

# Jowar Millet Crop Monitoring and Analysis Robot (JMAR): A Smart Solution for Plant and Soil Health in Jowar Millet Farming

Shlok Thumar<sup>1</sup>, Roohi Banu Pokhali<sup>2,\*</sup>

## Abstract

Farmers cultivating jowar millet (*Sorghum*) face significant challenges in maintaining crop health and optimizing yield due to the limitations of traditional plant disease detection and soil health assessment methods. Visual inspection and indigenous knowledge are labour-intensive, time-consuming, and often inaccurate, while soil monitoring requires specialized equipment that is not always affordable or accessible. These issues hinder timely intervention and can lead to crop losses and soil degradation. To address these challenges, this research proposes the Jowar Monitoring and Analysis Robot (JMAR), an autonomous, real-time system that integrates soil parameter collection, analysis, and plant inspection using advanced yet cost-effective technologies. JMAR is built using commercial off-the-shelf (COTS) components to ensure affordability, modularity, and ease of deployment. It also operates independently of internet connectivity, making it highly suitable for remote agricultural environments. The system is composed of two main components: soil parameter collection nodes and a robotic plant health monitoring node. The soil nodes are equipped with a multi-sensor module to measure essential soil properties such as moisture, pH, temperature, electrical conductivity, and nutrient levels, along with a DHT sensor for monitoring ambient conditions. The robotic plant monitoring unit integrates an ESP32-CAM module and uses a lightweight machine learning model for early detection of plant diseases. Data from both nodes is transmitted wirelessly using LoRa and NRF24L01 RF modules to a remote analysis centre or laboratory. This enables timely and accurate decision-making for farm management. By automating the monitoring process and providing real-time, data-driven insights, JMAR supports precision agriculture, enhances resource efficiency, and promotes sustainability. It empowers farmers with actionable information, helping improve productivity and resilience, especially in small and medium-sized jowar farms operating under resource constraints.

**Keywords:** Jowar (*Sorghum*), Commercially-of-the-Shelf (COTS), sensors, soil parameters, plant health, microcontroller

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## INTRODUCTION

*Sorghum* (Jowar) is a staple crop in semi-arid regions, playing a crucial role in food security, especially in rural India. With 8.49 million hectares dedicated to jowar cultivation in 2022, producing 11.85 million tons, its economic and agricultural significance is undeniable [1]. However, factors such as climate change, soil degradation, and plant diseases pose serious threats to its production [2, 3]. Common diseases like rust, grain mould, anthracnose, downy mildew, and charcoal rot contribute to substantial yield losses. Additionally, soil health issues, including nutrient deficiencies and poor water retention, further reduce

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productivity. Farmers often struggle to detect plant diseases in their early stages, exacerbating crop losses and long-term soil fertility decline [4].

Traditionally, soil health monitoring relies on collecting soil samples from fields and sending them to laboratories for testing [5]. This process is time-consuming, expensive, and impractical for frequent or large-scale assessments, with limitations in sample frequency, risk of contamination during transportation, and restricted access to testing facilities [6]. Recent advancements have introduced portable soil testing kits and IoT-enabled sensors that provide real-time data on soil moisture, nutrient content and pH. However, these standalone technologies often lack integration with plant health monitoring and require external expertise for interpretation, limiting their practicality in everyday farming operations [7].

Similarly, plant health monitoring has traditionally relied on visual inspection by farmers, where symptoms such as leaf discoloration, wilting, and fungal growth are manually identified. However, this method is highly subjective, labour-intensive, and reactive rather than preventive [8]. Modern technologies, such as remote sensing through drones and satellite imaging, have enabled large-scale plant health monitoring. Techniques like the Normalized Difference Vegetation Index (NDVI) facilitate early stress detection [9, 10]. However, these approaches are costly, weather-dependent, and require technical expertise, making them inaccessible to small-scale farmers [11]. While research has explored drone-based NDVI evaluations and satellite imaging for jowar cultivation, these solutions remain expensive and lack the capability for detailed, plant-level disease detection, limiting their widespread adoption [12].

Despite advancements in agricultural technology, existing solutions fail to provide an affordable, real-time, and fully integrated approach tailored to the needs of jowar farmers. Most methods focus separately on either soil health monitoring or plant disease detection, rely on costly laboratory testing, or depend on internet-based cloud processing, making them impractical for widespread use, especially in remote farmlands. The lack of a scalable and farmer-friendly solution hinders real-time decision-making, affecting overall crop productivity.

