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Corresponding Author

Ramanjit Kaur

e-mail: ramaan180103@yahoo.com

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Artificial Intelligence in Weed Management: Ushering in a New Era of Agricultural Precision

Sk Asraful Ali¹, Ramanjit Kaur^{1*}, Kadagonda Nithinkumar¹, Jhonsonraju Sankati¹, Sunil Kumar², Sunil Kumar Prajapati¹ and Sushree Swetalika Sahoo³

Abstract

Weed management remains a major challenge in modern agriculture, directly influencing crop yield, quality, and long-term sustainability. Conventional practices such as manual removal, mechanical methods, and chemical herbicides are often labor-intensive, costly, and environmentally damaging, while also contributing to the growing problem of herbicide resistance. The adoption of Artificial Intelligence (AI) offers a transformative solution by enabling precision, efficiency, and sustainability in weed control. AI-powered systems equipped with imaging, machine vision, and sensor technologies can accurately differentiate weeds from crops, ensuring highly targeted interventions through robotic weeding, smart sprayers, and other advanced tools. These innovations significantly reduce herbicide dependency, lower production costs, and minimize ecological risks while maintaining effective weed suppression. Although challenges such as high initial investment, weather dependency, and regulatory barriers persist, AI-driven weed management holds immense potential to advance sustainable farming, ensuring higher productivity and environmental stewardship.

1. Introduction

Weed management remains a formidable challenge in contemporary agriculture, posing significant threats to crop productivity, quality, and overall agricultural sustainability. Traditional methods, encompassing manual weeding, mechanical tillage, and chemical herbicides, often suffer from considerable drawbacks such as labor intensiveness, soil degradation, environmental pollution, and the emergence of herbicide-resistant weed species. Fortunately, the advent of Artificial Intelligence (AI) is rapidly revolutionizing weed management by offering innovative, intelligent, and sustainable solutions that promise to enhance precision, reduce environmental impact, and improve cost-efficiency.

Author's Address

¹ICAR-Indian Agricultural Research Institute, Pusa Campus, New Delhi (110 012), India

²Dr. Rajendra Prasad Central Agricultural University, Samastipur, Bihar (848 125), India

³Odisha University of Agriculture and Technology, Bhubaneswar, Odisha (751 003), India

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Artificial Intelligence serves as a pivotal force in advancing agricultural weed identification, significantly improving the accuracy and speed of detection beyond what conventional manual or automated tools can achieve. AI-powered systems analyze vast image datasets captured by diverse platforms, including drones, satellites, and ground-based cameras, to intelligently differentiate between crops and weeds across various growth stages and in diverse soil conditions. This capability is crucial for enabling targeted interventions, thereby reducing the reliance on blanket herbicide applications and fostering more sustainable weed management practices beneficial to farmers, agribusinesses, and the environment. The core of AI's effectiveness in this domain lies in its ability to process thousands of images in real-time, extracting plant features and identifying weed species with remarkable accuracy. Furthermore, by integrating data from soil moisture, weather conditions, and weed population dynamics, AI systems provide actionable insights for precise and timely interventions, such as adjusting spraying or mechanical removal methods on-site.

The precision offered by AI-driven systems is unparalleled, as they can distinguish between crops and weeds with high accuracy, enabling the specific targeting of herbicides, reducing unintended harm to crops, and promoting resource conservation. For instance, weed detection AI can achieve over 90% accuracy in identifying and eliminating weeds, detecting weeds as small as 2-3 leaves. This level of precision not only enhances the effectiveness of weed control but also minimizes the volume of chemicals used, leading to lower input costs and a reduced environmental footprint. The ability of AI to adapt to different weed species and optimize treatment through continuous learning further solidifies its role as a game-changer in modern farming.

2. Advanced AI-Powered Technologies in Weed Management

The precision weed management landscape has been transformed by the emergence of groundbreaking AI-powered tools and systems that were previously unimaginable. These technologies are redefining how weeds are identified, monitored, and eliminated across the globe, contributing significantly to sustainable agricultural practices.

