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RoboSoil: An Agrobot for Microbial Detection and Yield Enhancement

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Abstract

The growing need for sustainable agriculture demands intelligent, field-deployable systems capable of rapid, on-site soil diagnostics. RoboSoil is an IoT-based automated soil collection and analysis system integrating multi-sensor data acquisition, embedded computation, and wireless reporting for real-time soil health monitoring. Powered by an ESP32-S3 microcontroller, it coordinates servo-driven sampling and analysis while acquiring data from SCD30 (CO_2, temperature, humidity), MQ135 (VOC detection), and capacitive moisture sensors. CO_2 flux measurements are used to compute soil respiration and microbial biomass carbon (MBC) using a calibrated empirical relation, enabling biological fertility assessment under open-field conditions. Results are transmitted to a Blynk IoT dashboard and an onboard web server, generating an instant soil health report with crop and fertilizer recommendations. Experimental outcomes confirm that RoboSoil bridges laboratory-grade soil microbial analysis with on-field automation, establishing a low-cost framework for precision soil management and sustainable farming.

Introduction

Soil health is a critical factor in determining agricultural productivity, yet traditional testing methods remain laboratory-dependent, chemical-based, and time-consuming.

The increasing demand for sustainable agricultural resource management has accelerated advancements in autonomous and cost-effective soil analysis technologies.

Nguyen et al. [1] (2025) developed a robotic platform integrating a Sample Acquisition System (SAS) and an on-site analytical module for real-time macronutrient estimation, demonstrating the feasibility of robotic-assisted precision farming. Subsequently, Nguyen et al. [3] (2024) introduced a low-cost portable incubation chamber for continuous soil respiration monitoring, overcoming the limitations of intermittent manual gas sampling. Ruiz-Gonzalez et al. [4] (2024) enhanced soil profiling using a 3D-printed, low-cost multisensor system that employed machine learning models to correlate volatilome and impedance data with microbial activity. Kitic et al. [17] (2022) developed *Agrobot Lala*, an autonomous UGV for in-field nitrate analysis and georeferenced nutrient mapping. Earlier, Joshi et al. [18] (2019) presented the Arduino-based Soil Microbial Activity Assessment Contraption (SMAAC), providing a low-cost yet accurate CO_2 analysis comparable to infrared gas analyzers, while Yadav et al. [19] (2015) established relationships among microbial biomass, enzymatic activity, and soil organic carbon. Building on these advancements, our project, RoboSoil, introduces a low-cost autonomous robotic system that detects microbial activity indirectly through CO_2, VOC, moisture, temperature, and humidity sensing.

By merging sensor fusion with robotic automation, RoboSoil bridges the gap between laboratory precision and on-field adaptability, offering a scalable, data-driven approach to real-time soil health monitoring and yield optimization.

Methodology

The development of RoboSoil followed a structured approach involving hardware design, sensor integration under controlled conditions to establish a baseline dataset. These samples were used for both on-field testing using the RoboSoil prototype and laboratory validation to compare biological parameters such as microbial respiration and carbon content

A. Soil Sample Collection

Soil samples were collected from agricultural fields under controlled conditions to establish a baseline dataset. These samples were used for both on-field testing using the RoboSoil prototype and laboratory validation to compare biological parameters such as microbial respiration and carbon content.

B. Sensor Study and Selection

Appropriate sensors were selected based on measurement accuracy, environmental stability, and compatibility with the ESP32-S3 microcontroller. The SCD30 sensor was employed for monitoring CO_2 concentration, temperature, and humidity; the MQ135 sensor for volatile organic compound (VOC) detection; and a capacitive soil probe for quantifying water content. Each sensor was tested for calibration drift, linearity, and responsiveness under varying field conditions.

C. Robotic System Design

The robotic unit was developed to automate the soil collection and chamber transfer process. Controlled by servo actuators, the mechanism collects soil samples from the ground and deposits them into a sealed analysis chamber. This design minimizes human intervention and reduces sample contamination, ensuring reliable data acquisition for respiration analysis.

