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A review on weeders

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Abstract

Weeds are one of the major biological constraints in agricultural production, causing significant yield losses around 30-40% by competing with crops for nutrients, water, light, and space. Efficient weed management is therefore essential for sustainable crop production. Various weed control methods — manual, chemical, mechanical, and precision-based are widely practiced. Traditional manual tools such as khurpi, spade, wheel hoe, and push-pull weeders exhibit high weeding efficiency (72–99%) but suffer from low field capacity and require intensive labor and time. Chemical control, although cost-effective, poses environmental hazards, health risks, and ecological imbalance due to excessive herbicide use.

In recent years, mechanical weed control has gained prominence due to its eco-friendly nature, improved soil aeration, and enhancement of water retention. Modern machines such as tractor-operated weeders, finger weeders, torsion weeders, and flame weeders are increasingly used, particularly in row crops. Advances in automation and precision agriculture have led to the development of intelligent weeding systems using sensors, robotics, and computing technologies. These systems reduce labor dependency and enhance operational efficiency. Future innovations involving remote sensing, UAVs, and robotic systems are expected to ensure sustainable and precise weed management.

Keywords: Weeders, mechanical weed control, power weeders, agricultural mechanization, sustainable agriculture

1. Introduction

The global population is expected to reach nearly nine billion by the year 2050, which will require a substantial increase in food production by approximately 70–100% to meet the growing demand (FAO, 2023) ^[15]. This rising demand places considerable pressure on existing agricultural systems, raising concerns about the sustainability and efficiency of current farming practices. Crop productivity is adversely affected by several factors, including climate change, water scarcity, weeds and the excessive application of agrochemicals such as pesticides, fertilizers, herbicides, and insecticides, which degrade soil fertility over time. Among these constraints, ineffective weed management has been identified as one of the most significant contributors to yield reduction.

Weeds are commonly defined as unwanted or undesirable plants that interfere with agricultural activities. Within cropping systems, weeds compete aggressively with cultivated plants for essential resources such as water, nutrients, sunlight, and space, ultimately reducing both crop yield and quality. The extent of yield loss caused by weeds depends on several interacting factors, including weed density, time of emergence, crop species, and weed type (Chauhan, 2020; Fahad *et al.*, 2015) ^[8, 14]. At the global level, weeds are responsible for approximately 34% of total yield losses, surpassing the impact of animal pests and diseases, which account for 18% and 16%, respectively (Oerke, 2006) ^[32].

The severity of weed-induced losses varies across regions. In developed countries, average yield losses due to weeds are estimated at around 5%, whereas in developing countries these losses rise to approximately 10%, and may reach up to 25% in countries with less advanced agricultural systems such as India (Oerke, 2006) ^[32]. In extreme cases, yield reductions can reach up to 65%, depending on crop type, weed species, and management practices (Devojee *et al.*, 2018) ^[12]. The economic implications of weed infestation are also considerable. In India, the cost of weed management is estimated to be about ₹6000 per hectare for kharif crops and ₹4000 per hectare for rabi crops, contributing approximately 33% and 22% of the total cost of

cultivation, respectively (Yaduraju & Mishra cited in Oerke, 2006) [32].

Weed management involves the application of scientific and technical knowledge to regulate weed populations in agricultural fields (Ghersa *et al.*, 2000; Jacob & Guo, 2014) [17]. Various weed control methods are employed, including manual, mechanical, and chemical approaches, applicable to both intra-row and inter-row cropping systems. Manual weeding, although widely practiced, is laborious, time-consuming, and costly. Mechanical weeding utilizes a range of implements designed for specific crops, offering improved efficiency and reduced labor dependence, although proper operation and maintenance are essential for effective performance.

Chemical weed control, while effective in reducing labor requirements and ensuring rapid weed suppression, poses significant risks to environmental sustainability and human health due to excessive herbicide use (Olaoye & Adekanye, 2013) [33]. Mechanical weed control primarily relies on the application of physical force to remove or destroy weeds using manual labor, animal power, or machinery. Common physical methods include hand weeding, hoeing, digging, mowing, cutting, tillage, burning, intercropping, and mulching (Singh, 2014). In India, weed control is predominantly carried out manually or with simple hand tools. These physical methods are considered effective and environmentally sustainable, as they do not leave harmful chemical residues in the soil or on crops. Intra-row weed control techniques, including soil steaming, laser-based weeding, and flame weeding, have been developed to address these concerns (Raffaelli *et al.*, 2013; Fontanelli *et al.*, 2015) [36, 16]. However, their application is limited by high operational costs, energy requirements, and dependence on specific soil and crop conditions (Melander & Kristensen, 2011; Marx *et al.*, 2012) [29, 28].

