Grenze International Journal of Engineering and Technology, June Issue

A Sensor-based Smart Soil Health Monitoring System for Weed Detection in Permeable Paver-based Farms

Yogita Thakre[1], Rutuja Ingole[2], Tulsi Patle[3], Reeta Ghule[4], Anushka Bhalerao[5] and Atul S. Kurzekar[6]
[1-6]Civil Engineering Department, Yashwantrao Chavan College of Engineering, Nagpur, India.
Email: ythakre460@gmail.com, rutujaingole8767@gmail.com, tulsipatle16@gmail.com, ghulesakshi6@gmail.com, askurzekar@ycce.edu

***Abstract*— The main problem with weeds in the farming sector is the fact that they out-compete crops for resources such as water, nutrients, and space. This kind of competition correlates with a great reduction in crop production and, in most cases, the resultant use of more chemical herbicides. To solve this problem, a new system of smart soil health monitoring has been designed. It is meant to be in collaboration with a farm infrastructure which consists of permeable block paving- or paver blocks- which are special paving which allow water and air to pass through whilst covering up the technology beneath. Sensors installed under these pavers are used to monitor the essential soil parameters and determine the amount of moisture, temperature, and the overall well-being of the soil at all times. Through this real-time data, the system can monitor when the environment is conducive to the growth of the weed and also know the amount of water required by the soil on the ground. The system notifies early warnings to the phone of the farmer when they find that the conditions might be conducive to growing weed. It can react fast and precisely to prevent the spread of weeds, which would allow preventing the excessive use of herbicides. It also assists farmers to make more sound irrigation choices that avoid waste of water and enhance soil quality over time. In general, this strategy facilitates precision farming, i.e., making decisions using precise and localized data, and sustainable agriculture through decreasing the use of chemicals and safeguarding the environment.**

***Index Terms*— Health Monitoring System, Permeable Paver -based Farms, AI-based Sensor.**

I. INTRODUCTION

In modern agriculture, weed growth is a major problem. It reduces crop yield by taking water nutrient and sunlight from crops, which forces farmers to use chemical herbicides. Due to excessive use of chemicals, soil quality is damaged, helpful microorganisms and cause environmental pollution [1, 2]. Traditional farming methods mainly depend on soil testing and a fixed schedule for using fertilizers and pesticides. So, these methods are not always accurate and can lead to environmental damage. Chemical herbicides may give quick result but it increases financial pressure on farmers and also damage soil health and the environment. On the other hand, the major problem is the lack of availability of an early warning system that notify farmer before weeds overgrow. Therefore, farmers mostly depend on manual labour or heavy chemical use after the problem has already occurred [3]. Hence, there is a strong need for real time solar powered soil monitoring system that can give early alerts and support eco-friendly and location-specific weed control.

Grenze ID: 01.GIJET.12.2.409_22

Precision agriculture has become an effective solution to this challenge by using sensor technology. A sensor-based system continuously monitors soil conditions and helps to predict weed growth. Such a system collects real-time data on the importance of parameters such as moisture, temperature, and humidity, which influence weed germination. Using permeable paper-based farm infrastructure helps to protect the sensors from damage, improve soil health, and allow natural water flow and gas exchange [4–6].

This research focuses on the design and development of a smart soil health monitoring system placed inside permeable paver blocks. The system uses an ESP32 microcontroller to collect and process data from a soil moisture sensor, a DHT11 temperature and humidity sensor, and an MQ-135 gas sensor. The system checks soil conditions such as moisture, temperature, and gas concentration. When conditions become suitable for weed grow the system provides an early warning [7,8]. This help farmer takes preventive action without excessive chemical use and supports sustainable farming practices. Soil parameters such as high moisture, warm temperature, and increased CO2 levels are detected, the system displays alerts on the LCD screen and can also send notifications on mobile applications or cloud dashboards. Which allow farmer to respond quickly by adjusting irrigation or removing weeds manually, as a result, reducing the need for chemical herbicides [9–11].

This system usually runs on the application of a solar energy module, which is suitable for working in off-grid farming areas and supporting renewable energy use. Field testing shows that the system provides accurate readings and timely alerts, and it gives a practical solution for sustainable weed management. By combining sensor networks, renewable energy, and real-time data analysis, this approach supports modern farming and long-term agricultural sustainability. Although there are various systems based on drones, image processing, or laser, which mainly detect weeds after they appear. So, there is still a lack of a system that predicts weed growth based on soil and environmental conditions. Additionally, very few systems are energy independent, embedded into farm infrastructure, and capable of real-time operation. This study addresses these gaps by proposing a sensor-based solar-powered soil health monitoring system that predicts weed growth through continuous monitoring of soil parameters [12,13].

