configurable language settings.

Integration with Farm Systems ensures external API access with secure authentication.

Customizable Alerts allow users to set parameter-based alert rules, choose notification channels, and access a complete alert history.

Soil Health Reports support report generation, exporting in various formats, and customization of content.

User Roles & Permissions provide role definitions and administrative control over access rights.

Mobile App Notifications enable push notifications with user-defined preferences.

Customizable Data Visualization includes interactive charts, data filters, and parameter overlays.

GPS Integration ensures each reading is geotagged, visualized on a map, and accessible via location selection.

System Diagnostics & Troubleshooting supports a diagnostic dashboard, error code explanations, and backend error logging.

Soil Composition Trend Analysis provides long-term data storage and historical comparisons.

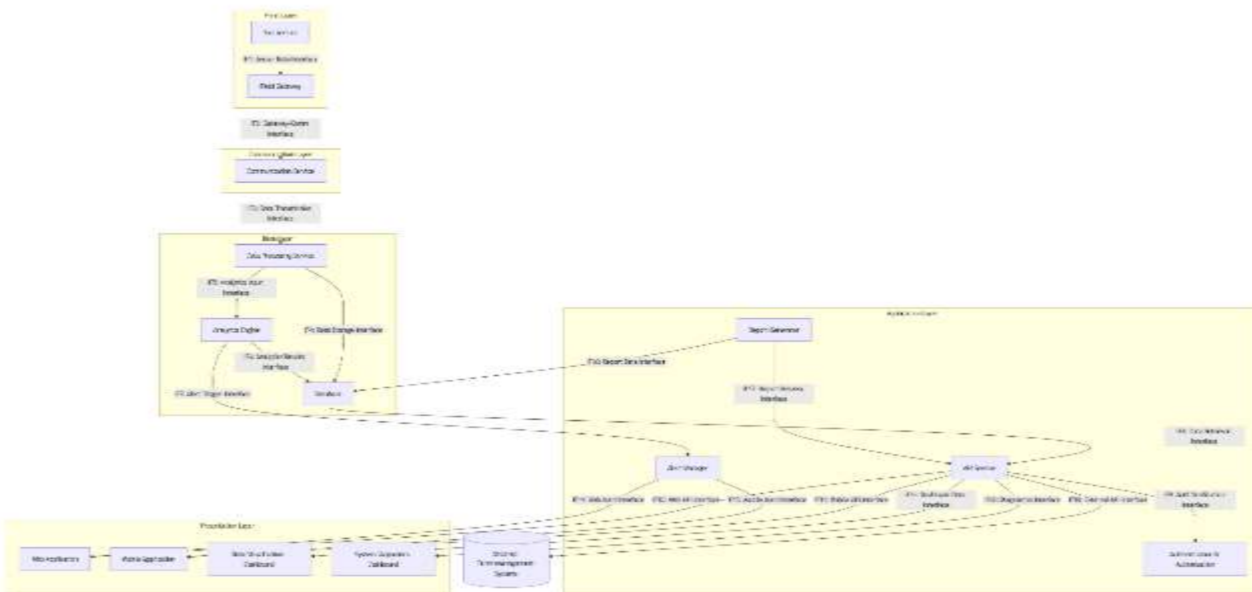
Cloud Backup & Restore ensures daily data backups and recovery within a 24-hour objective.

Power Efficiency & Offline Support requires sensors with low power consumption and long battery life, offline data storage, and optional Bluetooth sync via mobile.

1. High-Level Architectural Diagram

The **High-Level Architectural Diagram** illustrates a comprehensive soil monitoring system architecture divided into five distinct layers, creating a complete data flow from field sensors to user interfaces. The architecture follows a logical progression from data collection to presentation.

At the foundation, the Field Layer consists of Soil Sensors that collect various soil parameters (moisture, pH, nutrients, electroconductivity) and transmit this data to Field Gateways via the Sensor Data Interface (IF1). The Field Gateways aggregate data from multiple sensors, provide local storage capability, and connect to the Communication Layer through the Gateway-Comm Interface (IF2). This hardware foundation enables robust data collection directly from agricultural fields.



The **Communication Layer** houses the Communication Service, which manages secure transmission of data between field components and cloud infrastructure, implementing encryption and handling synchronization of offline data. This connects to the Data Layer through the Data Transmission Interface (IF3). Within the Data Layer, three critical components work together: the Data Processing Service (which validates and standardizes incoming data), the Analytics Engine (which applies AI algorithms for insights and recommendations), and the Database (which stores all system data with encryption and backup mechanisms). These components interact through several interfaces (IF4-IF7) to ensure data is properly processed, analyzed, and stored.