Modern drones and satellites, combined with AI analysis, enable continuous, large-scale weed monitoring. High-

resolution imagery processed by AI facilitates not only weed detection but also trend analysis and predictive modeling, which is particularly beneficial for extensive farms where manual scouting is impractical. Drones, or Unmanned Aerial Vehicles (UAVs), equipped with multispectral, hyperspectral, and thermal sensors, can capture images across various wavelengths to distinguish between crops and weeds based on their distinct spectral signatures (Ali et al., 2025). The YOLO v5 model enables the feasibility of Multi-layer Neural Networks which can be used for the detection, recognition, & mapping of weeds during the initial growth stages of crops. Hyperspectral sensors, for example, capture hundreds of narrow spectral bands, allowing for the identification of specific weed species (Jha et al., 2025). The integration of GPS and RTK positioning systems ensures high positional accuracy, enabling consistent coverage and data collection, vital for effective weed mapping.

Weeding robots represent a cutting-edge blend of artificial intelligence, robotics, and agricultural technology, designed to help farmers manage weeds more efficiently and sustainably. These robots use advanced machine vision systems - typically involving cameras and sensors - to distinguish weeds from crops by analyzing characteristics such as size, shape, and color. Once a weed is detected, the robot eliminates it using methods such as mechanical, thermal, laser, flame, or electrical weeders, or through targeted herbicide application, ensuring minimal impact on surrounding crops (Figure 1). Notable examples of robotic weeders include the Carbon Robotics LaserWeeder G2, FarmDroid FD20, AgriPass, Ecorobotix AVO, Steketee IC Weeder, and the Autonomous Delta Robot System. In India, Hyderabad-based Agritech startup Harvested Robotics has developed "Rakshak," an AI-driven laser-weeding robot that attaches to a tractor, providing a sustainable, chemical-free solution for weed control.

Smart sprayers represent a revolutionary advancement in precision agriculture, using AI and advanced sensors to apply herbicides only where needed rather than blanket

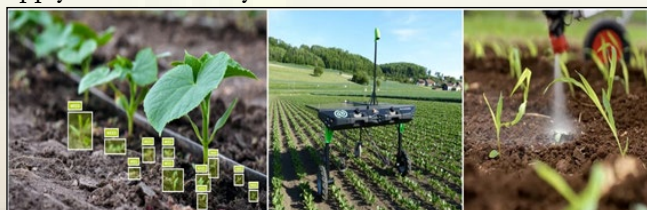


Figure 1: AI in weed management

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spraying entire fields. This targeted approach greatly reduces herbicide use, minimizes soil degradation, and protects crops from unnecessary chemical exposure. Using optical, hyperspectral, or thermal sensors, smart sprayers pinpoint weed locations and, with cameras capturing images at high speeds, can rapidly identify and classify weeds down to the species level. Systems like Greeneye's utilize proprietary datasets and algorithms to instantly determine the precise amount of herbicide needed for each weed type and location. These technologies maintain weed control effectiveness comparable to traditional

methods, achieving 90-97% efficacy. For example, Blue River Technology's "See & Spray" system has enabled up to 90% reductions in herbicide use, while Iowa State's 2024 trial using a John Deere's "See and Spray™ Ultimate" machine reported an average of 76% herbicide savings even under heavy weed pressure. Carbon Robotics has noted an 80% overall cost reduction, extending beyond just herbicide savings. Such innovations are vital for combating herbicide resistance and sustaining agricultural productivity (Table 1).

Table 1: Advanced AI-Powered technologies in weed management

Technology/ Company	Type	Remarks
FarmDroid FD20	Mechanical weeder	100% herbicide elimination
Carbon Robotics Laser Weeder G2	Laser weeder	100% herbicide elimination for targeted areas, 80% cost reduction
Harvested Robotics Rakshak (India)	Laser weeder	100% herbicide elimination for laser-treated areas
John Deere See and Spray™ Ultimate	Smart sprayer	28-62% herbicide savings
FBN-Greeneye Precision Spraying Program	Smart sprayer	86% reduction in non-residual herbicides
BOSCH-BASF One Smart Spray	Smart sprayer	Substantial herbicide reduction
AgTechLogic Intelligent Precision Spraying	Smart sprayer	Up to 90% chemical savings annually

3. Integration and Impact on Agricultural Systems

The integration of AI with other precision agriculture technologies, such as Geographic Information Systems (GIS) and machine learning, further enhances its effectiveness in weed management. GIS and remote sensing provide spatial data that, when combined with drone data, improve weed detection and mapping accuracy. Machine learning algorithms analyze large datasets from drones to identify weed species, monitor growth patterns, and predict infestations, enabling more precise and proactive weed management strategies. This sophisticated data integration provides real-time decision support, allowing farmers to adjust their weed control tactics in response to evolving field conditions.