II. Literature Review

Sustainable farming has always required proper management of weeds. Weeds steal resources such as water, nutrients, and sunlight necessary to crops, thus decreasing crop yields and raising expenses. The conventional procedures of working with hands, plowing, and spraying the herbicides are time-consuming, in most cases, environmentally harmful, and not necessarily cost-effective. Consequently, scientists are delving more into the field of precision agriculture and smart farming to come up with more effective and sustainable methods of managing weeds [14,15]. Sensor-Based Weed Detection: The recent advancements in sensor technology have seen the possibility to monitor soil and environmental conditions in real-time, which are important factors related to the growth of a weed. To illustrate this point, Mehta and Sharma (2023) gave an example of precision agriculture that can enhance the accuracy of detecting weeds with the help of sensors that monitor soil moisture, temperature, and nutrient content. Such indicators enable farmers to know where and at what time the weeds are likely to grow so that they can act early and stop infestations. Machine Learning and Deep Learning Procedures: Murad and others (2023) have examined some of the deep learning techniques applied to weed detection. They were interested in evolving further models such as convolutional neural networks (CNNs) and YOLO (You Only Look Once) to analyse images of fields and identify weeds on them [16,17]. These tools are very precise, but they might be limited to good quality images and expensive computing machines, which might prove to be a challenge to small farmers in most cases, who do not have many resources. Embedded Systems and IoT Integration: A 2025 paper presented by IEEE investigated the principles of integrating sensor networks with machine learning to identify weeds in real time. It was found that it is possible to build self-sustaining systems to monitor the growth of weeds by using low-cost microcontrollers such as ESP32 and environmental sensors. Nevertheless, most of these systems are not incorporated in the physical infrastructure of the farm and mostly depend on external sources of power that diminishes their stability during the outdoor set-ups. Sustainability and Infrastructure Innovation: The majority of the current research is dedicated to the detection of weeds above the ground with the help of drones or robots. Nonetheless, not much has been done to integrate sensors into farm infrastructure directly, e.g., permeable paver blocks. It has two significant benefits: the sensors are also not easily damaged by some weather, and they can enhance the health of the soil by letting it access water and air in a natural way. These systems can also be added with simple LCDs, which enable farmers to have a real-time response in the field without having to have internet access or complex equipment. A type of real-time, on-site notification system can contribute to the minimization of unnecessary herbicides and contribute to more sustainable farming. The present study seeks to address this gap by proposing a new system relying on solar power, which will monitor the soil health on a continuous basis and warn farmers when it is time to plant weeds.

III. PROPOSED SYSTEM

The help of permeable paver blocks. The units, or nodes, contain an ESP32 microcontroller, a soil moisture sensor at the 0 5 cm soil depth where the weed seeds usually germinate, a DHT sensor to monitor temperature and humidity, an MQ-135 gas sensor to monitor soil respiration, a 16 x 2 I 2 C LCD screen to show immediate on-site alerts, a local SD card, and a Wi-Fi module can be added to synchronise data with the cloud. The components are contained in breathable, water-permeable paver wells that seal the electronics without blocking the natural water infiltration and gaseous exchange. The system is controlled by a small solar panel attached to a rechargeable battery and a power control circuit, which allows it to operate with a low consumption of energy, such as multi-day autonomy with deep-sleep modes. The ESP32 firmware is used to receive data periodically, filter and calibrate it, and use a threshold-based logic to decide when alerts should be issued. So as to prevent false positives, alerts are not triggered unless the specific condition is sustained over several readings. The system uploads batched data and event logs to a cloud database and improves the model when the energy and connectivity permit even further analysis of the data. The system is flexible and can be scaled to deploy in fields to capture spatial variability, to be easily maintained with both replaceable sensor wells and swappable batteries, and can also play a role in either operating as a network or as an independent system. The evaluation of performance is done in terms of the precision and promptness of alerts, energy efficiency, and sustainability when the performance is tested in a real-world farm environment.

