Review of cutting-edge weed management strategy in agricultural systems

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Abstract: Weed control in agricultural systems is of the utmost importance. Weeds reduce crop yields by up to 30% to 40%. Different methods are used to control weeds, such as manual, chemical, mechanical, and precision weed management. Weeds are managed more effectively by using the hand weeding method, which nevertheless falls short due to the unavailability of labor during peak periods and increasing labor wages. Generally, manual weeding tools have higher weeding efficiency (72% to 99%) but lower field capacity (0.001 to 0.033 hm^2/h). Use of chemicals to control weeds is the most efficient and cost-effective strategy. Chemical weedicides have been used excessively and inappropriately, which has over time resulted in many issues with food and environmental damage. Mechanical weed control improves soil aeration, increases water retention capacity, slows weed growth, and has no negative effects on plants. Mechanical weed management techniques have been gaining importance recently. Automation in agriculture has significantly enhanced mechanization inputs for weed management. The development of precision weed management techniques offers an efficient way to control weeds, contributing to greater sustainability and improved agricultural productivity. Devices for agricultural automated navigation have been built on the rapid deployment of sensors, microcontrollers, and computing technologies into the field. The automated system saves time and reduces labor requirements and health risks associated with drudgery, all of which contribute to more effective farm operations. The new era of agriculture demands highly efficient and effective autonomous weed control techniques. Methods such as remote sensing, multispectral and hyperspectral imaging, and the use of robots or UAVs (drones) can significantly reduce labor requirements, enhance food production speed, maintain crop quality, address ecological imbalances, and ensure the precise application of agrochemicals. Weed monitoring is made more effective and safer for the environment through integrated weed management and UAVs. In the future, weed control by UAV or robot will be two of the key solutions because they do not pollute the environment or cause plant damage, nor do they compact the soil, because UAV sprays above the ground and robotic machines are lighter than tractor operated machines. This paper aims to review conventional, chemical, mechanical, and precision weed management methods.

Keywords: hyperspectral, multispectral, precision weed management, robot, remote sensing, unmanned aerial vehicle, weeds, weeder
DOI: 10.25165/j.ijabe.20251801.9583

Citation: Gatkal N R, Nalawade S M, Shelke M S, Sahni R K, Walunj A A, Kadam P B, et al. Review of cutting-edge weed management strategy in agricultural systems. Int J Agric & Biol Eng, 2025; 18(1): 25–42.

1 Introduction

The world population is expected to reach 9 billion by the year 2050. To meet the requirement of food for this population, the world's food production must increase by 70% to 100%[1]. The effectiveness of present agricultural practices will be challenged as food demands increase due to the increasing world population. Several factors are responsible for yield reduction, like climate change; water scarcity; overuse of fertilizer, pesticides, insecticides, and weedicides, which result in loss of soil fertility; and lack of proper weed management techniques. Among all the factors, improper weed management results in the highest yield loss.

Weeds are essentially plants that are considered unusual due to their interference with human activities and well-being[2]. Within a crop production system, weeds vie for the same resources as the crops - namely, water, nutrients, sunlight, and space - which ultimately restricts the productivity of the cultivated crops. The robust competition from aggressive weeds substantially diminishes crop yields and imposes additional expenses on crop production due to weed management. The extent of yield loss attributed to weeds depends on various factors, including weed density, the timing of

Received date: 2024-11-30 **Accepted date:** 2025-01-08
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their emergence, the specific weed species, and the type of crop being grown[3,4]. On a global scale, weeds represent the most significant threat, accounting for a potential loss of 34%, whereas animal pests and pathogens are comparatively less significant, leading to losses of 18% and 16%, respectively[5]. On average, it is estimated that weeds contribute to a 5% reduction in agricultural yield and economic losses in most developed nations, while this figure rises to 10% in developing countries and a substantial 25% in underdeveloped countries, such as India[5]. Yaduraju and Mishra[6] reported that weed management in India is Rs. 6000/hm^2 (33% total production cost) and Rs. 4000/hm^2 (22% total production cost) for kharif and rabi crops, respectively. In India, the annual yield losses due to weeds in grain crops were estimated at 11 billion USD[7]. Depending on the crop, the level of weed species, the types of plants, and management practices, weeds reduced crop yield by about 65%[8,9]. The labor required per hour per hectare for weeding operations was 560 respectively. Weed control is still essential for efficient crop loss management and high-quality crop production because conventional weed control methods still result in an average yield loss of 15%-20%[10,11]. The extent of yield reduction caused by weed competition varies significantly depending on the specific weed species and their interaction with the crop (Table 1).

Weed management is a technique that makes use of technical knowledge to guarantee the success of a particular weed population in an agricultural field[12,13]. Weeds in inter- and intra-row crops are controlled by various methods such as manual, mechanical, and chemical[14] (Figure 1). Hand weeding is a tedious, labor-intensive, costly method[15]. Mechanical weed control includes various weeders, but each weeder has unique features, since particular weeders are developed for particular crops[16]. Chemical weeding is harmful to both human operators and the environment[17]. Although there are several intra-row weed control methods, including soil steaming, laser radiation, and flame[18,19], the effectiveness of these methods is limited to certain soil and plant conditions. They also call for additional steam and flame generation systems, which are expensive and require more fuel[20,21]

Table 1 Reduction in crop yield of various crops due to weeds

Name of crop	Yield reduction/%	Reference
Direct seeded paddy	45-90	[22]
Transplanted paddy	15-38	[22]
Maize	28-93	[22-24]
Sorghum	6-40	[22]
Finger millet	26-27	[25]
Redgram	20-47	[22]
Soybean	40-60	[22,26]
Wheat	26-38	[27-31]
Oat	26-30	[30]
Lucerne	50-90	[32]
Chickpea	15-25	[30]
Lentil	20-30	[30]
Pea	20-30	[30]
Mustard	15-30	[30]
Lineseed	30-40	[30]
Safflower	35-60	[30]
Groundnut	20-50	[31]
Sesame	50-75	[31]
Sunflower	30-64	[31]
Castor	15-25	[31]
Cotton	74-96.5	[33]
Niger	30-33	[31]
Jute	58-70	[34]
Coriander	20-50	[35]
Sugarcane	40-67	[36]
Egyptian clover	30-40	[31]
Brinjal	49-90	[37]
Tapioca	40-50	[38]