2. Overview of Weed Control Methods

Weed management strategies can be broadly classified into manual, mechanical, chemical, and precision-based approaches. Each method has its own advantages and limitations, and their effectiveness depends on crop type, weed species, and environmental conditions (Melander & Kristensen, 2011) [29].

2.1 Manual Weeding

Manual weeding remains one of the oldest and most widely adopted weed control practices, particularly in developing countries (Chauhan, 2020) [8]. It involves the removal of weeds either by hand or with simple implements such as khurpi, hoe, and spade, and is considered environmentally safe due to the absence of chemical inputs (Melander & Kristensen, 2011) [29]. However, despite its effectiveness in selective weed removal, this method is constrained by low efficiency under modern agricultural conditions.

The major limitations of manual weeding include its labor-intensive and time-consuming nature, resulting in low field capacity and high drudgery (Westwood *et al.*, 2018) [45]. Increasing labor shortages and rising wages further reduce its practicality, especially for large-scale farming (Chauhan, 2020) [8]. Additionally, manual tools generally have limited working width, requiring more time to cover inter-row spaces and thereby lowering overall operational efficiency. In contrast, tractor-drawn cultivators are more effective in crops with wider row spacing, where mechanized weeding is feasible.

Traditionally, weed removal relied entirely on hand pulling; however, compared to modern approaches, manual weeding is costly, inefficient, and physically demanding (Jiao *et al.*, 2022)

[21]. Prolonged bending and repetitive movements expose workers to fatigue and musculoskeletal disorders (Tewari *et al.*, 1993; Chandel *et al.*, 2018) [41, 7]. Due to human limitations, the efficiency of manual weeding is typically limited to 65–85%, with some weeds often remaining untreated (Slaughter *et al.*, 2008) [39].

Moreover, traditional tools such as long-handled hoes may cause crop damage while failing to ensure complete weed removal (Gianessi & Reigner, 2007) [18]. To address these issues, improved manual weeders have been developed. For instance, the push-pull weeder designed by Tewari *et al.* (1993) [41] demonstrated enhanced efficiency. Similarly, Goel *et al.* (2008) [20] developed an ergonomically improved manual weeder for groundnut cultivation, which outperformed conventional tools such as wheel hoes and finger weeders. The developed implement achieved a high performance index (3689.74), low plant damage (2.46–7.96%), and reduced energy consumption (8.34–40.05 kJ/min) at 11.63% soil moisture. These findings indicate that improved manual weeders can significantly enhance efficiency while reducing operator fatigue.

2.2 Animal-Drawn Weeders

Animal-drawn weeders provide an intermediate level of mechanization and are suitable for small and marginal farmers particularly in regions where access to mechanized equipment is limited (Melander & Kristensen, 2011) [29]. These implements are designed to be operated using draft animals such as oxen or donkeys, making them accessible to farmers with limited financial resources. Typically equipped with adjustable blades or tines, animal-drawn weeders efficiently remove weeds growing between crop rows, thereby reducing competition for nutrients, water, and space.

Studies indicate that animal-drawn weeders can cover approximately 0.4–0.6 hectares per day, which is significantly higher than manual weeding methods that usually cover only 0.1–0.2 hectares per day. In addition to improving efficiency, animal-drawn weeders contribute to better soil aeration by loosening the soil during operation. Improved soil structure enhances root development, promotes plant growth, and ultimately leads to higher crop yields. (Chauhan, 2020) [8]. However, their efficiency is limited by dependence on animal power and lower precision near crop rows (Westwood *et al.*, 2018) [45].

Due to their affordability, simplicity, and adaptability, animal-drawn weeders represent a sustainable and practical option for weed management, especially in developing countries. Their adoption not only reduces labor costs but also supports increased agricultural productivity and rural livelihoods.

2.3 Chemical Weed Control

Chemical weed control involves the application of herbicides to suppress or eliminate unwanted plant species. Since their introduction in the mid-20th century, particularly after 1944, herbicide use has expanded rapidly due to its effectiveness, ease of application, and ability to cover large areas efficiently. Chemical methods have become a key component of modern weed management strategies; however, their use in inter-row cropping systems requires careful application to avoid potential crop injury (Suresh *et al.*, 2016) [40].