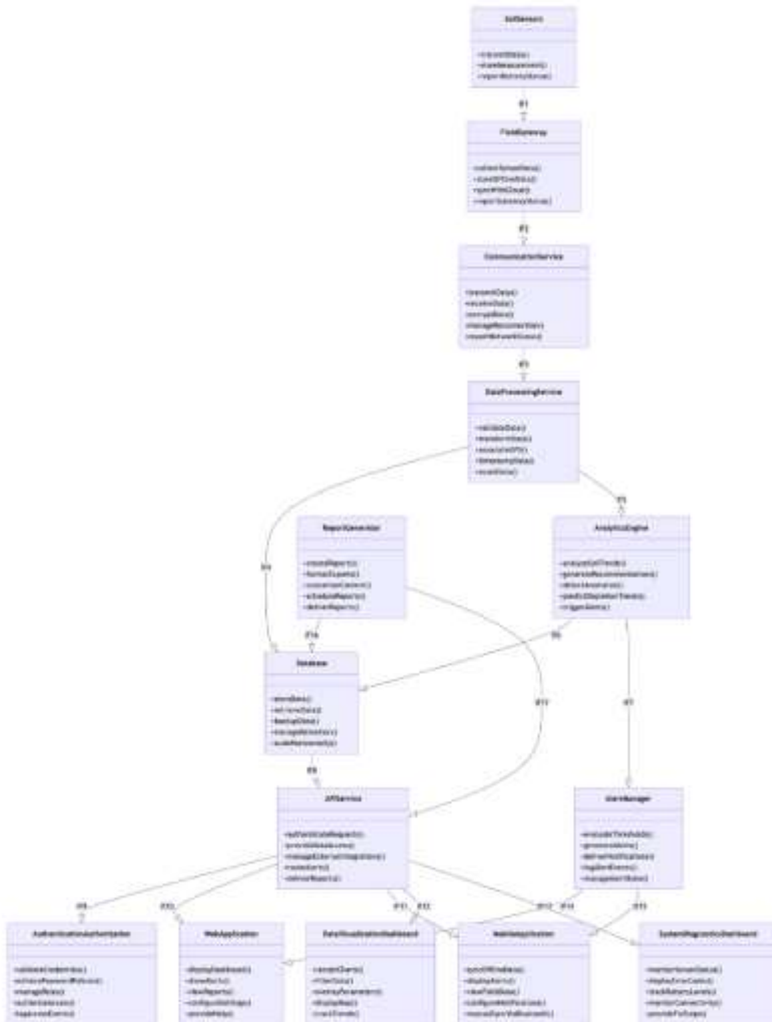
The **Application Layer** provides the business logic and core services, including the API Service (offering unified access to system functionality), Authentication & Authorization (managing user access control), Alert Manager (handling notifications based on thresholds), and Report

Generator (creating customizable reports). This layer communicates with both the Data Layer and the Presentation Layer through numerous interfaces (IF8-IF18). The API Service acts as a central hub, connecting to almost every presentation component.

The **Presentation Layer** delivers the user-facing interfaces: a responsive Web Application, a Mobile Application with offline capabilities, a Data Visualization Dashboard for interactive charts and maps, and a System Diagnostics Dashboard for monitoring system health. This layer also shows integration capability with External Farm Management Systems. All components in this layer consume data and functionality through the API interfaces provided by the Application Layer. The entire architecture demonstrates a modular design with clear separation of concerns, well-defined interfaces between components, and comprehensive functionality for agricultural soil monitoring and management.