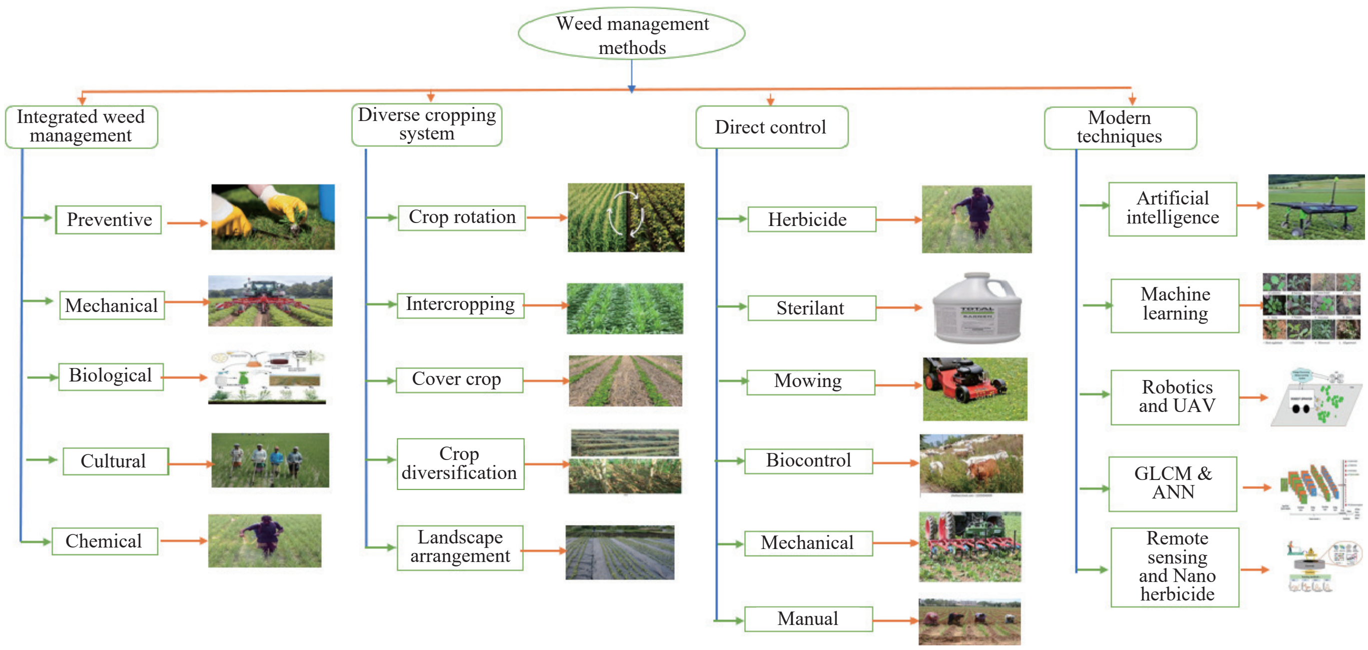


Figure 1 Types of weed management techniques

Manual, animal, or mechanical strength is used to remove or cut weeds due to the physical force of weed management. According to the type of weed and crop, either one or both of these techniques are used. The main physical weed control methods are hand weeding, hand hoeing, digging, mowing, cutting, tillage, burning, intercropping, and the use of mulch[23]. In India, weeds are mostly controlled by hand or with small hand tools. Currently, the physical method is the most effective and rapid for weed control because it does not leave any chemical or herbicide residue on crops.

Worldwide, there is also an increase in agricultural automation technology to manage weeds. Currently, India is facing two major challenges. The first is to provide food to such a large population at an affordable cost by using traditional methods. Secondly, with the unavailability of labor during critical periods and increasing labor wages day by day for agricultural operations, there is a need to search for alternative options. Precision weed management techniques such as sensors, microcontrollers, vision-based UAVs, and robotics can address these two major challenges in the upcoming years[23].

Therefore, a shift to sustainable weed management is needed as precision farming has the potential to save natural resources for the future and improve agriculture at a lower cost[39]. A variety of weed control methods are included in sustainable weed management, such as integrated weed management (IWM), which is based on the use of different weed control techniques[40]. In this scenario, a wide variety of innovative technologies have been developed and integrated into agricultural operations, which also significantly contribute to the advancement of weed management approaches that are both environmentally and economically beneficial[41]. Precision weed control reduces inputs while maintaining weed control effectiveness. This paper aims to review manual, mechanical, chemical, robotic, and sensor-based weed control methods used in the agricultural field.

2 Weed control methods

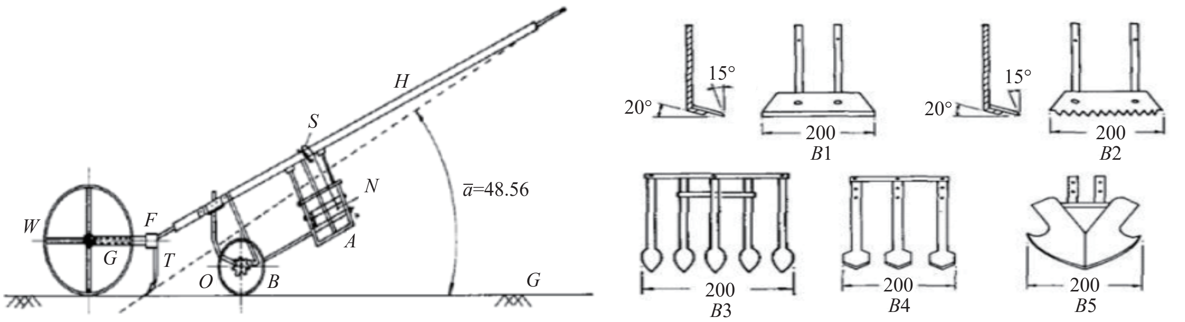
Different weed control methods include manual, mechanical, and chemical weeding, as well as the precision weed management method, unmanned vehicles, and robotics.

2.1 Conventional weed control methods

2.1.1 Manual weeding

Weeding is usually carried out with local hand tools, which is very labor-intensive[42]. Weeds are pulled by hand when using the manual method[43,44]. The manual weeder has a narrow working width and takes longer to cover the space between crops. A tractor-drawn cultivator was tested for weeding operations and found to be effective for weeding crops with wide row spacing.