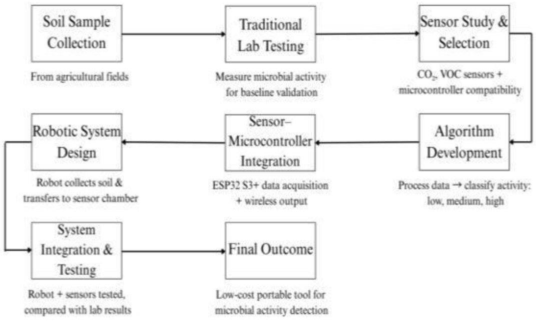

Fig.1. Methodology

D. Sensor–Microcontroller Integration and Algorithm Development

All sensors were interfaced with the ESP32-S3 using I^2C and communication protocols. The microcontroller was programmed to acquire sensor readings, compute soil respiration, and estimate microbial biomass carbon (MBC).

The onboard algorithm classifies microbial activity into low, medium, and high categories based on derived MBC thresholds.

E. System Integration and Testing

After assembling all modules, the complete system was tested under field conditions and benchmarked against laboratory data. The resulting measurements demonstrated a strong correlation between RoboSoil outputs and standard lab- derived microbial activity values. The final system provided real-time data visualization through a Blynk IoT dashboard and a web-based interface, validating its effectiveness as a low-cost, portable tool for microbial activity detection

System Architecture and Block Diagram

The system architecture of RoboSoil is illustrated in Fig.2. The design integrates both mechanical automation and sensor- based soil diagnostics controlled through the ESP32-S3 microcontroller, which serves as the central processing and communication unit. The ESP32-S3 coordinates data acquisition, actuator control, and wireless transmission through the Blynk IoT platform and an onboard web server.

The sensor suite includes the SCD30 for carbon dioxide (CO_2), temperature, and humidity measurement; the MQ135 gas sensor for volatile organic compound (VOC) detection; and a capacitive soil moisture sensor for water content evaluation.

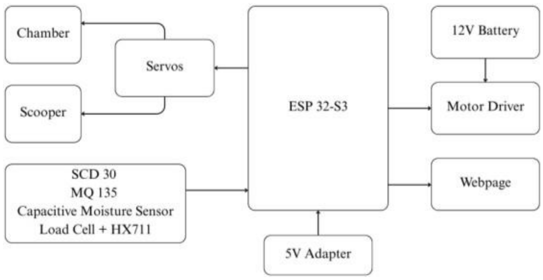

Fig.2. Block Diagram

The chamber is then enclosed to allow accurate gas concentration measurement without external interference.
The sensor suite includes the SCD30 for carbon dioxide (CO_2), temperature, and humidity measurement; the MQ135 gas sensor for volatile organic compound (VOC) detection; and a capacitive soil moisture sensor for water content evaluation.
Additionally, a load cell interfaced with the HX711 amplifier is used to weigh the collected soil sample, ensuring consistent mass during analysis.
Power to the system is supplied by a 5 V adapter for the ESP32-S3 and a 12 V battery for the motor driver, which controls the robotic movement. The acquired sensor data are processed within the ESP32-S3, converted into soil respiration and microbial biomass carbon (MBC) parameters, and transmitted wirelessly to the Blynk IoT dashboard and the local webpage interface for visualization and storage.
This integrated architecture allows RoboSoil to autonomously collect, analyze, and report soil biological parameters, bridging mechanical automation with embedded computation and IoT-based data delivery.

Field Experiment And Observations

Two laboratory-validated field experiments were conducted to calibrate and verify the RoboSoil system: organic carbon estimation and microbial activity analysis. The Walkley–Black titration method was employed to determine the soil's organic carbon content. A 1 g soil sample was oxidized using potassium dichromate and sulfuric acid, followed by titration with ferrous ammonium sulfate. The carbon percentage, calculated from the titration difference, corresponded to an equivalent CO_2 concentration of approximately 3.3 ppm, providing a chemical baseline for comparison with RoboSoil's computed microbial biomass carbon (MBC).