Component Diagram

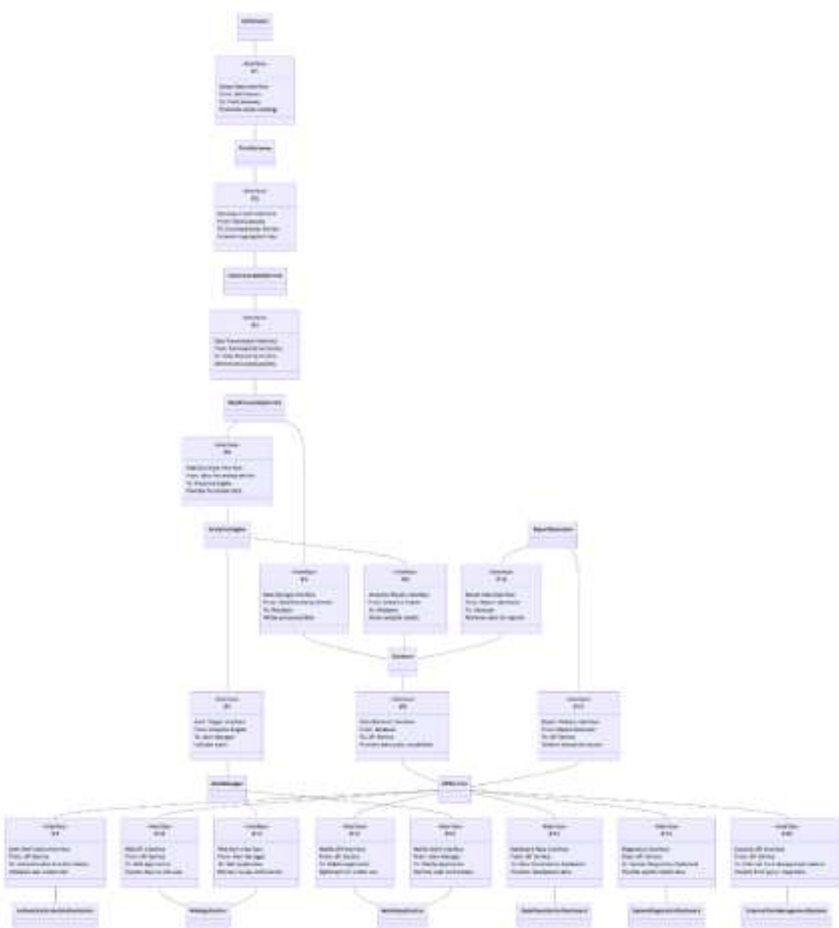
The Component Diagram illustrates a comprehensive soil composition monitoring and management system with a clear hierarchical architecture. The system follows a logical data flow path from physical soil sensors in the field through various processing layers to end-user applications. This architecture enables efficient soil parameter monitoring, data analysis, and actionable insights for agricultural management.



Thi Soil Composition Control System (SCCS) is a layered IoT architecture designed to monitor, process, and analyze soil data in real-time. At its foundation, Soil Sensors collect key environmental parameters such as moisture, pH, electroconductivity, and nutrient levels, transmitting them to a Field Gateway. The Field Gateway aggregates data from multiple sensors, temporarily stores it when offline, and forwards it to the cloud through the Communication Service. This Communication Service ensures secure transmission using encryption and handles synchronization after connectivity interruptions. Once received, the Data Processing Service validates, standardizes, and enriches the data with timestamps and GPS coordinates. The Analytics Engine processes the structured data using AI algorithms to generate insights, detect anomalies, and trigger alerts when thresholds are exceeded. All processed data and analysis results are stored in a centralized Database, enabling long-term trend tracking and reliable access. The API Service provides a unified interface for retrieving data, generating reports, and connecting external systems and frontend applications. Alerts are managed by the Alert Manager, which prioritizes and distributes notifications to web and mobile users. Finally, the Presentation Layer—including the Web Application, Mobile Application, Data Visualization Dashboard, and System Diagnostics Dashboard—offers intuitive tools for users to visualize, interpret, and act upon soil data. This comprehensive soil composition control system delivers significant value for agricultural operations by providing continuous monitoring of critical soil parameters, automated analysis for early problem detection, and actionable recommendations for optimal soil management. The modular design supports scaling from small farms to large agricultural enterprises, while the mobile and web interfaces ensure accessibility for various user contexts. Integration capabilities with external farm management systems further enhance the system's utility by allowing it to function within larger agricultural technology ecosystems.