The widespread adoption of herbicides accelerated during the Green Revolution, as farmers increasingly relied on them to improve weed control and enhance crop productivity. Herbicides have proven effective in reducing labor requirements, especially during peak agricultural seasons, and have served as a practical

alternative to manual and mechanical weeding methods. Recent studies report that chemical weed control can achieve weed management efficiencies ranging from 50% to 95%, contributing to improved crop yields and economic returns (Choudhary & Meena, 2025; Upadhyay *et al.*, 2024) ^[10, 42].

Despite these advantages, the excessive and indiscriminate use of herbicides has raised serious environmental and health concerns. Prolonged use can lead to soil and water contamination, the emergence of herbicide-resistant weed species, and adverse effects on human and animal health (Olaoye & Adekanye, 2013) ^[33]. Recent research further emphasizes that over-reliance on chemical weed control may disrupt agro-ecosystem balance and reduce long-term sustainability (Wang *et al.*, 2025) ^[44].

Effective weed management, along with pest and disease control, depends on the judicious use of pesticides and efficient plant protection equipment capable of accurately applying recommended doses to target areas (Jyoti *et al.*, 2020) ^[22]. In India, herbicides currently account for approximately 15–20% of total pesticide consumption, and their usage is steadily increasing due to labor shortages and the need for efficient weed control solutions (Choudhary & Meena, 2025) ^[10]. This trend highlights the growing importance of chemical weed control while underscoring the need for balanced and sustainable application practices.

2.4 Mechanical Weeding

Mechanical weed control is a fundamental and widely adopted approach for effective weed management in agricultural systems. Although traditionally practiced, it has evolved considerably in recent years with advancements in farm machinery and engineering technologies. Compared to chemical methods, mechanical weeding offers significant advantages, including the absence of chemical residues, reduced environmental impact, and minimal risk to crop health. It also suppresses weed growth through physical removal and soil disturbance, thereby contributing to sustainable crop production (Wang *et al.*, 2014; Upadhyay *et al.*, 2024) ^[43, 42].

Mechanical weeders are designed to perform operations such as cutting, uprooting, and burying weeds. Historically, these implements were powered by draft animals such as bullocks and buffaloes; however, with the progression of mechanization, tractors have become the primary power source for such operations (Gianessi & Sankula, 2003) ^[19]. Mechanical weed control is particularly favored in organic and low-input farming systems, where reducing herbicide use is essential (Melander & Kristensen, 2011) ^[29].

This method primarily involves inter-row weeding, which targets weeds growing between crop rows without causing significant damage to the crop. Mechanical weeding is most effective during the early stages of crop growth when weeds are small and easier to remove. However, at later growth stages, the use of tractors and cultivators may lead to crop damage due to insufficient ground clearance relative to plant height (Jiao *et al.*, 2022) ^[21]. Recent studies also highlight that proper adjustment and calibration of mechanical weeders are critical to improving efficiency and minimizing crop injury (Li *et al.*, 2023) ^[26].

Several improved mechanical weeders have been developed to enhance performance and reduce soil disturbance. For example, the basket weeder, a ground-driven implement, operates without requiring additional power beyond tractor draft and uses rotating baskets to remove weeds from the topsoil while minimizing disturbance to crop rows (Bowman, 1997). More recently, electrically powered inter-row weeders have been introduced.

Pandey *et al.* (2023) ^[34] developed an e-powered weeder equipped with a battery, DC motor, and rotary weeding unit, enabling efficient weed removal with reduced labor input. Furthermore, modern developments include sensor-assisted and semi-automated mechanical weeders that enhance precision and operational efficiency (Wang *et al.*, 2025) ^[44].

Different types of mechanical weeders operate at varying speeds and depths, resulting in differences in performance under diverse field conditions. Their effectiveness is commonly evaluated based on parameters such as weeding efficiency, field capacity, crop damage, and energy consumption. Recent findings suggest that advanced mechanical weeders can achieve weeding efficiencies exceeding 80% while significantly reducing labor requirements (Upadhyay *et al.*, 2024) ^[42].

2.5 Power Weeders

Power weeders are compact, lightweight machines powered by petrol or diesel engines, designed for efficient weed removal while simultaneously loosening the soil to improve aeration and moisture retention (Kachhot *et al.*, 2021) ^[23]. These machines are widely used for inter-cultivation and weeding operations in a variety of crops, including horticultural, plantation, and field crops such as vegetables, fruits, sugarcane, and paddy. The adoption of power weeders has significantly reduced labor requirements, operational time, and the physical drudgery associated with traditional weeding practices.

