Autonomous Multi-Crop Weeding and Nutrient Management

Mrs.Yeshwini[1], D.C Likitha[2], Ganavi N [2], Keerthana C [2], Manushree V [2]

[1]Assistant Professor Department of Electronics and communication,
KS School of engineering and management, Bangalore, India

[2]Students, Department of Electronics and communication, KS School of engineering and management, Bangalore, India

Corresponding Author Email:manushreev2006@gmail.com

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Abstract—
Agriculture faces major challenges such as weed growth, labor shortages, excessive fertilizer usage, and lack of real-time monitoring. This paper proposes an Autonomous Multi-Crop Weeding and Nutrient Management Machine using Artificial Intelligence (AI), Internet of Things (IoT), and embedded systems. The system uses AI-based image processing for weed detection and activates a mechanical cutter to remove weeds automatically. Soil pH and NPK sensors monitor nutrient levels and enable precision nutrient spraying only when required. An ESP32 microcontroller controls navigation, sensor interfacing, motor operation, and IoT communication. GPS, ultrasonic, and IMU sensors enable autonomous navigation and obstacle detection. Real-time data is transmitted to farmers through Wi-Fi or Bluetooth. The proposed system reduces labor dependency, minimizes chemical usage, improves crop productivity, and supports sustainable precision agriculture.

The proposed machine is designed to provide an integrated approach to precision agriculture by combining intelligent weed management, soil monitoring, nutrient management, and autonomous field operation in a single system. The camera-based detection mechanism continuously observes the crop area and identifies weeds, after which the mechanical weeding unit is activated for selective removal. Simultaneously, soil pH and NPK sensors provide continuous information about soil conditions, allowing the system to determine nutrient requirements and operate the spraying mechanism accordingly. The integration of GPS, ultrasonic, and IMU sensors supports autonomous movement, obstacle detection, and directional stability during field operations. The ESP32 coordinates the different subsystems and enables communication of important field and machine parameters through Wi-Fi or Bluetooth. This integrated operation reduces unnecessary human intervention and promotes efficient utilization of agricultural resources. By combining AI-based decision-making with embedded control, sensing, robotics, and IoT connectivity, the system provides a practical approach for reducing labor requirements, minimizing input wastage, improving crop management, and supporting sustainable and data-driven agricultural practices.

Keywords— Autonomous agriculture, ESP32, AI in farming, IoT, weed detection, precision farming, nutrient monitoring.

I. INTRODUCTION

Agriculture is one of the most important sectors for human survival and economic development. Farmers today face several challenges such as uncontrolled weed growth, labor shortages, improper fertilizer application, and lack of continuous field monitoring. Weeds compete with crops for essential resources like nutrients, water, sunlight, and space, which significantly reduces crop productivity and overall yield. Conventional weed removal methods are labor-intensive, time-consuming, and inefficient for large-scale. Recent advancements in Artificial Intelligence (AI), IoT, robotics, and computer vision have transformed traditional farming into precision agriculture.Smart agricultural systems improve productivity, reduce operational costs, and optimize the use of agricultural resources.

The proposed machine integrates AI-based weed detection, automatic weed removal, soil monitoring, precision nutrient spraying, and autonomous navigation.Camera-based image processing is used to distinguish crops from weeds during field operations.Soil pH and NPK sensors monitor soil conditions and support efficient nutrient management.The system reduces dependency on manual labor and enables efficient and intelligent agricultural operations. Once weeds are identified, a mechanical cutting mechanism is activated automatically to remove them without damaging nearby crops. This improves the efficiency of weed management while reducing the excessive use of chemical herbicides, thereby promoting environmentally friendly farming.The system monitors soil health using pH and NPK sensors and applies nutrients only when required, reducing fertilizer wastage, while GPS, ultrasonic, and IMU sensors enable autonomous navigation and obstacle avoidance. The ESP32 coordinates sensing, navigation, motor control, AI-based weed detection, nutrient delivery, and communication. IoT connectivity enables real-time monitoring of field conditions and machine status, supporting efficient and sustainable precision farming.

II. LITERATURE REVIEW

In [1], Tengxiang Yang et al. (2023) proposed an unmanned weeding robot with a path planning and control system designed for precision weed management in agricultural fields. The system uses YOLOv5-based image recognition and computer vision techniques to accurately identify weeds and perform precision spraying. The robot achieved approximately 87.7% weed detection accuracy and reduced herbicide usage by nearly 75% compared to conventional spraying methods. The system integrates autonomous agricultural navigation to support efficient movement and targeted weed management. However, the robot experienced a lateral path error of approximately 0.2 meters during navigation and required extensive training datasets to improve model performance. The authors demonstrated that combining AI-based weed detection with autonomous navigation can improve the efficiency of agricultural weed management while reducing excessive herbicide usage.