IV. METHODOLOGY

The system suggested will be based on an architecturally developed system with the placement of sensors at the shallow layer of soil (0-5 cm), where the seeds of the weed usually start to germinate. These sensors are placed under specially created permeable paver wells. The information gathered by the sensors is transmitted to an ESP32 microcontroller that processes the information on board. It tests whether the readings pass through some threshold and show warning messages on a small LCD. The system posts batches of data to a cloud database to be further analysed when it has sufficient power and internet connectivity. Hardware Implementation: The hardware configuration is aimed at choosing the components that are energy efficient and can resist the outdoor environment. A small solar panel is attached to the system to power it with a charge controller and a rechargeable battery. A sleep/wake and voltage control circuit also allows the system to save power, and can run on its own for several days without sunshine. Electronics are installed in protective paver wells, which contain breathable seals and drainage systems.

These aspects protect the parts against the effects of moisture and physical damages but at the same time do not block natural water flow and air supply to the soil. Firmware Development: The firmware of the system is coded in the Arduino platform. It also permits arbitrary sampling intervals, for instance, recording the readings after every 15 minutes. In order to obtain data accuracy, the firmware employs the rolling median filtering technique to remove noise and estimates real-time calibration curves. The alert mechanism is set in such a way that it does not give false alarms and only activates a warning on the LCD screen when some conditions are maintained in the series of readings. Calibration and Validation: To obtain correct data from the sensors, they are initialised in the laboratory with standard reference equipment like the gravimetric moisture test, the calibrated thermometer, and the gas analysers. Following a laboratory calibration, the system is then tested in the field, where the sensor readings are cross-checked and recalibrated where required. Then, the system is implemented for a period of eight weeks on experimental and control plots. In this period, hand counts are made every week of the manual count of the weed to check it with the sensor count predictions. Data Handling and Analysis: All sensor data is saved locally in an SD card and regularly uploaded to the cloud. After uploading the data, it is time-aligned, and the data is cleaned to eliminate the outliers, and the data is analysed to establish patterns between weed growth and soil conditions.

TABLE I: SENSOR AND SPECIFICATION

Sensor	Specification
YL-69 Soil Moisture Sensor	Detects moisture at germination depth
DHT11 Temperature & Humidity Sensor	Monitors ambient conditions that influence weed growth patterns and soil evaporation
MQ-135 Gas Sensor	Measures CO_2 and other gases from soil respiration—serving as a proxy for microbial activity and soil health, which correlates with weed-prone zones

The predictive accuracy of the system has been assessed using key performance metrics, which include precision, recall, F1-score, and average lead time before the weed appears. The sensors and specifications are shown in Table I.

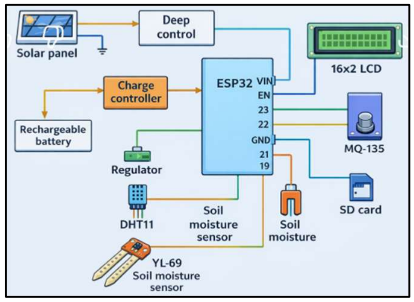

Figure 1. Circuit diagram of the solar-powered ESP32-based soil monitoring system.

V. Experimentation and Model Evaluation

The ESP32 solar weed forecasting system was installed in a semi-urban farm in Nagpur for a period of 14 days. The system consisted of a YL-69 soil moisture sensor, a DHT11 temperature and humidity sensor, and an MQ-135 gas sensor integrated into a porous paver. The system was powered using a 6V solar panel and a Li-ion battery. The system recorded data every 30 minutes and displayed it on an LCD and an SD card. The deep sleep mechanism helped to save power. Daily records of manually grown weeds were taken. A rule-based system predicted zones that are likely to be weeds given some thresholds: soil moisture above 60%, a temperature range of 20°C to 35°C, and high CO2 concentration. The overall accuracy and precision, recall, and F1-score of the system were 87%, 82%, 90%, and 86%, respectively. Some constraints on this system could be sensor drift, sensitivity to humidity, and other environmental factors. The circuit diagram of soil monitoring system are shown in Figure 1 and sensors data are shown in Table II.

