Micro-Sense AI: An AI-Driven Biosensors for Soil Microbial Health

1st Anjali Rupesh Jadhav
UG Student
Department of Information Technology
METS' Bhujbal Knowledge City, Institute of Engineering,
Adgaon, Nashik-422003, Maharashtra, India.

2nd Srushti Nitin Pagar
UG Student
Department of Information Technology
METS' Bhujbal Knowledge City, Institute of Engineering,
Adgaon, Nashik-422003, Maharashtra, India.

3rd Chaitanya Vijay Dhayade
UG Student
Department of Information Technology
METS' Bhujbal Knowledge City, Institute of Engineering,
Adgaon, Nashik-422003, Maharashtra, India.

4th Ganesh Dnyaneshwar Dabhade
UG Student
Department of Information Technology
METS' Bhujbal Knowledge City, Institute of Engineering,
Adgaon, Nashik-422003, Maharashtra, India.

5th Kishor Motiram Mahale
Assistant Professor
Department of Information Technology
METS' Bhujbal Knowledge City, Institute of Engineering,
Adgaon, Nashik-422003, Maharashtra, India.

***Abstract*—Soil plays an very Important role in agriculture. Farmers generally test the soil conventionally. They collect the sample from the farm and then send to laboratory and report comes within days or weeks, to overcome this problem our project steps in. Conventional soil testing techniques involve farmers to take samples of soil, have them analyzed at laboratories, which take days or even weeks to obtain reports, and by the time decisions for applying fertilizer have to be taken, it may already have been done, hence the results cannot always be utilized effectively. Our aim is to monitor the soil microbial health Powered sensor which works on solar or battery. The system enables real-time, low-cost, and remote soil health monitoring for long term farming. This project mainly based on the system is software as well as hardware. The idea behind this project is thus very evident, we would like to assist farmers in getting more productivity per unit land, in cutting down unnecessary fertilizer usage, keeping microbes healthy, and working on optimal balance of critical soil parameters such as CO_2 and nitrate, as these two are reliable indicators of soil respiration, nutrient cycling, and general fertility.This project uses IoT enabled biosensor to keep the record of soil parameters which is analyzed by AI. sensors like CO_2, Nitrate, Moisture,Temperature,pH are used and then analyzed by AI algorithms. It calculates a soil boilogical health score and provides guidance to farmers related to soil microbial health. A simple Soil biological health score card will be generated by the trained model which is easily readable by the farmers. the system recommends fertilizers and crops suitable for the soil which will help farmer to take quick and ecofriendly actions which will help farmers to enhance their yield.**

***Index Terms*—Soil Health Monitoring, Artificial Intelligence (AI), Internet of Things (IoT), Biosensors, Smart Agriculture, Microbial Activity Detection**

I. INTRODUCTION

Traditional soil testing primarily focuses on chemicals like N-P-K, pH and physical texture or parameters. This Traditional testing fails to monitor the fundamental biological health of the soil. The functioning of soil is treated as "black-box".Conventional soil testing are time consuming, expensive, and provide only a static snapshot of the soil, which is difficult for farmers to make decisions quickly about fertilization and crop management. This leads to the overuse or misuse of fertilizers, which can harm microbial activity, reduce soil fertility, and negatively impact long-term agricultural productivity. Microbes like bacteria, fungi, archaea, and protozoa play a important and irreplaceable role in soil by acting as the engine that drives nearly all soil processes, converting raw materials into the long term plant life and maintain ecosystem stability. Monitoring microbial health is important because more than half of farming is dependent on microbes for converting organic matter into plant-available nutrients and maintaining long-term soil fertility.

This paper represents Micro-Sense AI, an AI driven, IoT based system which is designed to monitor soil microbial health in real time. This system indicates or measures critical soil parameters such as Carbon dioxide(CO_2), nitrate levels, moisture, temperature, and pH. The sensor takes a reading of the soil's biology, and that data instantly zips over to a powerful mini-computer called the ESP32. From there, it goes straight to the cloud where our specialized AI gets to work. This AI crunches the numbers and delivers something simple yet powerful i.e. the Soil Biological Health Score (SBHS).