In [2], Piyush Pandey et al. (2021) presented a detailed study on autonomous robotic weeding systems, focusing on weed detection, robotic actuation, and autonomous path planning. The research emphasized the integration of advanced computer vision techniques with robotic mechanisms to improve the efficiency of weed management. Various sensing technologies were also discussed to support autonomous operation and accurate weed detection. The study highlighted the importance of coordinated detection, actuation, and planning for effective robotic weeding. However, practical deployment faced challenges due to varying environmental conditions and changes in lighting. The authors concluded that robust sensing and computer vision techniques are essential for reliable autonomous weed management in real-world agricultural environments. The study further highlighted that autonomous robotic systems can reduce dependence on manual labor. Accurate weed detection and timely robotic actuation were identified as important factors for effective weed removal. The integration of sensing technologies with control methods can improve the adaptability of robotic systems.

In [3], Dafni Despoina Avgoustaki et al. (2022) proposed an autonomous mobile robot equipped with a multi spectral camera for monitoring crop development and detecting nutrient deficiencies. The system used vegetation indices such as NDVI (Normalized Difference Vegetation Index) and PRI (Photochemical Reflectance Index) to identify crop stress and nitrogen deficiency before visible symptoms appeared. The research demonstrated that multi spectral imaging can improve early assessment of crop health and support precision farming practices. The use of an autonomous robotic platform enabled continuous monitoring of crop conditions and provided valuable information for agricultural management. The study highlighted the potential of combining multi spectral imaging with autonomous robotics for efficient crop monitoring and nutrient assessment. However, the system was mainly tested under controlled environmental conditions, which limited the evaluation of its performance in real-world outdoor agricultural fields.

In [4], T. M. Wolf and S. K. Harrison (2022) compared a weed-sensing sprayer with a conventional broadcast sprayer for agricultural weed management. The proposed system used infrared sensors to detect the presence of weeds and applied herbicides only to the targeted areas. This approach significantly reduced chemical usage while maintaining effective weed control. The study demonstrated that targeted spraying can improve the efficiency of herbicide application and reduce unnecessary chemical consumption. The system provided an effective alternative to conventional broadcast spraying by enabling selective treatment of weed-infested areas. However, the technology faced limitations in detecting very small weeds and required a higher initial investment compared to conventional spraying systems.

In [5], Ahad Ahmed Laskar et al. (2024) explored the role of smart systems and precision farming technologies in improving soil fertility management. The study focused on integrating IoT sensors, GPS-based automation, and data-driven agricultural practices for real-time soil monitoring and crop management. The research demonstrated that smart agricultural systems can improve crop productivity by enabling better monitoring of soil conditions and agricultural activities. The integration of IoT technologies also supports efficient and optimized fertilizer application according to crop and soil requirements. The study highlighted the potential of data-driven farming technologies in improving resource utilization and promoting effective soil fertility management. However, large-scale adoption of such systems remains challenging due to high implementation costs and technical complexity.

In [6], Goran Kitić et al. (2022) introduced an autonomous robotic system named “Lala” for real-time, in-field soil sampling and nitrate analysis. The system used an autonomous ground vehicle integrated with soil sensing modules to support precision fertilization and soil assessment. It enabled georeferenced soil analysis, allowing soil information to be associated with specific field locations for better agricultural management. The autonomous operation reduced the need for manual effort in soil monitoring and sampling activities. The study demonstrated the potential of robotic soil sensing systems for improving precision agriculture and fertilizer management. However, the system involved high operational complexity, expensive hardware requirements, and longer analysis time for each soil sample.

In [7], K. S. Gundampati and S. K. Udgata (2025) proposed an explainable AI-based approach for weed and crop localization using Grad-CAM techniques. The system identified weeds without requiring manually annotated bounding boxes, thereby reducing the complexity involved in model training. The study demonstrated that explainable AI can improve the transparency and interpretability of AI-based decision-making in agricultural applications.

The approach provided a better understanding of how the AI model identifies and localizes weeds in crop fields. It highlighted the potential of explainable AI for developing efficient and transparent agricultural vision systems. However, the localization accuracy was less precise for small weeds compared with traditional segmentation-based methods.