To address these challenges, this research introduces the Jowar Monitoring and Analysis Robot (JMAR), a cost-effective, autonomous system designed for real-time plant disease detection and soil health monitoring. JMAR offers a comprehensive solution by integrating soil sensors, a DHT sensor for environmental monitoring, and a camera-based machine learning model for plant health assessment. Built using commercial off-the-shelf (COTS) components, JMAR ensures affordability and reliability while operating independently of internet connectivity, making it highly suitable for remote farming conditions. By automating real-time soil and plant health assessment, JMAR eliminates dependency on costly laboratory tests and subjective visual inspections, allowing farmers to make data-driven decisions instantly. With machine learning-based disease identification, real-time sensing, and wireless data transmission, JMAR provides a scalable and practical precision agriculture solution that empowers farmers to mitigate crop losses and enhance yield sustainability.

This study is structured as follows: the next Section presents the proposed JMAR architecture, detailing the components and operational workflow of the system. The Technologies Used are described in the Section next to it, covering the hardware and communication modules integrated into the soil parameter collection node and plant health monitoring node. This is followed by the Section which discusses the Prototype Development, providing insights into the hardware assembly and implementation of both nodes. The Tiny-ML Based Classification Model is introduced in the Section after that, outlining the machine learning approach for plant health assessment. Finally, the Section which concludes the study and suggests future improvements for enhancing precision agriculture in jowar farming.

### PROPOSED JMAR ARCHITECTURE

To overcome the challenges of soil health monitoring and plant disease detection in jowar cultivation, we propose the Jowar Monitoring and Analysis Robot (JMAR), an integrated, autonomous system designed for real-time field assessment. JMAR consists of two primary components: soil parameter collection nodes and a plant health monitoring node, as illustrated in Figure 1. The soil parameter collection nodes continuously monitor critical soil properties and wirelessly transmit the data to the plant health monitoring node via radio communication.

Simultaneously, the plant health monitoring node, mounted on a robotic platform, captures and analyses images of jowar plants to assess their health. The aggregated soil and plant health data are then transmitted to a data analysis centre, laboratory, or farmer’s device for further processing and decision-making, ensuring timely interventions and optimized resource management (Figure 1).

As depicted in Figure 2, the soil parameter collection nodes are strategically deployed across the field, typically at a density of four to five nodes per acre, to provide comprehensive coverage. Each node is equipped with soil sensors [13] and a DHT sensor [14] to measure essential parameters such as moisture, temperature, and nutrient levels. These nodes utilize NRF24L01 RF communication to relay real-time soil data to a central soil health monitoring master node, which acts as a hub for consolidating field-wide soil information (Figure 2) [11].

The plant health monitoring node is a robotic vehicle (car) equipped with a high-resolution camera and onboard storage to capture images of jowar plants at various growth stages.

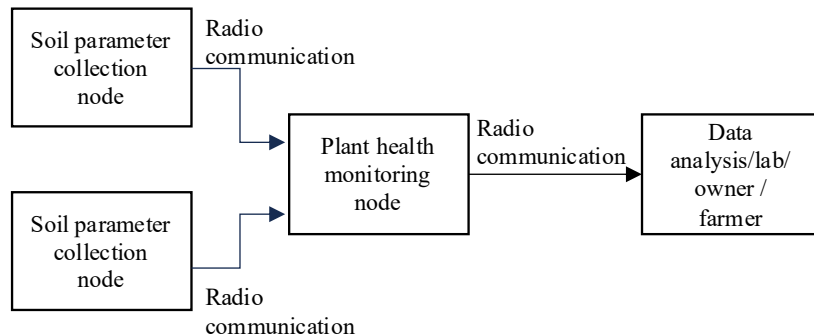


Figure 1. JMAR top level block diagram.