This score is not just a number it is the action plan. It gives you clear, smart advice on exactly what fertilizer to use and how much, which crops will thrive, and what the next step should be taken. By packing advanced hardware, smart software, and AI into one low-cost, solar-powered, and eco-friendly package, we're giving farmers the power to make decisions based on real data. This not only boosts your yields but keeps your soil healthy for generations.

II. Ease of Use

Our project designs the Micro-Sense AI system so that any farmer can use it easily and immediately. The project goal is very simple : no complicated manuals, no reports, no frustrating setups, just relevant information.

A. Sensors as a lab

Farmers need to place the sensors in the soil. Complex setup is not required. Here sensors works as labs. Sensors automatically start reading the health of the soil, and updates as your setup time.

B. Automatic and Effortless

There is no need to reach out to the fields and gather data like farmers gather soil in traditional testing. No manual data collection is needed. The sensor ESP32 gets the reading from biosensors and use wireless connectivity to send all the readings to the cloud automatically. The system gives Data driven decisions.

C. Clear Answers, No Complex Data

Farmers get the soil update on there device which is linked to the cloud. Soil updates are received on a simple app or dashboard. The easy to read Soil Biological Health Score(SBHS) give clear idea of the soil to the farmers.

D. Actionable Recommendations

The system provides clear, actionable guidance, like fertilizer recommendations or crops to plant. This gives a direct solution to the farmers.

E. Low maintenance and Power efficient

The sensors are solar powered or battery-operated, which reduces the need of maintenance. The system is built for long term.

III. Sensors used in Micro-Sense AI System

A. CO2 Sensor (MG-811)

- It measures the carbon dioxide concentration in the soil.
- CO_2 levels indicates microbial respiration i.e. The CO_2 sensor measures how much the microbes are "breathing". More CO_2 means the soil life is highly active, which is a sign of healthy soil.
- MG-811 is a tiny device which acts like a battery within the soil. When CO_2 from the microbes inside the soil enters the sensor, it creates a small electrical signal (i.e. voltage). More the CO_2 is, stronger the electrical signal it sends. The ESP32 micro-controller measures the strength of this signal which determines the exact concentration of CO_2 in the soil.
- Specifications:
  - Operating Voltage: 6V ± 0.1V.
  - Detection Range: 350 – 10,000 ppm.
  - Output Signal: Analog voltage.
  - Features: High sensitivity and fast response time.

B. Nitrate Sensor

- It detects nitrate (NO_2) concentration in soil. Features: High accuracy and stable readings even in varying soil conditions.
- Nitrate is a key nutrient for plant growth.
- Nitrate monitoring helps prevent over fertilization and keep nutrient balance for plants
- This uses an ion selectrive electrode(ISE) which detects nitrate ions in the soil.
- Specifications:
  - Range: 0 – 1000 mg/L
  - Output Type: Analog/Serial.
  - Features: High accuracy and stable readings even in varying soil conditions

C. Soil Moisture Sensor

- It Measures the water content in soil.
- It helps to determine irrigation requirements and it supports better microbial activity.
- It works on principle of capacitance which changes in soil dielectric constant due to moisture affect the output voltage.
- Specifications:
  - Operating Voltage: 3.3 – 5V
  - Output: Analog signal
  - Advantages: Corrosion-resistant and long lifespan compared to resistive sensors.

D. Temperature Sensor

- It monitors soil temperature.
- The temperature of the soil directly determines how active microbes are, how nutrients are released, and how well seeds can germinate.
- It converts temperature into a digital signal using an internal thermistor.
- Specifications:
  - Range: –40°C to +80°C
  - Accuracy: ±0.5°C
  - Features: Low power consumption and high reliability

E. pH sensor

- It measures soil acidity or alkalinity.