3.2 System Interface Diagram

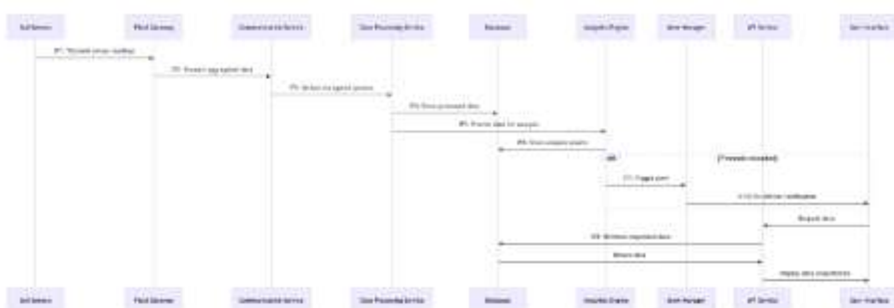
The System Interface Diagram illustrates a comprehensive soil composition monitoring system with a detailed focus on the interfaces between components. This architectural representation maps the data flow from physical soil sensors through multiple processing layers to end-user applications, with each interface clearly defined. The linear hierarchy demonstrates how data travels through the system, with explicit definition of which components communicate with each other and what information passes between them.



The interface structure of the Soil Composition Control System (SCCS) clearly defines how data moves across different components, ensuring a transparent and modular system architecture Sensor readings flow from Soil Sensors to the Field Gateway over IF1, then leave the field through IF2 and IF3 as the Communication Service encrypts and relays them to the Data Processing Service. After validation, the Data Processing Service writes cleansed data to the Database via IF4 and hands a formatted copy to the Analytics Engine through IF5; the engine stores its insights back in the Database on IF6 and signals the Alert Manager on IF7 whenever thresholds are breached. The Report Generator pulls information from the Database with IF16, returns finished documents to the API Service on IF17, and the Database itself exposes all stored content to that same API hub via IF8. Acting as the system's crossroads, the API Service authenticates users over IF9, feeds data and alerts to web, mobile, dashboards, and diagnostics through IF10-IF13, and opens the platform to external farm-management software through IF18. Alerts fan out from the Alert Manager to browsers on IF14 and to mobile devices on IF15, completing a clear, end-to-end path from field sensors to actionable user information.

4. Data Flow System

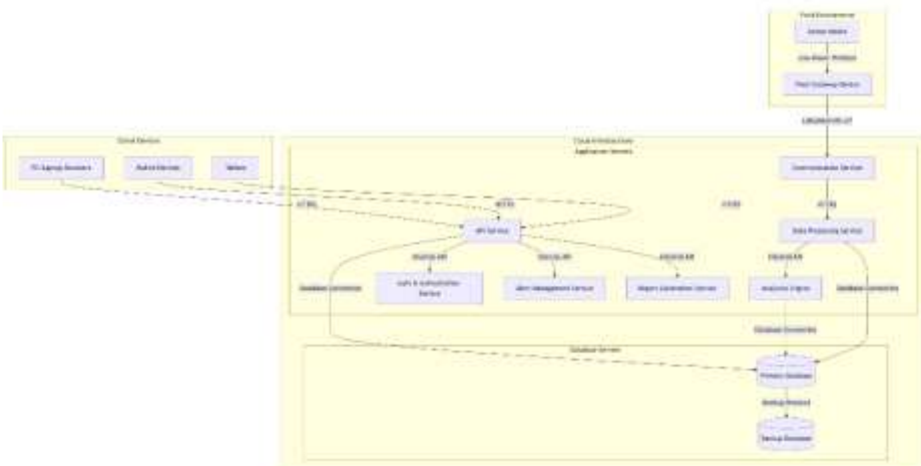
This Data Flow System Sequence Diagram illustrates the chronological data flow through the Soil Composition Control System, depicting how information travels from physical sensors to end users. Unlike the previous component and team diagrams, this representation focuses on the temporal dimension of system operations, showing the specific order of interactions between components and the nature of data exchanged at each step.



The sequence begins with Soil Sensors transmitting raw readings to the Field Gateway via IF1. The Field Gateway aggregates data from multiple sensors and forwards it to the Communication Service over IF2. The Communication Service then encrypts and delivers these packets to the Data Processing Service through IF3, where the data undergoes validation and formatting. Once processed, the data is stored in the Database via IF4, and simultaneously sent to the Analytics Engine through IF5 for further analysis. The engine computes trends and recommendations, then saves its results back into the Database using IF6. If any thresholds are exceeded, the Analytics Engine triggers an alert via IF7, prompting the Alert Manager to generate notifications, which are delivered through IF14 and IF15. Separately, a User Interface may request information via the API Service. The API queries the Database using IF8, retrieves the requested data, and sends it back to the interface. The user interface then displays the results, completing the end-to-end flow from field data acquisition to actionable user insight. Overall, the diagram reflects a robust, modular data pipeline that ensures timely monitoring, analysis, storage, alerting, and user access within the SCCS architecture.