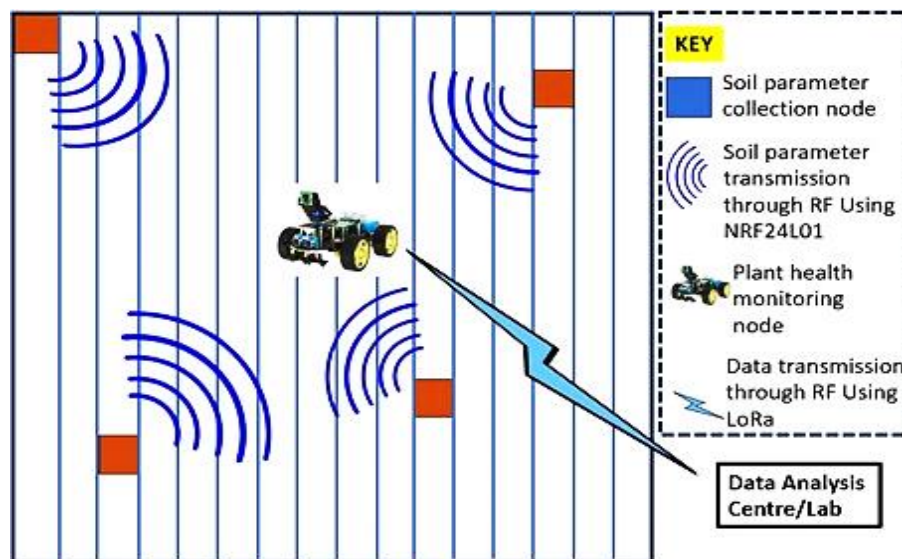


Figure 2. JMAR operational overview.

A GPS module enables autonomous navigation, ensuring systematic field coverage while synchronizing plant image capture with soil parameter data. The collected information, including both soil metrics and plant health status, is transmitted via LoRa-based RF communication to a remote data analysis centre or laboratory for further machine learning-based classification and diagnosis.

By integrating automated soil analysis, plant health monitoring, and wireless data transmission, JMAR provides a cost-effective and scalable solution for precision agriculture. Its affordable, sensor-driven approach eliminates the need for expensive laboratory testing and subjective visual inspections, making advanced agricultural technology accessible to small and medium-scale farmers.

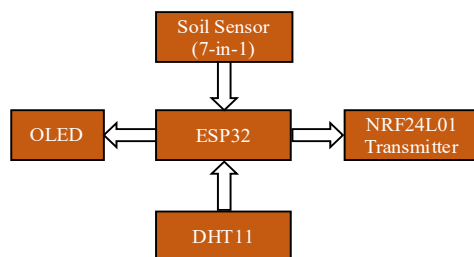
## TECHNOLOGIES USED

The implementation of JMAR relies on a combination of advanced yet cost-effective technologies to ensure seamless integration into agricultural workflows. This section outlines the key hardware and software components employed in the system, emphasizing their roles in enabling real-time soil and plant health monitoring.

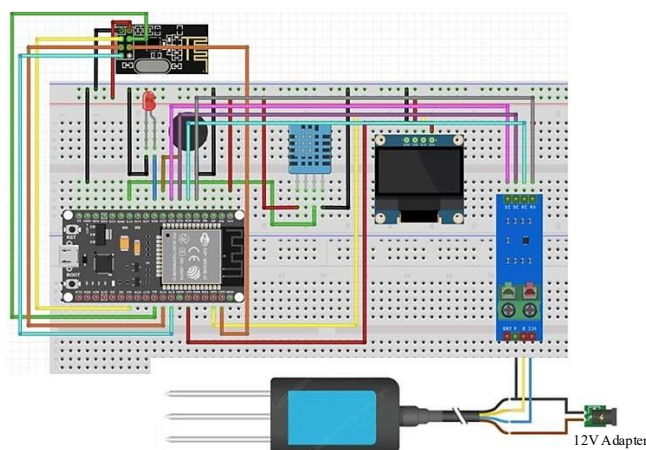
### Soil Parameter Collection Node

The Soil Parameter Collection Node is built using Commercial Off-The-Shelf (COTS) technologies, ensuring affordability and accessibility for farmers. This node is equipped with a 7-in-1 soil sensor that measures moisture content, temperature, pH level, electrical conductivity (EC), nitrogen (N), phosphorus (P), potassium (K), and organic matter content [13]. Additionally, a DHT11 sensor is integrated to monitor the ambient temperature and humidity, providing essential environmental context for soil conditions (Figure 3) [14].