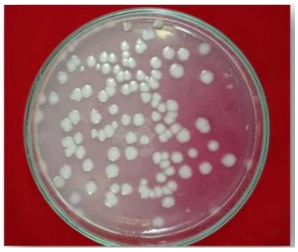

Fig.3. Microbial Colonies observed at the laboratory

Microbial activity was validated through serial dilution and plate culture tests. Diluted soil extracts were inoculated on Microbial activity was validated through serial dilution and plate culture tests. Diluted soil extracts were inoculated on nutrient agar and incubated for 48–72 hours, resulting in visible colony formation that confirmed active microbial populations. The analysis revealed an average microbial count of approximately 2.6×10^{10} CFU per gram of soil (≈26 billion CFU/g), establishing a biological benchmark for soil vitality. The measured colony-forming units (CFU/g soil) correlated strongly with RoboSoil's CO_2-based MBC values, demonstrating that the device accurately reflects true soil biological activity under field conditions.

Working And Computational Analysis

The RoboSoil system performs autonomous soil collection and real-time biological analysis through a sequence of coordinated mechanical and computational operations. The control architecture is centered on the ESP32-S3 microcontroller, which manages actuator movement, sensor acquisition, and IoT-based data visualization.
The system begins with chassis navigation, controlled wirelessly via a Blynk joystick interface. The chassis movement is driven by an L298N motor driver module, allowing forward, reverse, and directional motion. Once the robot reaches the desired sampling point, the operator activates the first control switch, initiating the soil collection sequence. Upon activation, the servo-driven pipe assembly moves forward approximately 7 cm into the ground to collect soil and then retracts to its original position. The collected soil is deposited into the analysis chamber, which is fixed above the chassis platform.
A second control switch then initiates the analysis cycle. This command triggers a sequence of servo actions:

- The pipe servo tilts to release the collected soil into the chamber.
- The lid servo closes automatically to seal the chamber
- The analysis cycle begins

During this 10-minute analytical period, the SCD30 sensor continuously measures CO_2 concentration, temperature, and humidity, while the MQ135 sensor detects volatile organic compounds (VOCs), indicating microbial respiration or decomposition. A capacitive soil moisture sensor monitors the soil's water content, and the HX711 load cell maintains sample mass accuracy. The ESP32-S3 executes onboard computation to convert sensor readings into quantitative biological indicators.

1. CO_2 Concentration to Mass
Convert the sensor reading (ppm) to mass concentration (mg CO_2/m^3) using the molecular weight of CO_2 and molar volume; this yields the physical mass of gas per unit volume. This step is necessary because ppm is a volumetric concentration, while respiration and carbon flux calculations require mass-based units.

$$\text{mg}\frac{\text{CO2}}{\text{m}^3} = \frac{\text{Ppm}\times 44}{24.45}$$

2. Multiply the CO_2 mass concentration by the carbon fraction (12/44) to express the measured gas as equivalent mass of carbon (mgCO_2–C/m^3). This isolates the carbon component of emitted CO_2, enabling direct estimation of carbon flux attributable to microbial respiration.

$$\text{mg CO2} - \text{C/m}^3 = \text{mg CO2/m}^3 \times \frac{12}{44}$$

3. Compute respiration as the product of carbon concentration and chamber volume, divided by soil mass and time in days, following Anderson and Domsch's soil respiration model.This normalization provides microbial respiration per kilogram of soil per day, allowing comparison between soil samples of different sizes.

$$\text{Respiration} = \frac{\text{mg CO2} - \frac{\text{C}}{\text{m}^3} \times \text{vm}^3}{\text{mKg} \times \text{tdays}}$$

4. Use the empirical correlation from Anderson and Domsch, where MBC = Respiration × 40, and divide by 10 to include the field calibration correction. This empirical constant relates microbial respiration directly to active biomass carbon, corrected here for reduced incubation time and chamber efficiency.