Earlier, farmers used to remove weeds using just their hands. Manual weeding is time-consuming, labor-intensive, tedious, inefficient, and costly compared to other methods[45]. This method has been eliminated since it puts workers in a bending posture for a longer period and creates health risks[46-49]. Due to missed weeds or human error, only 65% to 85% of weeds are successfully removed with the hand weeding method[50]. Furthermore, it has been asserted that employing long-treated hoes would damage the crops and leave a few weeds in the field[51]. Tewari et al.[46] developed and evaluated a push-pull weeder (Figure 2a). Furthermore, five types of blades (straight flat, straight flat with serrated edge, five tines, sweep type, and double plough type blade) were tested (Figure 2b). The width of cut, cutting angle, and sharpness angle for each blade were 20 cm, 20°, and 15°, respectively. The straight flat blade works better than all other blades. Goel et al.[52] developed and ergonomically tested a manual weeder in groundnut field with highest performance index (3689.74), lowest plant damage rate (2.46% to 7.96%), and lowest energy consumption rate (8.34 to 40.05 kJ/min) at 11.63% moisture content when compared to other weeders such as wheel finger weeder, wheel hoe, and traditional weeding. Table 2 presents different manual weeders and their performance parameters.



a. Push pull weeder b. Different types of blade

Note: B1=Straight flat blade; B2=Straight flat blade with serrated edge; B3=Five tines blade; B4=Sweep type blade; B5=Double plough type blade

Figure 2 Manual operated push-pull weeder and different types of blades

Table 2 Manual weeding tools

Tools	Width of cut/ mm	Field capacity/ $hm^2 \cdot h^{-1}$	Weeding efficiency/ %	Work rate/ $man \cdot h \cdot hm^{-2}$	Energy requirement/ $MJ \cdot hm^{-2}$
Khurpi	80	0.001-0.002	92-99	300-500	567.62
Gruber	-	0.004-0.008	82-96	109	212.62
Spade	220	0.0002	75.7-92	120-126	326.62
Wheel hoe	230	0.008-0.009	72-94	86	167.30
Push-pull type weeder	150-250	0.026-0.033	80-90	100-125	140.5

(Source: [10])

2.1.2 Chemical weeding

The chemical method applies herbicides to kill weeds. Since 1944, there has been a significant increase in herbicide use. Weed management can be effectively achieved by chemical methods, but in inter-row crops, these methods create problems for crops[53]. Since the "Green Revolution", farmers have increasingly relied on herbicides to manage weeds and boost profits. Herbicides have helped address labor shortages during peak agricultural seasons, improved weed control through repeated applications, and provided an effective alternative where physical weed management methods often prove inadequate. Most of the time, farmers accept mechanical or manual weed control methods because chemical methods have a negative impact on the environment and are harmful to human and animal health[17]. By distributing, spreading, and depositing recommended chemical doses on the desired target, usage of pesticide and effective plant protection devices plays a vital role in the management of diseases, pests, and weeds[54]. Choudhury et al.[55] reported that more than 10% of the nation's total agricultural land is covered with herbicides. Herbicide application accounts for 20% of total pesticide application in India for weed control.

2.1.3 Mechanical weeding

Mechanical control is among the most important weed management methods. Although it is one of the ancient weed control methods, recent advances in technology have helped to shape it as an innovative weed control technique. Mechanical weeding has several advantages over chemical weeding, i.e., slow growth of weeds and no adverse effect on plant growth. Mechanical inter-row weeders serve the purpose of either completely or partially removing weeds[56]. Various mechanical weeders have been designed for tasks such as cutting, uprooting, and burying weeds in the soil. In the earlier stages of development, these weeding implements were typically pulled by draft animals like bullocks and buffaloes. However, over time, there has been a transition to using tractors as the primary power source[57]. Mechanical weed management is predominantly adopted by farmers who prefer to avoid the use of herbicides. This approach involves inter-row weeding, which targets and removes weeds from the spaces between crop rows without affecting the crop. The effectiveness of mechanical weed management is most pronounced during the early stages of crop growth. During the later stages of crop growth, tractors and cultivators can potentially damage the crop foliage. This is because their ground clearance is often less than the height of the growing crop plants[45]. The basket weeder was developed[58] and operated without the need for any additional power source apart from the tractor's draft. This ground-driven implement is equipped with rectangular-shaped round baskets which efficiently remove weeds from the top layer of the soil while minimizing soil disturbance in the crop rows. It works optimally in soil with high moisture content and is effective at speeds ranging from 6.4 to 12.9 km/h.

Tamil Nadu Agricultural University (TNAU), Coimbatore, developed a tractor-mounted rotary weeder with three rows, which consisted of four "L"-shaped blades on each flange[59]. This machine was tested in a sugarcane field at speeds ranging from 2 to 4 km/h, width of 2.0-2.4 m, and row spacing between 67.5-90.0 cm. The weeding efficiency was in the range from 61% to 82% with crop damage less than 3%. Additionally, the developed weeder significantly saves labor by more than 70% and costs by more than 50%. Sutthiwaree et al.[60] designed a weeder with three rows of coil spring full sweep tines that gave optimum performance when tested in a sugarcane field. It achieved a field capacity of 0.54 hm^2/h, a weeding efficiency of 94.66%, and a fuel consumption of 5.58 L/hm^2.

In Germany (Asperg Gartnereibedarf, Germany), a split-hoe was used to manage weeds in the inter-row between herbaceous, horticultural, and greenhouse plants. A split hoe can be used to eliminate weeds growing between the rows, between 0.4-0.5 m and 0.2-0.25 m. To protect the crop plants, a shield is provided. It ends up leaving an 80 mm-wide swath of uncultivated soil. Weeding was carried out using gangs of spike wheels that are positioned on a horizontal axis and are powered by the tractor's power takeoff (PTO)[61].

Most prior weeders were designed to be horizontal, and research on vertical-axis rotating weeders is limited. To eliminate an external powering mechanism that provides the power to remove unwanted plants, a self-propelling vertical-axis rotary weeder was developed[62]. The machine was tested in maize crop with operating depths of 2-4 cm and crop growth stages of 15 and 30 DAS. The developed weeder performed excellently at all phases of crop development, with plant damage ranging from 1.98% to 5.88% and weeding efficiency between 65%-70%.