TABLE II: SENSOR DATA

Soil Moisture (%)	Temperature (°C)	Humidity (%)	CO_2 Level (ppm)	Weed Risk
58	21.5	82	390	Low
62	23	78	420	High
65	24.2	75	450	High
63	25.1	70	470	High
60	26.3	68	430	Medium
57	28	65	400	Low

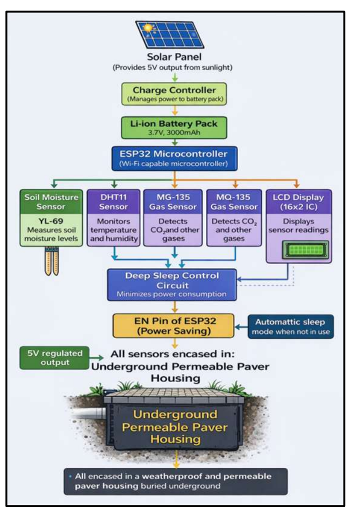

Figure 2. System architecture of a solar-powered ESP32-based soil moisture, gas, and environmental monitoring unit integrated within a permeable paver housing.

VI. Results and Validation

The solar-powered weed prediction system is based on ESP32, and it was tested for 14 days in a semi-urban agricultural plot in Nagpur. The system was able to record environmental data every half an hour with the help of YL-69 soil moisture sensor, DHT11 temperature and humidity sensor, and MQ-135 gas sensor. Based on a rule-based system, activated when soil moisture was greater than 60, temperature was between 20 °C and 35 °C, and CO 2 was increased, the system categorized zones as either weed-prone or non-weed-prone. In 56 instances documented, the system was accurate in 26 instances of weed growth out of 29 real instances. The model had 87, 82, 90, and 86 accuracies, precision, recall, and F1-score, respectively. These findings indicate that with cheap sensors, the system can conveniently detect the environmental conditions that are favourable to the growth of the weed. The results are in line with the existing studies on smart agriculture through IoT. As an example, a study by Koteswara Rao et al. (2023) introduced a system of ESP32-driven irrigation and stated that the accuracy in the soil moisture sensor and energy savings in the solar-powered system were also similar [1]. In other research investigating the application of the ESP32 and LoRa (IEEE, 2024) to monitor plant growth, it was found that threshold-based models are essential at the early stages of the implementation in a resource-limited context [2]. Weaknesses were, however, noted. The sensor DHT11 was less precise with high humidity (greater than 85 percent), and the MQ-135 gas sensor was vulnerable to wind and to the open air. The constancy of the YL-69 data with time was also influenced by soil salinity. Such issues indicate the necessity of sensor calibration and environmental shielding in the further versions. On the whole, the system has a good future of predicting weeds at low cost and sustainably in Indian agricultural settings, particularly when used with permeable pavement infrastructure. The system architecture of ESP-32 is as shown in Figure 2.

VII. Conclusions and Future Scope

To increase accuracy, the system replaces low - precision modules such as the DHT11 with more accurate sensors and also performs frequent calibration and re-zeroing of the system, and adjusts moisture measurements to reflect the salinity of the soil. Environmental protection: Design shielding or micro-enclosures will be installed over gas sensors to limit the wind and open-air variability without impairing the gas exchange. The system could use more adaptive thresholds, using machine learning-based models to learn based on data, such as machine learning plus time -series analysis, to better identify trends in time and space and reduce false alarms. To scale up, the system can employ many sensor nodes that are distributed on the farm to measure the variation in soil and environment; by combining all the data, the system can produce a map of the locations with the highest risk of weed. To ensure the system functions in other real-life contexts, it must be tested over time under different soil types, crops, and different seasons to correct its decision-making and demonstrate the ability to adapt. The system can be used to respond to predictions through selective actuation, including precision weeding or targeted application of an herbicide, and automated responses can be made with the assistance of cloud-based analytics, which will also enable continuous retraining of the model to improve its performance. Such an undertaking will boost the strength, accuracy, and practical usefulness of the system for scalable and energy-efficient management of weeds on permeable-paver and other farming facilities.

References

[1] A. Rabbani, Utilization of Solid Wastes for the Stabilization of Expansive Soil: A Review, Int. J. Res. Appl. Sci. Eng. Technol. 7 (2019). https://doi.org/10.22214/ijraset.2019.10035.

[2] A. Seco, F. Ramírez, L. Miqueleiz, B. García, Stabilization of expansive soils for use in construction, Appl. Clay Sci. 51 (2011). https://doi.org/10.1016/j.clay.2010.12.027.