5. System Deployment Architecture

The System Deployment Architecture Diagram illustrates a comprehensive IoT ecosystem designed for monitoring, analyzing, and managing soil composition to support precision agriculture. This multi-layered architecture follows a clear edge-to-cloud approach, providing a complete solution from field sensors to user interfaces.



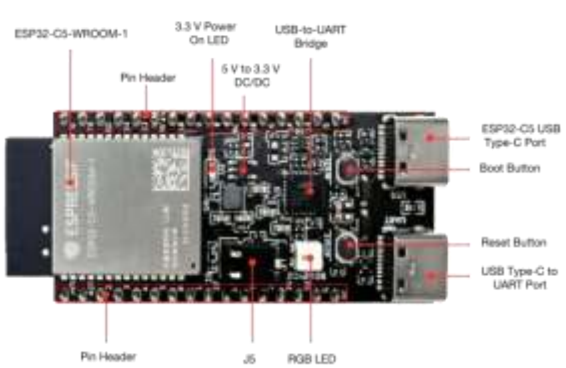
In the field, sensor nodes send data via low-power protocols to gateway devices, which forward it to the Communication Service in the cloud. From there, data moves securely to the Data Processing Service, which validates and routes it to both the Analytics Engine and Primary Database. Within the cloud, the API Service acts as the central hub, allowing secure access for web and mobile clients. It connects internally with the Auth & Authorization Service, Alert Management Service, and Report Generation Service. These components coordinate tasks like user authentication, alert delivery, and report generation based on analytical insights. All critical data is stored in the Primary Database, with a Backup Database maintained via a backup protocol. Client devices such as browsers, mobile phones, and tablets connect over HTTPS to visualize and manage system data, completing the flow from field to user interface.

Hardware Components:

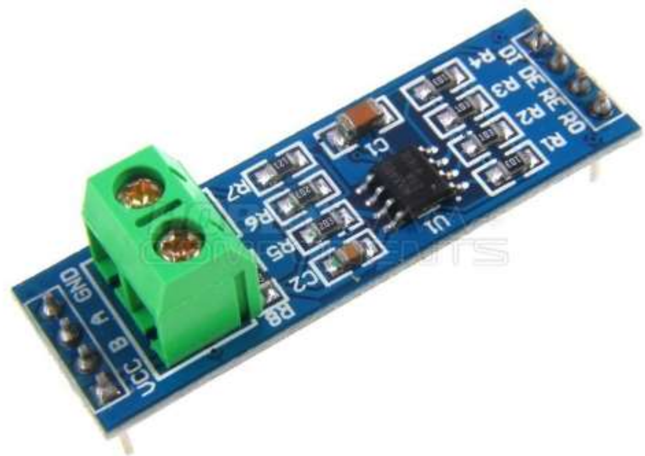
The hardware setup of the Soil Composition Control System incorporates three essential components that ensure accurate measurement, reliable transmission, and efficient processing of soil data in agricultural environments.

At the core of data acquisition is the **7-in-1 Soil Sensor with RS485 interface**, a high-precision instrument capable of measuring seven distinct soil parameters. These include key indicators such as moisture content, temperature, pH, electroconductivity, and essential nutrient levels. Its RS485 communication capability allows for stable, long-distance data transmission, making it well-suited for deployment across wide agricultural fields where sensor placement must be flexible.

To process and manage the data collected by the sensor, the system utilizes the **ESP32 microcontroller**, a powerful and cost-effective platform ideal for IoT-based smart agriculture solutions. The ESP32 features built-in Wi-Fi and Bluetooth capabilities, supporting both local wireless communication and cloud connectivity. It offers various processing options, including single-core or dual-core Tensilica Xtensa and RISC-V configurations. The microcontroller is engineered with integrated components such as antenna switches, RF balun, amplifiers, noise filters, and power management systems, enabling energy-efficient performance and reliable sensor integration in the field.



Facilitating communication between the sensor and the controller is the **RS-485 module**, a robust industrial-grade interface designed for differential signal transmission. Its use ensures reliable data transfer across long distances, particularly in electrically noisy environments common in agricultural settings. This module is widely adopted in sensor networks and industrial automation due to its durability and effectiveness.



Together, these components form a reliable, energy-efficient, and scalable hardware architecture for real-time soil monitoring and smart farming applications.