The assessment of self-propelled rotary weeders and a tractor-operated sweep weeder was conducted with cotton[63]. The study reported a weeding efficiency of 94%-95% and plant damage of 1%-4%, a field capacity of 0.11 hm^2/h to 0.13 hm^2/h for self-propelled weeders, and 0.2-0.4 hm^2/h for tractor-operated weeders. Pandey[64] designed and developed an e-powered inter-row weeder which consisted of a battery (24 V, 24 Ah), DC motor with speed controller, drive wheel, weeding unit (drum and tool), main frame, transport wheel, and handle. The weeding efficiency, plant damage, field capacity, total manpower required for weeding, and cost of operation was 91.68%, 3.14%, 0.049 hm^2/h, 20.41 man-h/hm^2, and 1168.37 Rs/hm^2, respectively, at forward speed of 3 km/h. Various mechanical weeders that can effectively remove inter-row weeds at different speeds and depths with their effectiveness are presented in Table 3.

Table 3 Inter-row weeders and their performance parameters

Tools	Depth of cut, mm	Field capacity/ hm^2·h^{-1}	Weeding efficiency, %	Speed of operation/ km·h^{-1}
Rotary weeder	40-50	0.24-0.50	61-87	2.0-4.0
Sweep cultivator	20-40	0.54	84-94	2.0-4.0
Chemical weeding	on surface	2.00-5.00	90	2.9-9.7
Self-propelled rotary power weeder	20-50	0.08-0.09	91-95	1.3-2.5
E-powered inter-row weeder	45	0.049	91.68	3.0

2.2 Power weeder for inter-row weeding

The power weeder is a compact, light-weight machine powered by either petrol or diesel engines that is used to remove weeds but also keep the soil surface loose, ensuring better soil aeration and water holding capacity[65]. The main purpose of this machine is to inter-cultivate or de-weed between rows of different agriculture, horticulture, and plantation crops such as paddy, sugarcane, fruits, vegetables, etc. The development of the power weeder is beneficial for reducing the time involved in weeding operation, reducing drudgery due to continuous changing in posture of farm workers, andreducingthecostofoperation.Withtheuseofthepowerweeder,10man-h are required to cover one-hectare area as compared to 167 man-h for weeding manually for maize crop[66]. The power weeder has higher field capacity compared to hand khurpi, peg type dry land weeder, and animal-drawn blade hoe[67]. The manual weeder has a limitation of working width and requires more time to cover area between crops. Tractor-drawn cultivators were evaluated for weeding operation and found successful for weeding in large row spaced crops[44]. The rotary type of weeder stirs the soil more accurately, disturbs the weed roots, and removes them from the soil. In addition, this helps in keeping the soil in loose condition for proper aeration. The major advantage of rotary power weeder is that the power being used for rotary weeder blades requires less draft and improved field performance.

Gatkal et al.[68] studied the performance and economical evaluation of two row self-propelled narrow crop rotary weeders in mustard crop at three forward speeds (1.5, 2.0, 2.5 km/h), three rotary speeds (330, 360, 390 r/min) and two blade lengths (180, 195 mm), respectively. Sahu and Raheman[69] developed a solar energy-operated weeder for wetland paddy crop. Kachhot et al.[65] developed a solar-operated walking type power weeder. The weeder was operated at three forward speeds of 1.0-1.5 km/h, 1.5-2.0 km/h, and 2.0-2.5 km/h. Kumari et al.[62] developed a solar-operated power weeder and its performance was evaluated in maize crop. A number of three blades per flange was better to give maximum weeding efficiency and minimum plant damage as compared to two blades per flange. Dhruwe et al.[70] evaluated a field performance of L-shaped blade rotary tiller cum inter-row weeder. The machine was operated with four forward speeds and the distance traveled per unit time increased by increasing the operational speed. Chandel et al.[71] studied the self-propelled rotary power weeder in the three vegetable crops of tomato, yard long bean, and okra. A weeder was operated at three forward speeds (2.3 km/h, 2.0 km/h, and 2.4 km/h) in tomato, yard long bean, and okra, respectively. The depth and width of cut, effective field capacity, and weeding efficiency, plant damage, and cost of operation of different developed weeders are listed in Table 4.

Table 4 Performance evaluation carried out by different studies for different rotary power weeders

Power source	Width of cut/mm	Depth of cut/mm	Type of blade	Field capacity/ $hm^2 \cdot h^{-1}$	Weeding efficiency/%	Plant damage/%	Cost of operation/ $Rs \cdot hm^{-2}$	Source
5.5 hp diesel	660	-	L-type	0.0347	98.74	0.94	3878	[72]
Solar panel (battery 12V 12A)	350	30	-	0.12	90.24	7.40	-	[65]
5 hp diesel engine	600	50	L-shape	0.09	80.12	2.9	1733	[68]
SPV powering system capacity (20 Ah)	200, 250, 300	30 - 70	Plane blades	0.06	83	2-3	3607	[69]
1.03 KW engine	120 to 180	40 - 50	Rotary blade	0.0257	61.53	Nill	3823	[73]
160 W solar panel	240	35	-	0.021	88.03	1.96	-	[62]
5 HP diesel engine	100	80	L-type	0.19	94	-	970	[70]
4 kW air-cooled diesel engine	400	53, 46, and 50	L-shape	0.092, 0.080, 0.096	96, 94, and 97	1.6, 2.8, and 1.9	589	[71]

3 Mechanical weed management in intra-row crops

Despite the use of mechanical weeders for eliminating weeds in the inter-row crops, the weeds in intra-row crops are still uncontrolled. Therefore, intra-row weeders have been designed and developed from time to time. The spring-tine harrow weeder operated at a working width and speed of 6 to 24 cm and 6-8 km/h, respectively[74]. The major factors affecting weed-crop interaction included height of crops and weeds, growth phase differences, duration of operation, forward speed, tine angle, and weed composition[75]. Kouwenhoven[74] developed a manually operated brush weeder which consists of flexible brushes made of fiberglass or nylon that revolve around a vertical or horizontal axis (Figure 3a). A guard is provided to avoid crop damage. A tool for controlling weeds between vegetable rows, the torsion weeder is usually used in conjunction with additional inter-row cultivation blades[48]. The developed torsion weeder, consisting of two spring tines connected to a rigid frame that is inclined downward or backward inside a row, allowed the two fast segments to work closely together and parallel to the soil surface (Figure 3b). The tines suppress the weeds within the rows. Any steering error, however, detracts from the yield and damages the main crop. The work has a very low operating capacity because it must also operate at relatively low forward speeds[48,76,77]. A finger weeder is a simple mechanical intra-row weeder made of two sets of metal cones that have been blunted and are powered by metallic tines that are vertically orientated. While the crop row is in between the cones, the cones have rubber spikes, also known as weeder fingers, that are horizontally pointing outward (Figure 3c). The finger weeder performs well in loose soil but not in compacted or incrusted soil or where long stem residues are left over on the ground[48]. A rubber finger which was penetrated in soil surface was used to remove small weeds closer to fingers (Table 5).