An ESP32 microcontroller is employed as the primary processing unit, enabling efficient data acquisition and real-time analysis [15]. For wireless data transmission without requiring Wi-Fi, the system utilizes an NRF24L01 RF module [16], ensuring seamless communication between sensor nodes and the plant health monitoring node as shown in Figures 3 and 4. The collected data is displayed on an OLED screen, providing farmers with a simple and intuitive interface for on-site monitoring (Figure 4).



**Figure 3.** Soil parameter collection node block diagram.



**Figure 4.** Implementation of soil parameter collection node.

### Plant Health Monitoring Node

The Plant Health Monitoring Node is a robotic vehicle designed for autonomous plant health inspection and soil data acquisition. It features an ESP32 microcontroller as the main processing unit, responsible for controlling motor functions, sensor integration, and data transmission as shown in Figure 5. The ESP32 is mounted on a sturdy chassis with four DC motors, which are controlled by a DRV8833 motor driver, enabling smooth navigation across agricultural fields [17].

To facilitate autonomous movement, a GP1818MK GPS module is integrated, providing real-time location data [18]. The robot follows a waypoint-based navigation system, where predefined GPS coordinates guide it systematically across the jowar field. The car moves along soil lanes, capturing images of plants at regular intervals. Upon reaching a designated waypoint, the ESP32 triggers the camera module to capture images, ensuring comprehensive field coverage. This dynamic GPS-based path adjustment enhances accuracy and ensures no section of the field is left unmonitored.

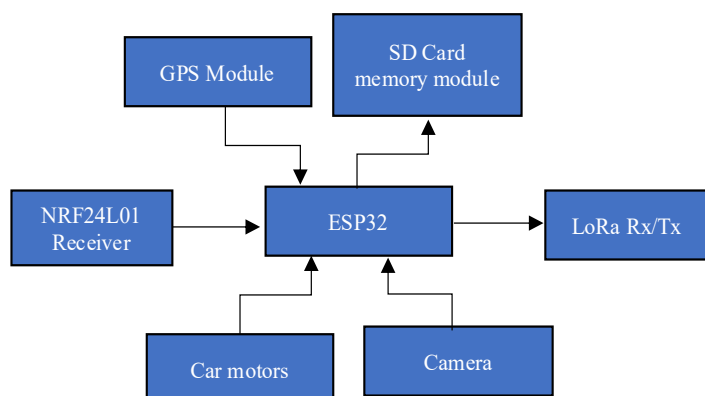
For plant health assessment, the robot is equipped with a camera module that captures images of jowar plants at different growth stages. To optimize onboard memory usage and data transmission, a lightweight machine learning model (such as MobileNetV2 or TinyML-based image classification) is implemented on the ESP32. Instead of storing all captured images, only images flagged as "requiring attention" are saved on the SD card and transmitted to the lab for further analysis. This reduces unnecessary data storage and transmission while ensuring efficient disease detection.

The ESP32 microcontroller is also equipped with multiple NRF24L01 receivers, each with a unique address to distinguish between different Soil Parameter Collection Nodes. These receivers gather real-time soil health data, including moisture levels, temperature, pH, and nutrient concentrations. The collected data is stored locally and transmitted via a LoRa module to a remote Data Analysis Centre, ensuring long-range wireless communication without relying on continuous internet connectivity (Figure 5).

By integrating low-cost sensors, machine learning-based plant disease classification, GPS-based navigation, and efficient data transmission, the Plant Health Monitoring Node provides an autonomous, scalable, and real-time agricultural monitoring solution. Future advancements can focus on enhanced AI models for improved disease classification and autonomous path-planning techniques for more efficient field navigation.

### PROTOTYPE DEVELOPMENT

This section details the development process of the JMAR prototype, highlighting the integration of hardware components and system functionalities. The following subsections provide an in-depth overview of the prototypes for both the Soil Parameter Collection Node and the Plant Health Monitoring Node, demonstrating their design, assembly, and operational capabilities.