Software Components

The project's workflow encompasses real-time data collection from sensors, statistical and geospatial analysis, predictive modeling, and interactive visualization—all supported by an open-source technology stack selected for flexibility, community support, and cost-efficiency.

Python and R are chosen as the primary programming environments. Python supports scripting, data manipulation, and machine learning through libraries like Pandas, NumPy, and Scikit-learn. R, with packages like caret, sf, and ggplot2, is leveraged for advanced statistical modeling and publication-grade visualizations. These languages complement each other, providing a dual-language environment that balances automation and statistical rigor.

For geospatial analysis, the toolkit includes GDAL for backend data translation, QGIS for desktop GIS operations, and R's sf and raster (terra) packages for programmatic spatial data processing. These tools allow seamless handling of raster and vector data crucial for mapping and spatial modeling of soil properties. Data collection from the field is supported by Raspberry Pi devices, which are used as cost-effective platforms for real-time sensor integration and edge computing.

On the database side, PostgreSQL, extended with PostGIS, serves as a centralized data repository capable of managing structured and geospatial data. Visualization is managed through tools like

Grafana, which supports real-time dashboards, and ggplot2 for detailed static plots. These platforms allow stakeholders to monitor soil parameters and modeling outputs interactively.

Finally, Git and GitHub provide robust version control and collaboration infrastructure. These tools support reproducibility and teamwork, ensuring the integrity and transparency of both code and analysis workflows. Overall, the report outlines a strategic and cohesive integration of technologies aimed at advancing soil monitoring and management through data science and geoinformatics.

Implementation

The ESP32 microcontroller reads soil moisture levels using an analog moisture sensor connected to GPIO36. The sensor outputs an analog voltage that corresponds to the soil's moisture level, which the ESP32 reads using the `analogRead()` function with a 12-bit resolution. Every 10 seconds, the ESP32 collects a new reading and sends it as a JSON payload to a remote server over Wi-Fi using an HTTP POST request. The payload includes the device ID and the current moisture value, enabling real-time monitoring of soil conditions remotely.

The data is sent from the ESP32 microcontroller over Wi-Fi to HiveMQ cloud platform. HiveMQ acts as an MQTT broker in the cloud, allowing the device to publish soil moisture readings to a specific topic. Once published, the dashboard subscribes to that topic to receive the data in real time. HiveMQ stores and manages the messages, making it easier to handle multiple devices, remote access, and data monitoring from anywhere.

The ESP32 continuously reads data from a soil moisture sensor connected to GPIO36, which is configured as an analog input. Using the `analogRead()` function, the device captures raw analog values that represent the current moisture level in the soil. This raw value typically ranges between 0 and 4095 due to the 12-bit resolution of the analog-to-digital converter.

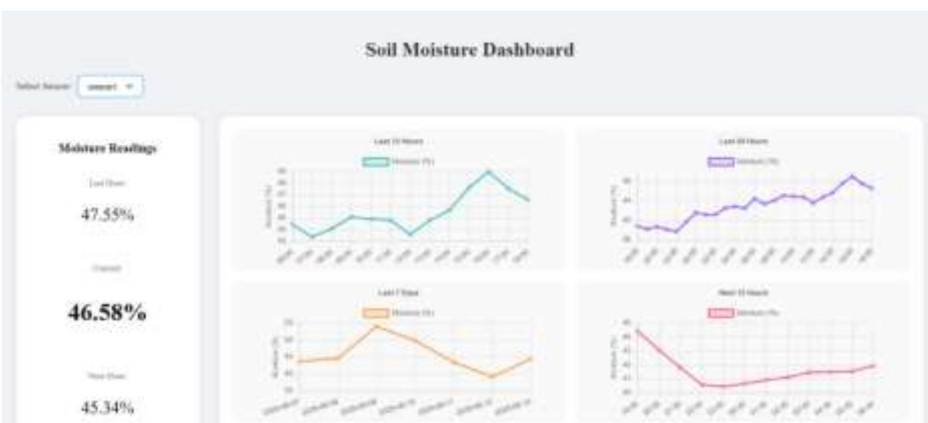
Once the value is obtained, the device does not perform any advanced processing or decision-making locally. The data is simply printed to the serial monitor to aid in debugging and monitoring. There is no thresholding or local control logic implemented to act upon the moisture reading.