In terms of efficiency, power weeders offer a substantial advantage over manual methods. For example, a power weeder can cover one hectare in approximately 10 man-hours, whereas manual weeding in crops like maize may require up to 167 man-hours (Dixit & Syed, 2008) ^[13]. Manual weeders are limited by their narrow working width and slower operational speed, making them less suitable for large-scale farming. In contrast, tractor-drawn cultivators are more effective in crops with wider row spacing, where mechanized operations can be performed efficiently.

Rotary-type power weeders are particularly effective, as they remove weeds by disturbing their root systems while simultaneously pulverizing and loosening the soil. This process enhances soil aeration, which is essential for proper root development and crop growth. Additionally, the powered rotary action reduces draft requirements and improves field performance, resulting in higher operational efficiency (Upadhyay *et al.*, 2024) ^[42].

Recent advancements in power weeding technologies include the development of electrically operated and sensor-assisted weeders, which enhance precision and reduce energy consumption (Li *et al.*, 2023; Wang *et al.*, 2025) ^[26, 44]. These modern systems are increasingly aligned with precision agriculture practices, enabling more efficient and sustainable weed management. The performance of power weeders is generally evaluated based on parameters such as depth and width of cut, effective field capacity, weeding efficiency, crop damage, and cost of operation.

3. Challenges in Intra-row Weeding

Weeds growing within crop rows (intra-row weeds) are often not effectively controlled by inter-row mechanical weeders, which has led to the development of specialized intra-row weeding technologies. Intra-row weed control is particularly challenging because it requires precise removal of weeds without damaging adjacent crop plants (Rasmussen, 1990) ^[38]. In recent years, research has focused on improving the precision and efficiency of such systems through better design and operational

optimization (Upadhyay *et al.*, 2024) ^[42].

One of the early mechanical solutions is the spring-tine harrow weeder, which operates at a working width of 6–24 cm and a forward speed of 6–8 km h⁻¹ (Kouwenhoven, 1997) ^[25]. Its performance depends on several factors, including crop and weed height, growth stage, forward speed, tine angle, and weed composition (Rasmussen, 1990) ^[38]. A brush weeder, consisting of flexible nylon or fiberglass brushes rotating along vertical or horizontal axes, has also been developed for intra-row weed removal. The inclusion of protective guards helps minimize crop damage during operation (Kouwenhoven, 1997) ^[25].

The torsion weeder is another commonly used implement, typically operated in combination with inter-row cultivation tools. It consists of two spring tines mounted on a rigid frame and positioned to work close to the soil surface within the crop row. While effective in suppressing weeds, its performance is highly sensitive to steering accuracy, and any deviation can damage crops and reduce yield. Additionally, its operation at low forward speeds limits field capacity (Bleeker *et al.*, 2002; Melander *et al.*, 2004) ^[5, 29].

The finger weeder is a widely used intra-row implement consisting of rotating cones fitted with flexible rubber spikes (weeder fingers) that penetrate the soil surface and remove small weeds near crop plants. However, its effectiveness decreases under conditions such as compacted soil, crust formation, or the presence of crop residues. Recent studies suggest that combining finger weeders with other mechanical tools can enhance overall weeding efficiency and adaptability under varying field conditions (Li *et al.*, 2023) ^[26].

Recent advancements in intra-row weed control focus on precision-based and automated systems. Sensor-assisted and robotic weeders are being developed to accurately detect and remove weeds within crop rows, minimizing crop damage and improving efficiency (Wang *et al.*, 2025) ^[44]. These innovations represent a shift toward intelligent and sustainable weed management systems capable of overcoming the limitations of conventional mechanical methods.

4. Advances in Autonomous and Robotic Weeding

4.1 Robotic Inter-row Weeding

Robotics in weed control is advancing agriculture toward greater efficiency, precision, and sustainability by reducing dependence on herbicides. Modern robotic systems utilize advanced sensing technologies, including RGB, multispectral, and hyperspectral imaging, for real-time weed detection and targeted control. These systems, combined with robotic arms and autonomous navigation, enable precise intra-row and inter-row weeding operations, addressing labor shortages and rising wage costs (Yan *et al.*, 2024; Upadhyay *et al.*, 2024) ^[46, 42].