**Figure 5.** Plant health monitoring block diagram.

### Soil Parameter Collection Node Prototype

The hardware prototype of the Soil Parameter Collection Node has been developed using Commercial Off-The-Shelf (COTS) components, ensuring affordability and ease of deployment. As shown in Figure 6, the prototype integrates an ESP32 microcontroller as the central processing unit, interfacing with a 7-in-1 soil sensor to measure key soil parameters, including moisture content, temperature, pH level, electrical conductivity (EC), nitrogen (N), phosphorus (P), potassium (K), and organic matter content [13]. Additionally, a DHT11 sensor is included to monitor ambient temperature and humidity, offering a more comprehensive analysis of environmental factors affecting soil health [14]. The NRF24L01 RF module is used for wireless data transmission, enabling efficient communication between sensor nodes and the Plant Health Monitoring Node without relying on Wi-Fi [16]. To ensure smooth communication between the soil sensor and the ESP32, an RS485-to-TTL converter is integrated, enabling accurate serial data exchange (Figure 6).

To provide real-time feedback, an OLED display (SH1106-based module) is incorporated, allowing users to view sensor readings instantly without external devices. The entire system is powered via a 12 V adapter, ensuring stable and efficient operation. The prototype, as depicted in Figure 7, is built on a breadboard, allowing for modular testing and iterative development before transitioning to a more permanent PCB-based design. This setup enables easy modifications for optimization and debugging. Future enhancements may include solar-powered energy sources for self-sustaining operation and LoRa-based communication for long-range data transmission, making it suitable for deployment in remote agricultural regions (Figure 7).



ESP32



OLED



7-in-1 moisture used in soil monitoring node



DHT11



RS485 to TTL



NRF24L01

**Figure 6.** Components used in soil monitoring node.

### Plant Health Monitoring Node

The Plant Health Monitoring Node has been designed as an autonomous robotic system capable of navigating through agricultural fields, capturing plant health data, and transmitting soil parameters from the Soil Parameter Collection Node. As shown in Figure 8, the prototype consists of an ESP32 microcontroller as the primary processing unit, which controls various sensors, motors, and communication modules. The robotic platform is equipped with four 12 V DC motors, which are driven by a motor driver (DRV8833) to ensure smooth movement across different terrains [17]. A GP1818MK GPS module is integrated to enable waypoint-based navigation, allowing the robot to autonomously traverse the field based on predefined coordinates (Figure 8).

For plant health assessment, an ESP32-CAM module is used to capture high-resolution images of crops at various growth stages. The system implements a lightweight machine learning model (such as MobileNetV2 or TinyML-based image classification) to detect anomalies or early signs of disease.

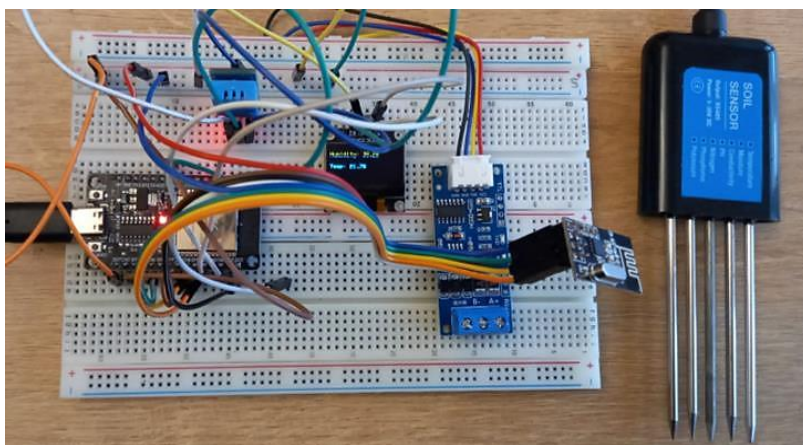
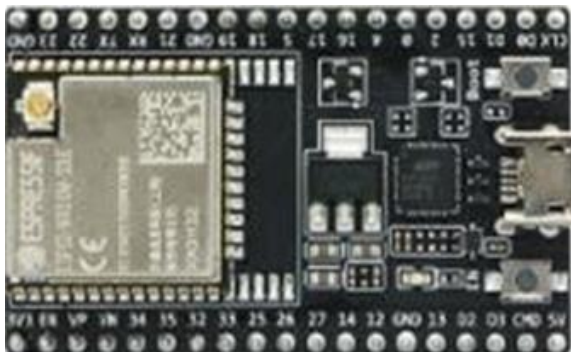
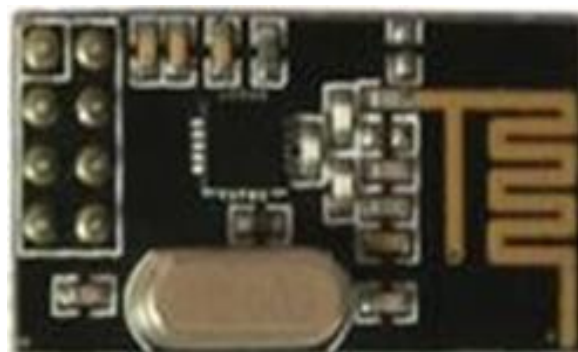


Figure 7. Prototype of soil parameter monitoring node.