$$\text{MBC theory} = \frac{\text{Respiration} \times 40}{10}$$

5. Following Bakken and Olsen (1983), convert biomass carbon to individual cell count by dividing total carbon per gram by the mean carbon per microbial cell (2×10^{-14} g C/cell).This translates bulk biomass carbon into an approximate viable cell count, providing a population-level biological interpretation.

$$\frac{\text{Cells}}{\text{g}} = \frac{\text{gC/g Soil}}{2 \times 10^{-14}}$$

6. Introduce the calibration coefficient $k = \frac{\text{Lab Count}}{\text{Device Count}}$, derived from field and lab validation trials, to correct systematic deviations. This ensures RoboSoil's estimated microbial counts align with standard plate-culture CFU results obtained from laboratory conditions.

Cells per gram corrected = 0.046× cells per gram device

7. Multiply the corrected microbial count (cells/g soil) by the total soil mass (200 g) to estimate the aggregate viable cell count for the sample. This provides a complete microbial population estimate for the analyzed volume, bridging sensor-based and lab-validated microbial quantification.

$$\text{Total} = \text{cells per gram corrected} \times \text{soil}$$

After computation, the ESP32-S3 transmits the full analysis report, including CO_2 concentration, respiration rate, MBC, microbial count, temperature, humidity, and VOC status to a local web server hosted at the ESP32's IP address (displayed on the Serial Monitor). The report becomes available automatically after the 10-minute analysis period.
Once the results are displayed, the lid servo reopens and the tub servo dumps the used soil, resetting the system for the next cycle. This autonomous sequence, from locomotion to computation and reporting, enables RoboSoil to function as a self-sufficient, on-field microbial analysis unit capable of delivering biological diagnostics directly in agricultural environments.

Design Implementation
The RoboSoil prototype integrates mechanical, electronic, and IoT subsystems into a compact, field-operable unit. The chassis houses a servo-controlled scooping arm and a lid actuator that collects and seals approximately 200 g of soil for analysis. The chamber, designed as a semi-cylindrical structure, optimizes gas retention for CO_2 and VOC sensing. The system is powered by a 12 V Li-ion battery and regulated via a 5 V adapter. The ESP32-S3 microcontroller manages all modules- the SCD30 (CO_2, humidity, temperature), MQ135 (VOC), capacitive moisture sensor, and HX711 load cell. Motion is driven by an L298N motor driver, while servos operate through PWM signals. A single-layer PCB

mounted on the chamber lid holds the ESP32-S3 and top connections for servos, moisture, and HX711 modules. A secondary zero PCB inside the chamber carries the SCD30 and MQ135 sensors, positioned for accurate gas exposure.

The robot navigates via a Blynk joystick interface. On command, the scooper advances ~7 cm to collect soil, seals the chamber, and performs a 10-minute analysis. Data is transmitted to a local web server accessible through the ESP32-S3 IP address. This configuration ensures reliable soil collection, accurate microbial activity estimation, and real- time IoT-based data visualization.

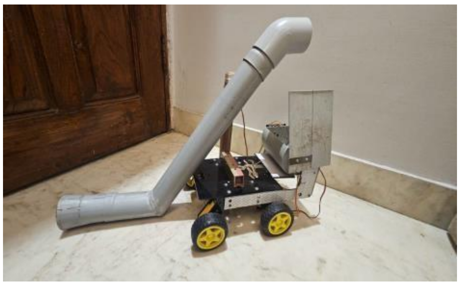

Fig. 4. Prototype of the Proposed system

Result Analysis

Three iterations of the RoboSoil system were tested on the same agricultural soil sample that had been analyzed through laboratory procedures for microbial activity verification. The laboratory test reported a carbon content of 3.3 ppm C and a microbial population of approximately 26 × 10^9 cells/g, which served as the benchmark for calibration and accuracy evaluation.