After reading the sensor value, the device constructs a JSON object that includes a unique device identifier (`device_id`) and the current `moisture_value`. This JSON payload is then sent to a server using an HTTP POST request. The transmission occurs over a Wi-Fi connection, which is established during the device's initialization phase in the `setup()` function. The server URL points to a local machine on the network, indicating that the project is currently designed for a closed or local environment rather than direct cloud communication.

The moisture sensor continuously monitors the soil and sends the collected data to the cloud. Once the data reaches the server or cloud platform, it is stored and processed to extract meaningful insights. Analysis routines and prediction algorithms are applied to estimate future moisture levels and detect potential dryness trends. These results are then displayed on a user-friendly dashboard using graphs and clear written information to help users easily understand the current and predicted soil conditions. Based on these predictions, the system can automatically control the irrigation system within the greenhouse. When low moisture levels are detected or forecasted, the irrigation is triggered to maintain optimal soil conditions for healthy plant growth.

First, the ESP32 reads the soil moisture level using an analog sensor connected to GPIO36. The raw analog value is then packaged into a JSON object along with the device ID. This data is sent using the MQTT protocol to HiveMQ, a cloud-based MQTT broker that manages real-time messaging between devices and applications. HiveMQ receives the data and makes it available for further processing or storage in a connected backend system. Once stored, the data can be accessed and used to generate visualizations, analyze trends, and predict future moisture levels. These results are then displayed on dashboards and can support decisions like automatically triggering irrigation in future system upgrades.

The web interface presents the soil moisture data in a clean and structured dashboard. On the left side, it shows key moisture readings including the value from the last hour, the current reading, and a prediction for the next hour. In the center and right sections, the dashboard displays multiple graphs for different time ranges: the last 12 hours, last 24 hours, last 7 days, and predictions for the next 12 hours. Each chart uses a different color to help distinguish the time frames, and the Y-axis represents the soil moisture percentage. At the top, there is a dropdown menu that allows the user to select a specific sensor, making it easy to monitor data from multiple sources. Overall, the dashboard offers a visual and intuitive way to track moisture trends and make informed decisions.



Right now, the web application shows the data visualization dashboard with predictions and allows the user to select the needed sensor. In full implementation the control board could allow users to manually trigger the irrigation system or set some automatic thresholds for moisture levels that, when reached, activate or deactivate irrigation.

The main focus was on historical data analysis and predictive modeling. Using Python, the system collects real-time soil moisture data from IoT devices via the MQTT protocol and stores it in a PostgreSQL database. To analyze this data, the software provides REST API endpoints that compute statistical summaries over different time intervals—such as the last hour, 12 hours, 24 hours, and 7 days—allowing for historical trend evaluation.

For behavior planning and forecasting, an ARIMA time series model was integrated. This model is trained on the last 72 hours of moisture data and used to predict moisture levels for the next 12 hours, supporting proactive decision-making. All operations, including database interactions and data predictions, are logged for traceability.

In our current project implementation, the data flow is designed to operate in an uplink configuration, where soil moisture data is transmitted from the IoT devices to the cloud infrastructure. Once received and processed in the cloud, this data is made available via a web interface through a RESTful API, enabling real-time monitoring and historical analysis.

At this stage, the system focuses primarily on data acquisition, storage, and visualization. However, in the next phase of development, we intend to extend the functionality by enabling data-driven actuation. Specifically, the processed data will be used to trigger an automated irrigation system. Based on predefined thresholds or predictive models, control signals will be transmitted from the cloud to the irrigation hardware, ensuring intelligent and efficient water management. This bidirectional communication will enhance the system's capabilities from simple monitoring to autonomous, behavior-driven execution.

Conclusion

The development of an IoT-based soil composition control system marks a significant step toward modernizing Moldova's agricultural practices. Through continuous monitoring and automated analytics, the system empowers farmers to make precise, data-driven decisions regarding irrigation, fertilization, and soil health maintenance. The integration of AI, edge computing, and cloud storage ensures scalability, accuracy, and real-time responsiveness, while overcoming traditional limitations such as infrequent testing and lack of local insight. Despite challenges like high initial investment and infrastructure gaps, the long-term benefits—improved crop yields, reduced environmental footprint, and greater economic sustainability—demonstrate the system's value. By aligning innovative technologies with the practical needs of Moldovan agriculture, this project not only supports local food security but also contributes to broader global goals of sustainable farming and environmental conservation.

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