ESP32



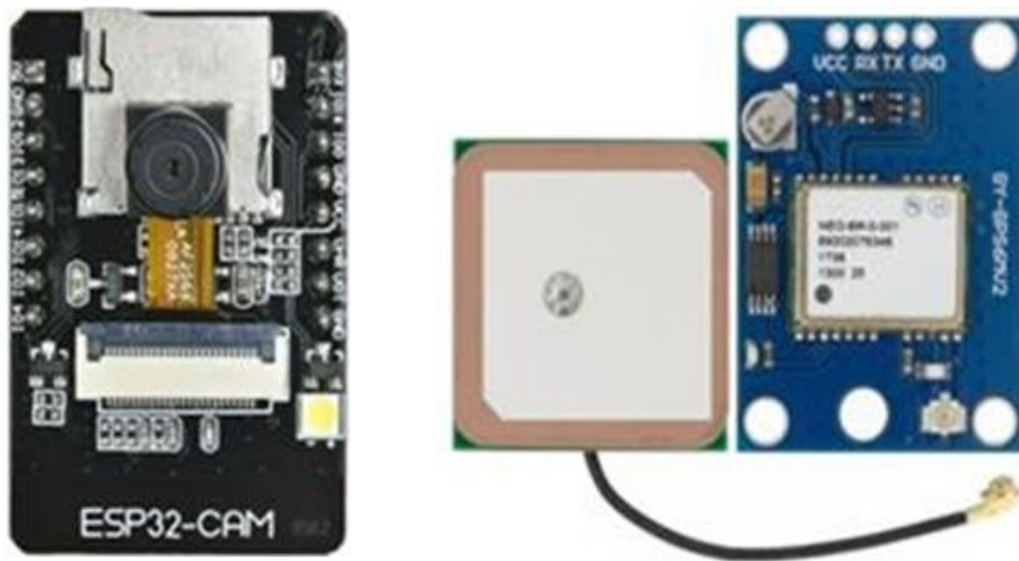
NRF24L01



LoRa



12V DC Motors



ESP32 Camera module

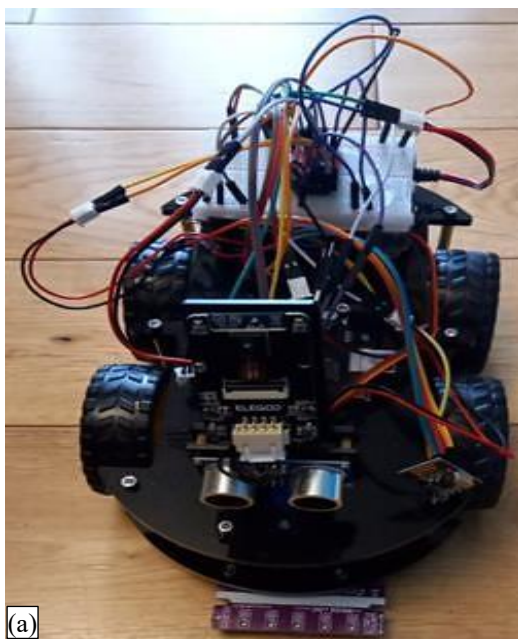
GP1818MK GPS

**Figure 8.** Components used in plant monitoring.

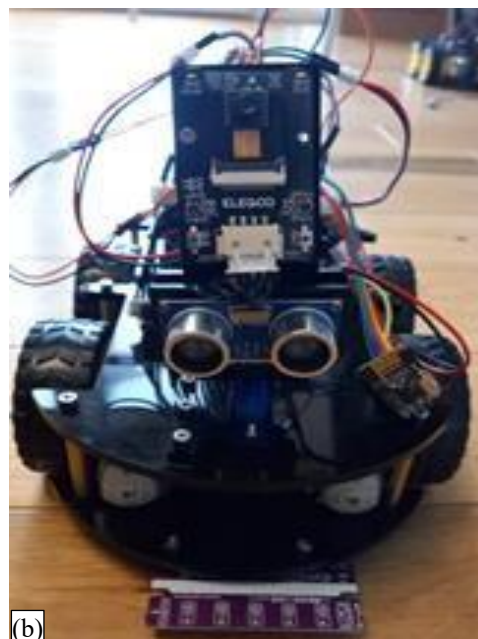
To enable long-range wireless data transmission, a LoRa module is included, ensuring that sensor readings and plant health data can be sent to a remote monitoring centre without requiring continuous internet access. Additionally, the NRF24L01 RF module allows seamless communication with the Soil Parameter Collection Node, gathering real-time soil health information. As shown in Figure 9, the prototype has been successfully assembled with all components integrated onto a chassis, providing a fully functional system for autonomous agricultural monitoring. Future enhancements may include advanced AI-based path optimization and solar-powered operation for improved efficiency in large-scale farming applications (Figure 8).

### TINY-ML BASED CLASSIFICATION MODEL

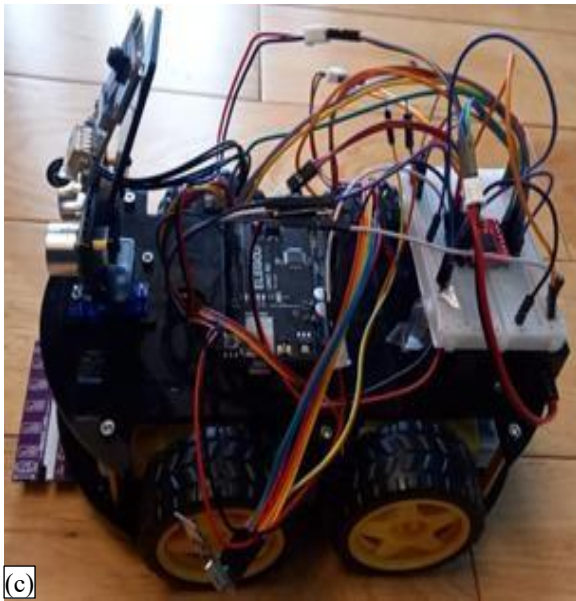
As explained in the previous section, images were taken at different stages of growth of a plant i.e., 4 weeks apart (stem, plant and leaves). All these images were labelled into two classes: healthy and diseased as shown in Figures 10 and 11, with 150 samples in each class.



(a)



(b)



**Figure 9.** Plant monitoring node prototype. (a) Front-left angled view showing the general build and wiring; (b) Front view clearly showing ultrasonic sensors and front layout; (c) Side view showing wheels, wiring, and side structure.



**Figure 10.** Images of healthy Jowar plants at various stages of vegetation.