Recent developments highlight a shift toward fully autonomous and intelligent weeding systems. Robots such as Tertill demonstrate simple sensor-based weed removal for small-scale applications, while advanced platforms like BoniRob and AgBot-II integrate machine vision, GPS, and AI for field-scale operations (Bawden *et al.*, 2017; Chebrolu *et al.*, 2017) ^[4, 9]. Studies report that robotic weeders can achieve weed control efficiencies of 70–95% while significantly reducing chemical usage (Wang *et al.*, 2025; Li *et al.*, 2023) ^[44].

Furthermore, recent innovations include solar-powered robots, machine learning-based weed identification systems, and hybrid platforms combining mechanical and laser-based weed control (Patel *et al.*, 2022) ^[35]. These technologies improve precision, reduce environmental impact, and enhance operational efficiency. Robotic weed control systems are expected to play a

critical role in future precision agriculture by enabling sustainable, autonomous, and site-specific weed management.

4.2 Robotic Intra-row Weeding

Automation in weed control enables precise identification and removal of weeds without damaging crop plants, thereby reducing the need for manual labor and herbicide use (Bakker, 2009; Slaughter *et al.*, 2008) ^[3, 39]. Intra-row robotic weeding requires advanced technologies capable of distinguishing crops from weeds (Zhang *et al.*, 2022) ^[47]. Modern systems integrate technologies such as machine vision, sensors, GPS/RTK guidance, and artificial intelligence to achieve accurate crop–weed differentiation and autonomous operation (Kocher *et al.*, 2009; Upadhyay *et al.*, 2024) ^[24, 42].

Recent advancements in deep learning and multispectral imaging have significantly improved weed detection accuracy, enabling real-time decision-making and site-specific weed management. Vision-based and sensor-guided systems can achieve positional accuracies within 5–10 mm and operational efficiencies of 80–95% under field conditions (Li *et al.*, 2023; Wang *et al.*, 2025) ^[26, 44]. Additionally, embedded platforms and robotic systems are capable of identifying multiple weed species and executing precise mechanical or electrical control actions (Frontiers in Plant Science, 2024).

Despite these advancements, system performance is influenced by factors such as crop spacing, forward speed, and soil conditions. Nevertheless, automated weed control systems represent a key component of precision agriculture, offering efficient, sustainable, and labor-saving solutions for future farming (Yan *et al.*, 2024) ^[46].

5. Precision Weeding Technologies

Pesticide application remains a dominant method for weed control; however, its excessive use raises serious environmental and sustainability concerns (Rani *et al.*, 2021) ^[37]. Precision agriculture offers a viable alternative by integrating sensors, data analytics, and site-specific management to improve productivity while reducing chemical inputs (Zhu *et al.*, 2018; Monteiro *et al.*, 2021) ^[48, 30]. Technologies such as IoT-based sensors, unmanned aerial vehicles (UAVs), and satellite imaging are increasingly utilized for efficient and targeted weed management (Upadhyay *et al.*, 2024) ^[42].

Variable Rate Technology (VRT) enables precise application of herbicides based on spatial variability, thereby optimizing input use and minimizing environmental impact (Lima & Mendes, 2020) ^[27]. Recent advancements in artificial intelligence, deep learning, and hyperspectral imaging have further enhanced weed detection accuracy, enabling real-time and site-specific weed control (Li *et al.*, 2023; Wang *et al.*, 2025) ^[26, 44]. In addition, remote sensing platforms, including satellites and UAVs, provide high-resolution data for large-scale weed mapping and decision support (Burgos *et al.*, 2020) ^[6].

Overall, precision farming technologies are transforming weed management by promoting efficient, data-driven, and sustainable practices, reducing dependence on conventional pesticide-based approaches (Westwood *et al.*, 2018; Yan *et al.*, 2024) ^[45, 46].

6. Comparative Evaluation of Weeding Methods

Weed control methods vary widely in terms of efficiency, cost, labor requirements, and environmental impact (Chauhan, 2020) ^[8]. Manual methods are labor-intensive and time-consuming, while chemical methods offer high effectiveness but pose risks to environmental and human health. Mechanical and robotic

approaches provide a balanced alternative by improving operational efficiency and reducing reliance on herbicides (Melander & Kristensen, 2011; Upadhyay *et al.*, 2024) ^[29, 42]. Recent research highlights the importance of Integrated Weed Management (IWM), which combines cultural, mechanical, chemical, and advanced technological approaches for sustainable weed control (Westwood *et al.*, 2018; Wang *et al.*, 2025) ^[45, 44]. Such integrated strategies enhance productivity while minimizing ecological risks and improving long-term sustainability.