- The soil's pH level directly controls which types of microbes can thrive, and it dictates how much food i.e nutrients are available to the crops.
- It uses a glass electrode that generates voltage depending on hydrogen ion concentration.
- Specifications:
  - Range: 3.0 – 10.0 pH
  - Accuracy: ±0.1 pH
  - Features: Waterproof probe suitable for direct soil testing

IV. Architecture

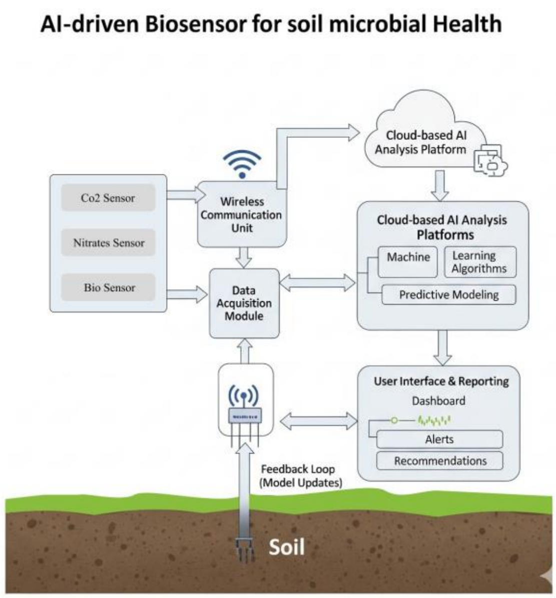

Fig. 1. System Architecture of AI-driven Biosensor for Soil Microbial Health.

The system consists of multiple soil-The design for the Micro-Sense AI system can be found in Fig. 1. It incorporates multiple embedded soil sensors: CO2, nitrate, moisture, temperature, and pH sensors, all linked to a data acquisition unit. These sensors capture and record soil data, which they send to a soil AI analysis system in the cloud, using a wireless communication unit (ESP32).

The cloud system utilizes machine learning to analyze the sensor data in conjunction with real-time scoring to generate a Soil Biological Health Score (SBHS). This score reflects the level microbial and active soil fertility. The system is designed to be user-friendly, presenting results on a dashboard with soil health indicators, alerts, recommendations, and advice on specific crops or fertilizers. The AI model's predictions and recommendations are designed to improve with use.

Dynamics of CO2 and Nitrate in Soil.

- Microbial Respiration: Soil microbes, which include bacteria and fungi, decompose organic matter. CO2 is released as a byproduct of decomposition. Soil active and healthy soil with high microbial activity will have greater CO2 evolution.
- Soil Temperature and Moisture: Microbial metabolism is accelerated with warm, moist soils, and so is the release of CO2 and nitrate mineralization. These processes are slowed down in extremely dry or waterlogged soils.
- Organic Matter Content: More organic matter provides abundant carbon sources for microbes, enhancing respiration and CO2 emission.
- Aeration: Sufficient levels of soil oxygen foster the activity of aerobic microbes that efficiently convert organic nitrogen to nitrate. Poorly aerated soils produce denitrifying microbes and worse loss of soil-borne nitrate.
- Fertilizer Application: Application of nitrogen fertilizers is profit motivated. Suppression of the microbial balance becomes a concern that needs managing.
- pH Levels: Optimal soil pH for microbial activity is neutral to slightly acidic soils which promotes the balanced release of soil CO2 and nitrate.

All the indicators mentioned above are constantly monitored by the Micro-Sense AI system to evaluate the soil health in biological and chemical conservation. Intelligent feedback promotes economically wise decisions for farmers, reduces unbalanced microbial activity, and supports sustainable agriculture.

V. Conclusion

Micro-Sense AI System is a precision Agrology classifying soil microbial health. With the help of biosensors, IoT, and AI, the Micro-Sense AI System monitors soil microbial health. It monitors soil health parameters by CO, nitrates, moisture, temp, pH and real insights on soil biology and fertility. This allows farmers to make evidence based decisions on the quantity of fertilizers to be used, the crop to be planted, eliminate wastage, and improve productivity in a timely manner. Micro-sense AI can assess soils continuously and instantaneously compared to traditional soil testing which provides no instant feedback. The Simple to use farmer interface provides instant feedback. Micro-Sense AI, a solar powered device, is safe for the environment and promotes eco-friendly farming. It is a device to help farmers sustain soil for the long term.

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