The images were first pre-processed to reduce the size of the images to  $192 \times 192$  pixels and a Convolutional Neural Network (CNN) was used to classify whether a plant, stem or leaf is healthy or not. The dataset was divided into 80:20 for training and testing purposes and the accuracy obtained was 94%. Once the model was trained, it was converted into TensorFlow Lite format in order to deploy it on edge devices like ESP32 (using Micro Python).



**Figure 11.** Images of unhealthy jowar plants.

## CONCLUSION

The Jowar Monitoring and Analysis Robot (JMAR) offers an autonomous, cost-effective solution for real-time soil health monitoring and plant disease detection in jowar cultivation. Integrating Commercial Off-The-Shelf (COTS) components such as soil sensors, a DHT sensor, an ESP32 microcontroller, and an ESP32-CAM, JMAR efficiently collects and analyses vital agricultural data. Utilizing NRF24L01 and LoRa-based wireless communication, the system ensures seamless operation in remote farmlands without the need for continuous internet connectivity.

JMAR's Soil Parameter Collection Node continuously monitors key soil parameters, while the Plant Health Monitoring Node autonomously navigates fields, capturing images for Tiny ML-based disease classification. This integrated approach empowers farmers with data-driven insights, enabling optimal resource management, early disease detection, and improved crop yields. With its modular design and scalability, JMAR holds immense potential for future advancements, making precision agriculture accessible to farmers in resource-limited environments.

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