7. Conclusion

Effective weed management is essential for ensuring sustainable agricultural productivity, particularly in the context of increasing global food demand and resource constraints (FAO, 2023) ^[15]. Weeds remain one of the most significant biotic constraints in crop production, causing substantial yield and economic losses if not managed efficiently (Oerke, 2006; Chauhan, 2020) ^[32, 8]. Traditional methods such as manual and animal-drawn weeding, although widely practiced, are labor-intensive, time-consuming, and increasingly impractical due to labor shortages and rising costs (Westwood *et al.*, 2018) ^[45].

Chemical weed control offers high efficiency and rapid action; however, its excessive and indiscriminate use poses serious environmental and health risks, including soil degradation and the development of herbicide-resistant weed species (Olaoye & Adekanye, 2013; Wang *et al.*, 2025) ^[33, 44]. In contrast, mechanical and power-operated weeders provide environmentally safer alternatives with improved efficiency, although their performance depends on proper design, field conditions, and operational management (Melander & Kristensen, 2011; Upadhyay *et al.*, 2024) ^[29, 42].

Recent advancements in automation, robotics, and precision agriculture have significantly transformed weed management practices. Technologies such as machine vision, artificial intelligence, IoT-based sensors, UAVs, and variable rate technology enable accurate weed detection and site-specific control, thereby reducing chemical inputs and enhancing efficiency (Li *et al.*, 2023; Yan *et al.*, 2024) ^[26, 46]. Robotic weeders capable of both inter-row and intra-row operations have demonstrated high precision and effectiveness, offering promising solutions to labor shortages and sustainability challenges (Wang *et al.*, 2025) ^[44].

Despite these technological advancements, challenges such as high initial investment, technical complexity, and adaptability under diverse field conditions remain significant barriers to widespread adoption. Therefore, Integrated Weed Management (IWM), which combines cultural, mechanical, chemical, and advanced technological approaches, is essential for achieving sustainable and effective weed control (Westwood *et al.*, 2018; Upadhyay *et al.*, 2024) ^[45, 42].

In conclusion, the future of weed management lies in the integration of advanced technologies with conventional practices to develop efficient, cost-effective, and environmentally sustainable solutions. Continued research, innovation, and adoption of precision and robotic technologies will play a critical role in enhancing agricultural productivity and ensuring global food security (FAO, 2023; Yan *et al.*, 2024) ^[15, 46].

8. Future Recommendations

Future research should prioritize the development of cost-effective, energy-efficient, and user-friendly weeding technologies that are accessible to small and marginal farmers, particularly in developing countries (Upadhyay *et al.*, 2024; Li

et al., 2023) ^[42, 26]. Emphasis should be placed on integrating artificial intelligence (AI), machine learning, and computer vision for accurate and real-time weed detection and classification, enabling precise intra-row and inter-row weed management (Zhang *et al.*, 2022; Wang *et al.*, 2025) ^[47, 44].

The advancement of autonomous robotic weeders and sensor-based systems should focus on improving adaptability under diverse field conditions, reducing system complexity, and lowering initial investment costs to enhance large-scale adoption (Yan *et al.*, 2024) ^[46]. Additionally, the integration of Internet of Things (IoT), unmanned aerial vehicles (UAVs), and remote sensing technologies can further strengthen site-specific weed management and decision support systems (Monteiro *et al.*, 2021; Burgos *et al.*, 2020) ^[30, 6].

Future strategies should also aim at minimizing herbicide dependency by promoting precision application techniques such as Variable Rate Technology (VRT) and combining them with mechanical and biological approaches under an Integrated Weed Management (IWM) framework (Lima & Mendes, 2020; Westwood *et al.*, 2018) ^[27, 45].

Moreover, research should address challenges related to energy efficiency, scalability, and real-time processing capabilities of advanced weeding systems. The development of solar-powered and low-energy robotic platforms can contribute significantly to sustainable agriculture (Wang *et al.*, 2025) ^[44].

Overall, a multidisciplinary approach involving agronomy, agricultural engineering, data science, and environmental science is essential to develop innovative, sustainable, and economically viable weed management solutions for future farming systems.

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