In [8], S. Sow et al. (2024) reviewed the applications of Artificial Intelligence (AI) for improving agricultural input-use efficiency. The study analyzed machine learning, deep learning, and computer vision techniques for applications such as weed control, irrigation management, and nutrient optimization. The research highlighted that AI-based technologies can improve the efficient utilization of agricultural resources and support better decision-making. These techniques can also help reduce environmental impact by optimizing the use of water, fertilizers, and other agricultural inputs. The authors concluded that AI has significant potential to enhance crop productivity and promote sustainable agricultural practices. However, the study identified challenges including the need for large datasets and sufficient computational resources for effective AI implementation.

In [9], Y. Du et al. (2022) developed a Deep-CNN-based robotic weed control system for under-canopy weed detection in precision farming. The system used deep convolutional neural networks optimized for edge computing to identify weeds accurately in agricultural fields. The proposed model achieved a high weed classification accuracy of 97.7%, demonstrating its effectiveness for precision weed management. The system was also capable of performing real-time weed detection on embedded devices, making it suitable for autonomous agricultural applications. The study highlighted the potential of combining deep learning with robotic systems for efficient and automated weed control.

However, the system performance was sensitive to lighting variations and camera contamination, which could affect detection accuracy in practical field conditions.

In [10], P. Jayapal and G. Ananthakrishnan (2026) proposed a weed detection system that combines YOLOv8 object detection with field geometry analysis using the Radon Transform technique. The system was developed for paddy fields and analyzed crop row patterns to identify weeds growing between the rows. The proposed approach achieved approximately 94% weed detection accuracy and demonstrated improved performance in structured agricultural fields. The integration of object detection with field geometry analysis enhanced the identification of weeds based on their position relative to crop rows. The study highlighted the effectiveness of combining deep learning with geometric analysis for precision weed detection. However, the system performance decreased in fields with curved planting rows or extremely dense weed growth.

III.METHODOLOGY

The methodology of the proposed Autonomous Multi-Crop Weeding and Nutrient Management Machine is divided into multiple stages involving system initialization, autonomous navigation, weed detection, soil monitoring, nutrient spraying, and IoT-based monitoring. The complete system integrates Artificial Intelligence (AI), Internet of Things (IoT), embedded systems, and robotics to perform precision agricultural operations efficiently.

A. System Initialization and Power management

The operation of the machine begins with the power supply unit, which provides electrical power to all hardware modules through a rechargeable 12V battery source. Voltage regulators and buck converters are used to provide regulated voltages such as 5V for sensors and communication modules and 3.3V for the ESP32 microcontroller. The ESP32 acts as the central controller of the system and initializes all connected peripherals, including sensors, motor drivers, communication units, and camera modules. During initialization, the controller checks the connectivity and operational status of each hardware component before starting field operations. Proper initialization ensures stable system performance and reliable communication between modules.

B. Autonomous Navigation and Mobility Control

The navigation system enables the machine to move autonomously through agricultural fields. GPS modules provide real-time location tracking, while the IMU sensor detects orientation, tilt, and movement of the machine. The navigation data helps the machine maintain directional stability while moving through crop rows. Ultrasonic sensors are used for obstacle detection and collision avoidance. These sensors continuously measure the distance between the machine and nearby objects. If an obstacle is detected within a predefined range, the ESP32 automatically controls the motor driver to stop machine. The mobility system consists of DC geared motors connected to wheels through a motor driver module such as L298N. The ESP32 sends control signals to regulate motor speed and direction for forward movement, turning, and row navigation. This autonomous movement capability reduces the need for human intervention during agricultural operations.

C. AI-Based Weed Detection System

The weed detection system uses an ESP32-CAM module to continuously capture images of crops and weeds while the machine moves across the field. The captured images are processed using Artificial Intelligence and computer vision techniques. AI models such as YOLO and OpenCV-based image processing algorithms are used to distinguish weeds from crops based on color, shape, texture, and spatial characteristics. The AI model is trained using agricultural image datasets containing different crop and weed samples. During operation, the system performs real-time image analysis and classifies detected plants as crops or weeds. Once a weed is identified, the ESP32 generates a control signal to activate the weeding mechanism. The use of AI-based weed detection improves detection accuracy, reduces manual monitoring, and minimizes the excessive use of chemical herbicides. The system supports precision farming by targeting weeds selectively instead of spraying chemicals over the entire field.