a. Brush weeder b. Torsion weeder c. Finger weeder d. ECO weeder

Figure 3 Mechanical intra-row weeders

Table 5 Field performance of intra-row weed management weeders

Device	Depth of operation/ mm	Field capacity/ $hm^2 \cdot h^{-1}$	Weeding efficiency/ %	Speed of operation/ $km \cdot h^{-1}$	Cost of operation, $Rs \cdot hm^{-2}$
Finger weeder	10-40	0.30-0.60	55-60	4.8-9.6	7000-7500
Torsion weeder	10-50	0.10-1.40	60-80	6.4-8.1	4000-4500
ECO weeder	25-50	0.05-0.15	60-80	0.8-2.4	9000-9500
Flame weeder	On surface	0.10-0.50	80-90	1.6-6.4	16 000-16 500

Sources: [48, 78-82]

ECO weeder is a tractor-operated three-point hitch implement which is used to remove weeds within intra-rows (Figure 3d). The PTO of tractor was used to operate the weeding unit of ECO weeder. The developed ECO weeder reduces weeding costs up to 60% compared to manual weeding. The field performance of intra-row weed management implements and the effect of speed on weed control are shown in Tables 5 and 6, respectively. Chandel et al.[78] developed a mechanical inter- and intra-row weeding system and tested it in field crops. The optimum rotary speed-to-forward speed ratio for intra-row tine weeder was 0.8:1.3, with weed mortality of 88.4% (8.5% buried and 79.9% uprooted), lower plant damage (<6%), and field capacity of 0.22-0.26 hm^2/h at the recommended speed of 0.50-0.56 m/s.

Table 6 Effect on speed of inter-/intra-row weed management

Device	Depth of operation/mm	Speed of operation/ $km \cdot h^{-1}$	Weeding efficiency/%
Brush weeder	20-30	< 3.50	60-80
Harrow	20-30	7.00	70-80
Hoe ridger	25-40	7.00	80-90
Sensor base vertical axis rotor weeder	20-60	1.00-2.58	75-90

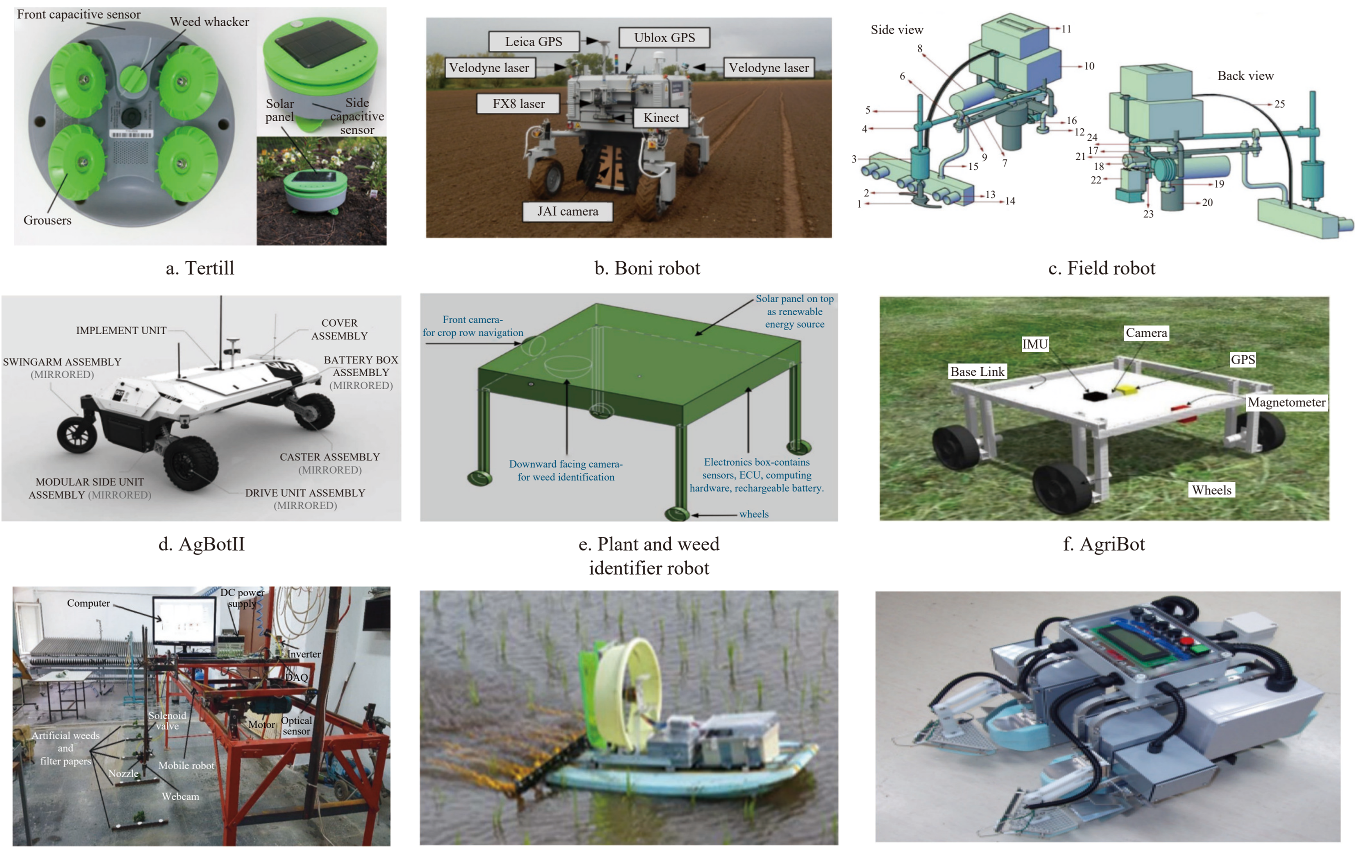
4 Autonomous weed management

Agriculture is approaching the next phase of efficiency, sustainability, and precision with the use of robotics in weed control. Robotics is essential for developing a weeding method that requires fewer herbicides. Because earlier weed identification and control are critical, contemporary weed robot designs require real-time image detection via multi- and hyperspectral sensors. Advanced sensor technology, such as self-driving automobiles and robotic arms, is transforming traditional weed management tactics. Weed management in inter-row crops is going to be totally autonomous in the future because of the labor shortage and increasing labor wages, but it is one of the most challenging tasks[83]. Merfield[84] suggested that all mechanical weeding tasks are distinctive and require various weeders and machinery modifications. In the near future, some of the autonomous robots with little or no modifications will be required for weed control (Table 7).