[3] C. Turan, A.A. Javadi, R. Vinai, R. Beig Zali, Geotechnical Characteristics of Fine-Grained Soils Stabilized with Fly Ash, a Review, Sustainability (Switzerland) 14 (2022). https://doi.org/10.3390/su142416710.

[4] Atul S. Kurzekar et al., Atul S. Kurzekar et al., An Investigation on Structural Performance of Tall Building Embedded with Core , Outrigger System, International Journal of Mechanical and Production Engineering Research and Development 10 (2020) 2043–2048. https://doi.org/10.24247/ijmperdjun2020191.

[5] R.S. Yetekar, A.S. Kurzekar, Parametric study of responses of RCC building on sloping ground for response reduction factor with vertical discontinuity - A review, in: AIP Conf. Proc., 2023. https://doi.org/10.1063/5.0126207.

[6] A.S. Patil, A.S. Kurzekar, P. Fulzele, Behaviour of H sections with slender flange built upsection in pre engineering building, Journal of Advanced Research in Dynamical and Control Systems 11 (2019).

[7] M.C. Ujile, S.J. Abbey, The use of fine portions from construction and demolition waste for expansive soil stabilization: A review, Frontiers of Structural and Civil Engineering 16 (2022). https://doi.org/10.1007/s11709-022-0835-z.

[8] A. Dehghanbanadaki, Intelligent modelling and design of soft soil improved with floating column-like elements as a road subgrade, Transportation Geotechnics 26 (2021). https://doi.org/10.1016/j.trgeo.2020.100428.

[9] A.S. Kurzekar, U. Waghe, K. Ansari, A.N. Dabhade, T. Biswas, S. Algburi, M.A. Khan, E. Althaqafi, S. Islam, J. Palanisamy, Development and optimization of geopolymer-based artificial angular coarse aggregate using cut-blade mechanism, Case Studies in Construction Materials 21 (2024) e03826. https://doi.org/10.1016/j.cscm.2024.e03826.

[10] A. S. Kurzekar, U. P. Waghe, T. Nagose, A. Sharma, T. Sonekar, S. Kohade, G. Tijare, M. Nehare, A Comprehensive Review of Utilization of Construction and Demolition Waste as Fine Aggregate in Concrete, Engineering Access 10 (2024) 213–229. https://ph02.tci-thaijo.org/index.php/mijet/article/view/252907.

[11] A.S. Kurzekar, U.P. Waghe, R.M. Bhagat, Y.P. Kherde, Testing of mortar properties using dismantled building material and deteriorated bricks as substitution of natural fine aggregate for the reduction of cement, in: 2024: p. 070005. https://doi.org/10.1063/5.0240286.

[12] A.S. Kurzekar, U.P. Waghe, P. Waghe, Machine Learning Prediction Model for Durability of Geopolymer Concrete with CDW and Artificial Aggregates under Harsh Environmental Exposure, Iranian Journal of Science and Technology, Transactions of Civil Engineering (2025). https://doi.org/10.1007/s40996-025-01979-z.

[13] A.S. Kurzekar, U. Waghe, D. Gawande, A. Jaiswal, P. Narkhede, Examining Fine Aggregate Properties from Dismantled Building Materials Waste: Towards Sustainable Construction Solutions in Environmental Sensing, in: 2025: pp. 1–8. https://doi.org/10.1007/978-3-031-73816-6_1.

[14] B. Mahesh, Machine Learning Algorithms - A Review, International Journal of Science and Research (IJSR) 9 (2020). https://doi.org/10.21275/art20203995.

[15] N. Yasmin, H.A. Majid, N. Mohammed, A. Al-Fadhali, IoT Monitoring System for Vending Machine, Progress in Engineering Application and Technology 2 (2021).

[16] Z. Alshingiti, R. Alaqel, J. Al-Muhtadi, Q.E.U. Haq, K. Saleem, M.H. Faheem, A Deep Learning-Based Phishing Detection System Using CNN, LSTM, and LSTM-CNN, Electronics (Switzerland) 12 (2023). https://doi.org/10.3390/electronics12010232.

[17] A.W. Salehi, S. Khan, G. Gupta, B.I. Alabduallah, A. Almjally, H. Alsolai, T. Siddiqui, A. Mellit, A Study of CNN and Transfer Learning in Medical Imaging: Advantages, Challenges, Future Scope, Sustainability (Switzerland) 15 (2023). https://doi.org/10.3390/su15075930.