D. Mechanical weeding mechanism

The mechanical weeding mechanism is responsible for removing weeds automatically after detection. The system consists of a rotating cutter blade or mechanical cutting unit driven by a DC motor. The blade is positioned near the ground surface to remove weeds without affecting nearby crops. When the AI model identifies weeds, the ESP32 activates the blade motor through the motor driver module. The cutter rotates at high speed and uproots or cuts weeds present in the field. After weed removal, the machine continues its movement toward the next crop area Compared to traditional herbicide-based weed control methods, the mechanical cutting approach reduces environmental pollution, decreases chemical dependency, and improves soil sustainability. The system also helps farmers reduce labor costs associated with manual weeding operations.

E. Soil Monitoring and Nutrient Management

The soil monitoring system continuously analyzes soil conditions using pH and NPK sensors. The pH sensor measures soil acidity and alkalinity levels, while the NPK sensor measures the concentration of essential nutrients such as nitrogen, phosphorus, and potassium. The sensor values are continuously monitored by the ESP32 and compared with predefined threshold values stored in the controller. If the nutrient level falls below the required threshold, the system automatically activates the nutrient delivery mechanism. The nutrient management system includes a DC pump, nutrient storage container, and spray nozzle arrangement. The pump transfers nutrient solution through the sprayer and distributes it near deficient crop areas. This precision nutrient delivery system ensures that fertilizers are applied only where required, reducing fertilizer wastage and improving soil fertility management. The integration of real-time soil monitoring with automated nutrient spraying supports precision agriculture and enhances crop productivity.

F. IoT Communication and Real-Time Monitoring

The proposed system incorporates IoT communication using the built-in Wi-Fi and Bluetooth capabilities of the ESP32 microcontroller. The IoT module transmits real-time field data such as soil nutrient levels, machine location, weed detection status, and machine operational conditions to a mobile application or cloud platform. Farmers can remotely monitor agricultural operations using a smartphone or monitoring device. The communication system enables real-time access to field conditions and machine performance, allowing farmers to make better agricultural decisions .IoT integration also helps maintain records of field activities, monitor fertilizer usage, and track machine movement across agricultural land. This improves operational efficiency and enables smart farming practices through data-driven agricultural management.

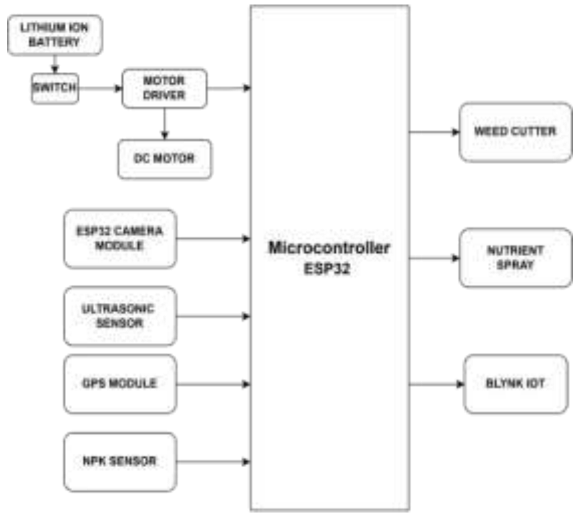
G. Overall System Integration

The complete system integrates AI, IoT, robotics, computer vision, and embedded systems into a single autonomous agricultural microcontroller coordinates platform. all The ESP32 modules including navigation, weed detection, soil monitoring, nutrient spraying. The synchronized operation of these modules enables efficient weed management, precision nutrient application, autonomous movement, and real-time monitoring. The proposed methodology reduces labor dependency, minimizes chemical usage, improves crop productivity, and promotes sustainable farming practices. The system provides an effective solution for modern precision agriculture and smart farming applications.