Tertill, a solar-powered, autonomous weeding robot for household gardens, was recently introduced and commercialized by Franklin Robotics (Billerica, MA) (Figure 4a). It works like a Roomba (iRobot, Bedford, MA) household vacuum cleaner, equipped with capacitive sensors on both sides to identify and avoid barriers such as enormous crops and walls, respectively. This robot eliminates the requirement for an intricate, heavy, and energy-intensive camera or GPS-guided detection system. Also, to activate the weed whacking mechanism, an extra capacitive sensor was used on the Tertill's bottom side to detect and identify weeds. The efficiency of Tertill was 54% to 75% and 16% to 29% with and without a weed whacker, respectively[85]. An agricultural robot, the BoniRob, was used during the full season of sugar beet fields (Figure 4b)[86]. The main parts of a field robot are the monorail, chassis, ball bearing, wheels, arms, blade, and adjusting mechanism (Figure 4c). An ultrasonic sensor was used to scan weeds and calculate the distance between weeds and the blade arm when the field robot paused between two cucumber plant rows. The signal is

Table 7 Autonomous weed management robots in row crops

Name	Country	Scope	Methods	Sensor	Mechanism	Weeding efficiency/%	Ref.
Tertill	USA	Pearl millet	Mechanical	Capacitive	Weed Whacking	54 to 75	[85]
Boni Rob	Germany	Sugar beet	Mechanical	RGB, NIR, and Ultrasonic	-	-	[86]
Field Robot	Malaysia	Cucumber	Mechanical	Ultrasonic	-	95	[87]
AgbotII	Australia	Lettuce, cauliflower, broccoli	Mechanical	RGB	Sliding	96	[88]
Plant and Weed Identifier Robot	Germany	Rice	Mechanical	Sensor module	-	84-99	[89]
Agribot	India	-	Mechanical	Camera	-	99.47	[90]
Mobile Robot	Turkey	_	Mechanical	Webscam	_	_	[91]
Weed Robot	Japan	Paddy	Mechanical	GPS sensor	_	_	[92]
Weed Robot	Japan	Paddy	Mechanical	Capacitive	-	-	[93]
Laser Weeding Robot	China	Corn	Mechanical	Camera	Track Tensioning Mechanism	88.94	[95]



a. Tertill b. Boni robot c. Field robot

d. AgBotII e. Plant and weed identifier robot f. AgriBot

g. Mobile robot h. Weed robot i. Weed robot

Figure 4 Autonomous robots for weeding operation in inter-row crops sent to start the rotation through the arm motor and blade motor[87]. The main components of a weed management robot are the modular side unit, implement unit, battery boxes, swing arms, drive units, caster assembly, and external covers. The power unit of AgBotII includes a gearbox, an emergency brake in the hub with 14 wheels, and a custom motor (Figure 4d). To deliver an energy-efficient accessibility within the desired speed range of 1.38-2.77 m/s requires an electric motor of 5 kW at 48 VDC with 75%-85% efficiency. A camera was mounted in front of AGBotII, facing downward, at a height that covered a 1 m field of view[88].

Shah et al.[89] developed a conceptual model of a plant and weed identifier robot designed on Onshape design software which is used in rice row crops with spacing of 0.25 m (Figure 4e). The width and height can also be adjusted according to plant growth stage. When the leaves are developing, this robot can identify them in the early stages. Also, a solar panel was mounted above the electronic box to provide a renewable source of energy for robot movement. After the robot identifies the weed, an algorithm displays the location of the weed in terms of the real-world coordinates of the robotic platform in relation to the image frame. The following robotic manipulator takes the real-world coordinates and uses inverse kinematics to move the end effectors to the correct position and executes mechanical or thermal weed management in addition to mulching if desired. An autonomous agricultural robot called AGRIBOT is a four-wheeled skid-steering prototype model designed for different jobs like monitoring and classification of crops and weeds (Figure 4f)[90]. Ozluoymak et al.[91] developed, designed, and carried out performance evaluation of target-oriented weed control using machine vision (Figure 4g). Uchida and Funaki et al.[92] developed a remote-controlled weeding robot that floats on the water surface using a body board. For stirring paddy fields, a chain was mounted to the back side of the robot (Figure 4h). Sori et al.[93] studied the performance of a weeding robot in wet paddy field (Figure 4i). The field capacity of the developed robot was 1.0-1.5 acres in 3 h at a speed of 20 m/min with a single charge.

Agribot as an Indian agricultural robot was developed by Gollakota and Srinivas[94] (Figure 5) with the primary goals of increasing production, decreasing labor costs, and speeding up agricultural operations. Agribot is used for farm operations such as seeding, spraying, weeding, and harvesting. All commands are executed using vision-based row guidance and image processing technology. This autonomous robot, equipped with a digital camera and a GPS module, aids in mapping the field before carrying out the activities.