The application of AI in weed management extends beyond direct control to encompass broader benefits for agricultural systems. AI-driven systems contribute to increased precision by accurately identifying weed species and assessing their growth stages, leading to more effective and targeted control strategies. This precision minimizes the risk of harming desirable crops and

promotes more informed decisions with each application. Environmentally optimized herbicide application, laser weeding, and mechanical removal techniques minimize chemical runoff, water contamination, and adverse effects on soil health. This reduction in chemical dependency actively protects the surrounding environment and biodiversity.

From an economic perspective, AI-driven systems significantly reduce labor costs and the volume of herbicides required through automated weed detection and targeted interventions, leading to direct cost reductions and improved profitability for farmers. While the initial investment in drone technology can be substantial, these costs are often offset over time through savings on labor and chemicals, and drones can rapidly cover extensive areas, enhancing overall farm productivity. Furthermore, AI-powered platforms aid farmers in achieving sustainability targets, regulatory compliance, and eligibility for eco-friendly certifications through features like carbon foot printing and precision input tracking. This holistic approach ensures not only increased efficiency and productivity, but also a stronger commitment to environmental stewardship.

4. Challenges and Future Directions

Despite the numerous advantages and dramatic advancements in AI-powered weed management, several challenges must be addressed to facilitate widespread global adoption. These include regulatory issues, technical limitations, weather dependency, and high initial costs. Diverse laws regulate drone use in agriculture, varying by country and imposing restrictions on flight paths, altitude, and proximity to populated areas. These regulations often necessitate special permits or certifications, limiting operational flexibility. Additionally, concerns about privacy and safety, such as potential data breaches or collisions, pose further challenges to widespread drone adoption.

Technical limitations also present significant hurdles. The success of drone-based weed management heavily relies on the quality of onboard sensors and cameras, as well as the system's ability to swiftly process and analyze substantial volumes of data. High-resolution imaging and advanced data processing, while crucial for precise weed detection, often elevate the cost and complexity of drone systems. Furthermore, limited battery life can restrict the operational range and duration of drones, posing challenges for their use in extensive agricultural fields. Weather conditions, including strong winds, rain, and fog, can significantly hinder flight performance and data accuracy, potentially delaying weed management activities and affecting the timely application of control measures. The initial investment in AI technologies, including drones, sensors, software, and training, can be a significant barrier for many farmers, particularly in developing regions. Looking ahead, several areas require further research to fully realize the benefits of AI-based weed management and encourage broader adoption. The development of cost-effective and user-friendly drone systems with advanced sensors and data processing capabilities is essential to make this technology accessible to a wider range of farmers, including those with limited technical expertise. Research should also explore the integration of drones with autonomous ground vehicles and robotics, which could enable fully automated systems

combining aerial and ground-based interventions for comprehensive and efficient weed control. Monitoring and managing herbicide-resistant weed populations using drones is another critical area for future research, as drones can be pivotal in the early detection and mapping of resistant weeds, allowing for timely and targeted management strategies. Developing robust frameworks for assessing the economic, environmental, and social impacts of drone-based weed management will be vital for guiding informed decision-making by farmers, stakeholders, and policymakers, ensuring that AI adoption aligns with sustainability goals and contributes to resilient agricultural systems.

5. Conclusion

Artificial Intelligence is revolutionizing precision agriculture by enabling sustainable and efficient weed management. AI-powered tools such as robotic weeders, smart sprayers, drones, and laser technologies offer targeted, cost-effective, and environmentally friendly alternatives to conventional practices while reducing herbicide dependence. Despite challenges like regulatory constraints, technical limitations, and high initial costs, ongoing research should emphasize integrated, user-friendly solutions. As AI advances, it promises to become vital for enhancing crop productivity, profitability, and sustainability in meeting global food demands.

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