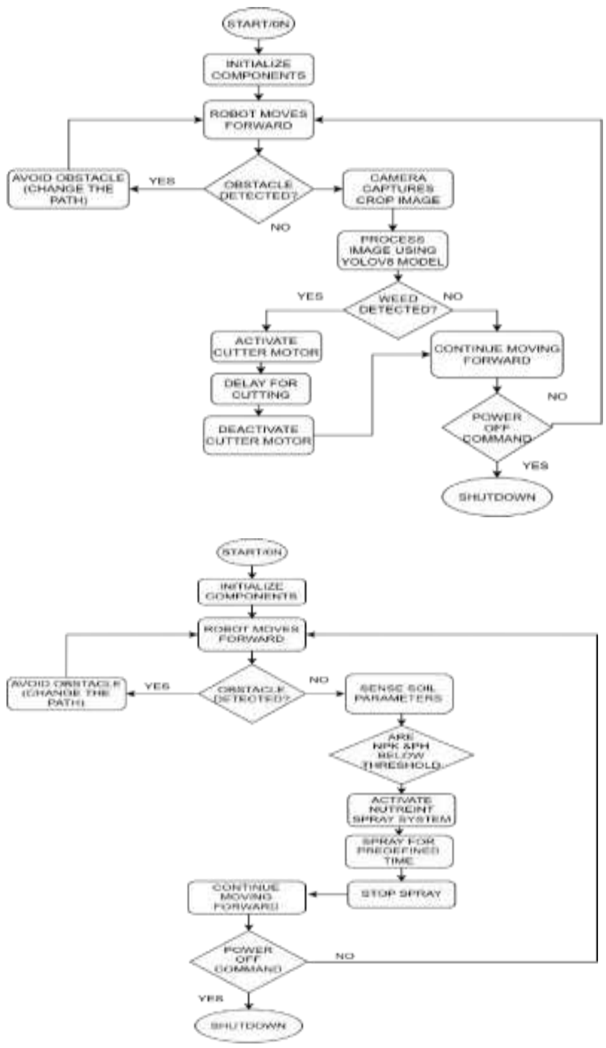
IV.CONCLUSION

The proposed Autonomous Multi-Crop Weeding and Nutrient Management Machine presents an intelligent and efficient solution for modern agricultural challenges by integrating Artificial Intelligence (AI), Internet of Things

BLOCK DIAGRAM



FLOW DIAGRAM



(IoT), robotics, computer vision, and embedded system technologies into a single autonomous platform. The system is specifically designed to address critical farming problems such as uncontrolled weed growth, labor shortages, excessive use of herbicides and fertilizers, inefficient soil monitoring, and lack of real-time field management. By automating multiple agricultural operations, the proposed machine significantly improves farming efficiency and supports precision agriculture practices. The AI-based weed detection system enables accurate identification of weeds using real-time image processing and computer vision techniques. Unlike conventional farming methods that depend heavily on manual labor and chemical herbicides, the proposed system uses a mechanical cutting mechanism to remove weeds automatically without affecting nearby crops. This approach not only reduces labor dependency and operational costs but also minimizes the harmful environmental impact caused by excessive chemical spraying. The integration of AI-driven weed identification enhances the reliability and effectiveness of autonomous weed management in agricultural fields. Another important feature of the proposed system is the precision nutrient management mechanism. Soil pH and NPK sensors continuously monitor soil health and nutrient levels in real time. Based on sensor readings, the nutrient delivery system activates automatically and sprays fertilizers only when nutrient deficiency is detected. This precision-based nutrient application reduces fertilizer wastage, improves soil fertility management, and enhances crop growth.

The autonomous navigation capability of the machine further improves its operational efficiency. The integration of GPS, ultrasonic sensors, and IMU sensors enables the machine to move intelligently through crop rows while detecting and avoiding obstacles. The ESP32 microcontroller coordinates all hardware modules including sensors, motor drivers, navigation systems, communication modules, and actuation mechanisms, ensuring smooth and synchronized system performance. The use of IoT communication through Wi-Fi and Bluetooth allows farmers to monitor field conditions, machine status, soil parameters, and weed detection results remotely through mobile applications or cloud-based monitoring systems. The proposed machine provides several advantages compared to traditional agricultural methods, including reduced labor requirements, minimized chemical usage, lower operational costs, improved crop productivity, and enhanced precision farming capabilities. By integrating multiple smart agricultural technologies into a single platform, the system demonstrates the practical application of automation and intelligent decision-making in modern farming environments. Furthermore, the project contributes toward the development of sustainable and environmentally friendly agricultural solutions. The reduction in excessive herbicide and fertilizer usage helps protect soil health and minimizes environmental pollution. The system also supports efficient resource utilization, which is essential for meeting the increasing global demand for food production while maintaining ecological balance.

Although the proposed system offers numerous benefits, future improvements can further enhance its performance and scalability. Advanced deep learning models, cloud-based data analytics, solar-powered energy systems, and drone-assisted monitoring can be integrated into future versions of the project to improve weed detection accuracy, energy efficiency, and large-scale field operation capabilities. The implementation of more powerful edge computing devices can also improve real-time AI processing performance in practical agricultural environments. In conclusion, the Autonomous Multi-Crop Weeding and Nutrient Management Machine provides an effective, reliable, and intelligent solution for smart agriculture and precision farming applications. The system successfully combines automation, AI, IoT, and robotics to improve agricultural productivity, optimize resource usage, and support sustainable farming practices. The proposed work demonstrates the potential of modern technology in transforming traditional agriculture into an efficient, data-driven, and autonomous farming ecosystem.

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