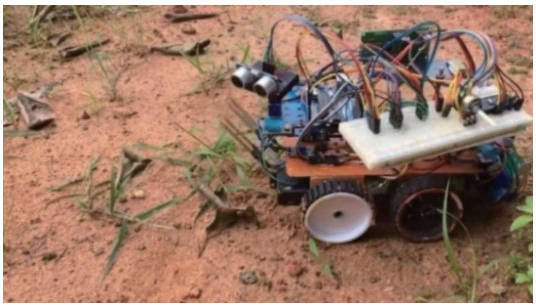


Figure 5 Agribot

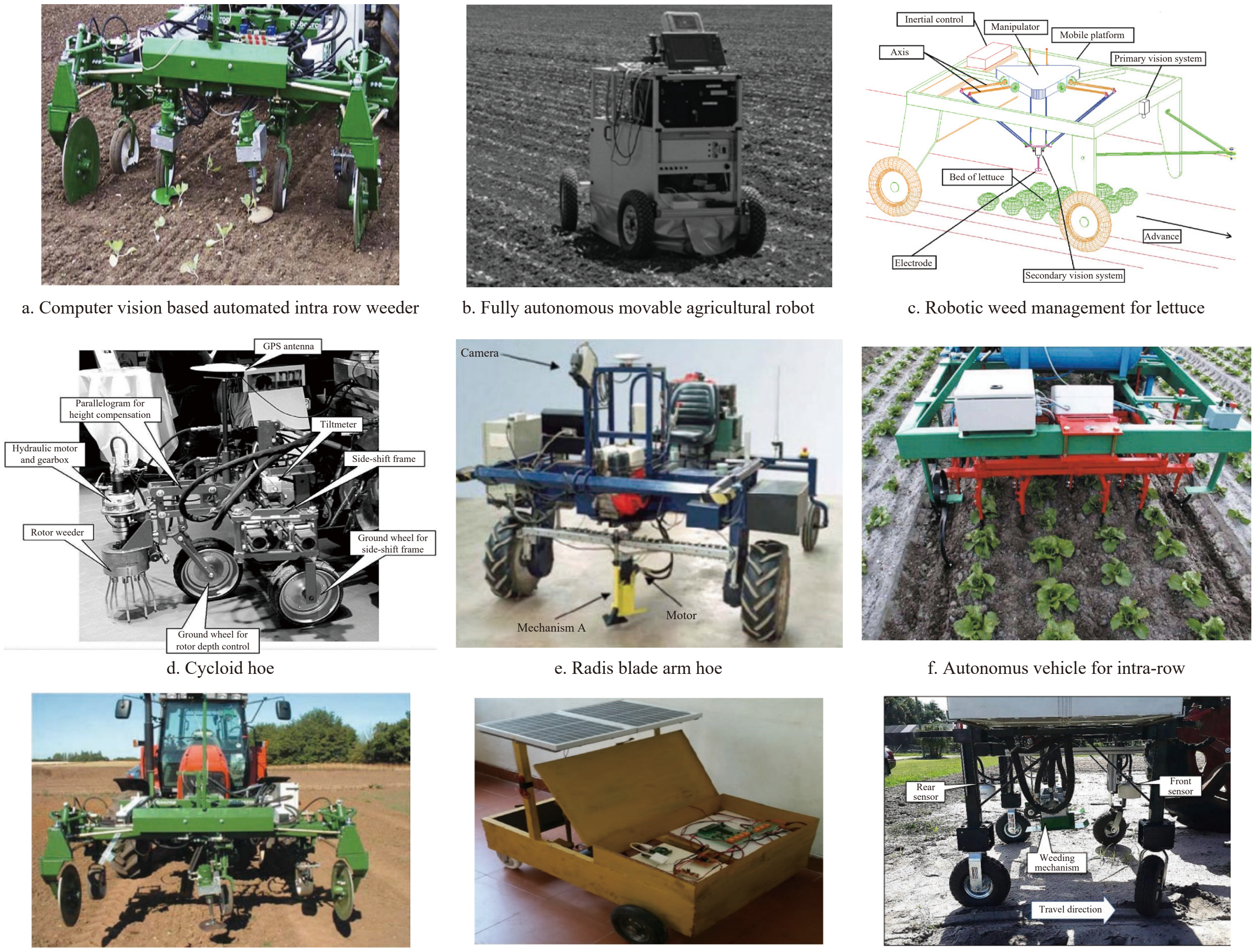
5 Automated technology for intra-row weeders

Automation may assist in distinguishing crop plants from weeds and removing the weeds exactly by mechanical device without requiring human involvement or damaging the crop plants[96]. Key improvements in technology, including guiding, detection and identification, in-row precision weed management, and mapping, are all incorporated into automation[50]. It limits the necessity for operators to continuously maneuver agricultural machinery, which decreases operator stress. With the use of electrical hardware, sensors, actuators, and software, it is focused on increasing efficiency and reducing resources[97].

The detection of weeds based on plant traits and visual structure has been given enormous significance by vision systems and image processing methods (Figure 6a). A computer vision guidance system can determine the exact position of a device, the center of the seed line, the margins of the ridges, and the offset distance from the crop's center line. Slaughter et al.[98] developed a machine vision guiding system using continuous color segmentation of direct-seeded crops in seed lines when the crop is missing due to poor germination. They employed a pair of cameras, and a 16 km/h field test was conducted with the system. RMS position errors ranged from 4.2 mm in weed-free conditions to 12 mm in weed-filled conditions. Slaughter[50] developed a computer vision-based row guidance system just like GPS for row crop navigation. With lower error, 12-27 mm crop rows were easily identified by machine at forward speed of 2.5-10 km/h, and the maximum error in the horizontal direction was 6-13 cm of GPS precision with RMS error. Also, the lateral movement of hydraulic/electromechanical system was controlled in this system[96,99,100].

To control weeds within intra-rows, higher accuracy is required[101], using several guidance systems developed for weed management in agriculture. In order to identify the differences between 20 weed species, Sukefeld et al.[102] uses Fourier characteristics and shape variables. Cotyledon weed and one or two pairs of weeds were correctly identified at rates of 69.5% and 75.4%, respectively. The detecting method distinguishes crops from weeds in wider row crops by operating continuously with a camera image and under uncontrolled lighting and motion conditions[103]. Astrand and Baerveldt[104] developed a fully autonomous movable agricultural robot (Figure 6b) employing a framework that incorporates twin cameras: one grey-scale camera for identifying crop rows and a second for weed rows. This helped with the detection of weeds and subsequent control. The robot operates in tandem with the columns, and the following camera makes use of a color-based vision system to identify a single crop within weeds. As a result, it concentrates on a visual system for crop row identification rather than weed control. To differentiate between weeds and crops, it classifies them based on color and shape. However, the efficiency of the machines in controlling weeds was not reported. Balsco et al.[105] developed a robotic weed management machine for transplanted lettuce which uses high-voltage electric current (15 kV electrical current discharge) to remove weeds (Figure 6c). A pair of vision-based machines were used, first to identify weeds on a size basis and second to position the electrical probe to remove those weeds. Also, weed and crop maps can be made based on images captured. The detection accuracy of the machines was 84% and 99% for weeds and lettuce plants, respectively.