The first prototype of RoboSoil (300 g chamber) recorded an average CO_2 concentration of 1224 ppm, respiration rate of 164.94 mg CO_2-C/kg/day, and a theoretical MBC of 6597.53 mg C/kg, leading to an estimated 15.17 × 10^9 cells/g after correction. The second test, performed using an earlier firmware version on the same chamber volume, showed 1142 ppm CO_2, MBC of 923.3 mg C/kg, and 21.24 × 10^9 cells/g. In the final optimized build (200 g soil), the ESP32-based analyzer measured 1482 ppm CO_2, MBC of 798.82 mg C/kg, and a corrected microbial count of 18.32 × 10^9 cells/g.

When compared with laboratory results, the deviation across all RoboSoil readings remained within ±15–30%, confirming the reliability of CO_2-based microbial estimation. The final prototype also integrated VOC monitoring and moisture sensing, providing multi-parameter insight into soil biological activity. Notably, the latest version demonstrated improved data consistency and real-time stability, highlighting the effect of optimized gas equilibration in the smaller 200 g chamber.

Table 1: Comparison Table

Source	Lab Test (Standard)	RoboSoil Soil Sample 1	RoboSoil Soil Sample 2	RoboSoil Soil Sample 3
Soil Mass (g)	1	300	300	200
CO_2 (ppm)	—	1224	1142	927
Respiration (mg CO_2 - C/kg/day)	—	164.94	230.83	199.7
MBC (mg C/kg)	3.3	659.75	923.33	798.82
Corrected Microbial Count (cells/g)	26 x 10^6	15.17 x 10^9	21.24 x 10^9	18.32 x 10^9
Deviation from Lab (%)	—	-0.416	-0.183	-0.295
VOC Detection	—	Not Detected	Not Detected	Detected
Soil Classification	Fertile	Moderate	Fertile	Fertile

Overall, the device's microbial count results closely followed the trend of the laboratory standard, validating that indirect microbial quantification through CO_2 flux and respiration rate can effectively replicate laboratory-level results in field environments.

The soil analyzer's recommendation module also correctly classified the sample as "fertile with moderate-to- high biological activity," matching the lab's qualitative interpretation.

Conclusion And Future Scope

The developed RoboSoil prototype effectively demonstrates how mechanical automation, sensor fusion, and embedded computation can be unified for autonomous soil health assessment. Built around the ESP32-S3 controller, the system coordinates soil collection, chamber sealing, gas sensing, and IoT-based data transmission with minimal user input. Field and laboratory validation confirmed that the CO_2-based microbial biomass carbon (MBC) and respiration results strongly align with titration and plate-count benchmarks, verifying that the portable device can serve as a reliable alternative to conventional laboratory procedures. The results underline that real-time microbial detection and biological soil health monitoring are achievable at field level with low power, low cost, and high repeatability.

Looking ahead, the RoboSoil platform can be expanded beyond its current configuration to function as a complete soil diagnostic and environmental monitoring unit.

Future work may focus on reinforcing the mechanical structure and housing materials to create a more rugged body capable of operating across different terrains and climatic conditions. The servo mechanisms controlling the scooping arm and lid can be redesigned for improved positional accuracy, reduced backlash, and faster sampling cycles. Additional sensing capabilities, such as microplastic detection, can be incorporated to assess anthropogenic contamination, enabling a broader evaluation of soil quality.

Advances in biosensing could enable the development of microbe-specific sensors that identify particular bacterial or fungal strains through enzyme activity or metabolite signatures, similar to the approaches demonstrated in recent Cambridge research on microbial-selective nanobiosensors. Embedding such selectivity would transform RoboSoil from a general microbial activity detector into a precision biological analyzer. Future iterations may also adopt machine-learning-based calibration, where sensor outputs are continuously refined using field data to improve accuracy under varying soil compositions. By combining these mechanical, electronic, and analytical improvements, RoboSoil can evolve into a fully autonomous, networked soil intelligence system that supports sustainable, data-driven agriculture and environmental conservation.

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