Zuydam[106] evaluated the real-time kinematics (RTK) differential global positioning system (DGPS) device for the guidance of an implement along a pre-stored electronic area map via satellite. The coordinate system that depicts the course of an implement served as the foundation for the field map. It was discovered that the actual orientation of the implement differed from a straight line by less than 20 mm. The weeding machine was



a. Computer vision based automated intra row weeder b. Fully autonomous movable agricultural robot c. Robotic weed management for lettuce

d. Cycloid hoe e. Radis blade arm hoe f. Autonomus vehicle for intra-row

g. Disc weeder h. Weed detecting robot with rashberi pie i. Automated intra row weeder for vegetable crops

Figure 6 Autonomous intra-row weeders for weed management

guided by a rover and base DGPS. For optimal performance, this base station needs to remain close to the rover unit. Through the employment of a side-shift mechanism to adjust lateral position, the implement was guided via GPS. Griepentrog et al.[107] designed a weeder for intra-row operation which employed crop seed maps produced at the time of sowing and an RTK base to eradicate the weeds (Figure 6d). The rotary weeder has eight tines that revolve along cycloid curves due to an electro-hydraulic motor. RTK-GPS can be used to direct the rotary tine cultivator (also known as the cycloid hoe) between the crop rows[108]. The accuracy was tested in field condition. Using a plastic stick in place of a crop, less than 2% of observations showed tine violations of the uncultivated area (10 mm from the center of sticks). On the contrary side, the efficacy of crop-weed differentiation and weed elimination was not evaluated. The results of the study demonstrate that the rotor weeding mechanism can control weeds and cut the soil without damaging agricultural plants. Weeds can be pulled out, clipped, and then covered with soil by the weeding mechanism. In the process of hoeing, the cycloid pattern is visible. The innovative concept is that the tines could be retracted inside the cylinder, allowing the tine tip to trace a smaller cycloid. Griepentrog et al.[109] studied the same machine at a speed of 1.44 km/h and reported that it caused immoderate crop damage and had extremely low weed control performance. Cycle hoe is also inappropriate for mechanical weed control due to a few drawbacks. Among the most frequently mentioned limitations is the design's intricacy, which increases the cost of capital and maintenance. The method is especially challenging to adapt because of an unbroken circle (18 mm) surrounding the plant. Another essential element is the type of soil. It will be challenging to control crop damage when soil clods come into contact with crops. The mechanical design of the device is difficult to utilize in cotyledon plants (at the true leaf stage) because of possible destruction.

Zuydam and Sonneveld[110] evaluated the precision of a laser-directing system for uprooting weeds. With an average steering accuracy of 6 mm over a length of 250 m, the selected laser can operate at a maximum distance of 500 m. The largest variation was no longer greater than 19 mm. Andersen[111] designed a different non-contact system and employed a laser light source that was positioned vertically to calculate the furrow's highest and lowest values. After that, the tool was led to generate the right lateral alignment. A weed-free detection system was developed by Kise et al.[112] employing near-infrared stereovision. The method relied on speed and row arc to indicate an inaccuracy of 30-50 mm RMSE. In order to discern among direct-seeded crop plantings, crop plant length, and the presence of weeds at numbers up to 200 weeds/m^2, Astrand and Baerveldt[104] designed a machine based on vision steering. The Hough transform, which estimates the row location using a few rectangular regions for crop size, served as the main inspiration for this machine. Cavalieri et al.[113] developed real-time and map-based intra-row weeding with a combination of revolving DSIC and cycloid hoes. The rotating disc consisted of a vertical spinning disc with two spring-loaded knives, which were moved by a hydraulic motor. The hydraulic controller was used to maintain its speed. The blades fold out while the disc revolves around at a constant 850 r/min because of both forces, particularly the centrifugal force, which is greater than the spring force. When the plant is identified, the disc rotates around 700 r/min and inertia forces lead the knives to fold in, which helps the disc to avoid direct contact with the plants[114,118]. At the front side at a fixed height along the crop row, a three-infrared transmitter, three-infrared receiver, and plant detection sensor are positioned[114]. A digital signal processor receives signals from the sensing of plants. The method of cutting activity above the soil surface causes low weeding efficiency. A weed eliminating, cut and cover led to lower weed-killing efficiency. Digital signal processors receive signals from plants that detect them. Because one cutting operation occurs above the soil surface, the efficacy of weeding is limited. The three potential outcomes - uproot, cut, and cover - all diminished the effectiveness of weed control. This made the detection method only useful for transplanted crops because it was also unable to distinguish between plants and weeds in an effective manner[115].

When no plants are present, the spinning arm goes into the intra-row area via an air pressure chamber, eliminating the intra-row weeds. Radis mechanism designed an intra-row weed management system with blades mounted on a pivoting arm (Figure 6e). Light sensors detect the plants, and this information is used to control the disc's position. Bakker[116] evaluated performance at a driving speed of 5 km/h, and weeds were only eliminated up to 20 mm. Due to plant damage caused by the intra-row hoe mechanical transition[117], the maximum speed for weeding operations with a Radis weeder was limited to 3 km/h. Vegetables that have a larger inter-row spacing and a minimum intra-row spacing of 220 mm are best suited for this method[116]. The system has a difficult time identifying the plant in a wide-row crop and controlling the speed of the intra-row weeding operation. Tillett et al.[99] evaluated a weeding system that used computer vision to identify plants. The automatic intra-row weeder incorporated a spinning half-circle disc to shield the crops from damage when weeding (Figure 6f). For forward and downward observation, a digital camera was installed in the weeder's middle position. Over the course of the observation period, the camera covered a length of around 2.5 m while being positioned vertically above the field of view's base. Treatments against weeds were applied 16, 23, and 33 days after transplanting (DAP). The most effective weeding times were 16 d and 23 d after planting because fewer weed plants were present by 77% and 87%, respectively, during those periods.

In transplanting intra-row spacing, a different innovative inter- and intra-row mechanical weeder may operate at a speed of 1.2 m/s[118] (Figure 6g). For weeding both inter- and intra-rows, it has duck foot and reciprocating blades. With the use of a camera and computer vision, the plants are identified and distinguished from the weeds. The maximum speed that can be achieved is 2.2 m/s. The plants reportedly received severe damage. Sujaritha et al.[119] developed a robot capable of detecting weeds by integrating a Raspberry Pi computer with the proper input-output components, such as cameras, micro-lights, and motors, with an electric device (Figure 6h). The weed detection system was developed using Python programming and Raspbian operational devices. The developed robot prototype was able to identify the sugarcane plantation among nine different weed types. The technique developed has a handling time of 0.02 s and properly detects 92.9% of the weeds. Jakasania et al.[120] developed an intra-row weeding unit and tested it in a soil bin laboratory. The least amount of plant damage was noted with a plant spacing of 35 cm and an operating speed of 1.0 km/h.

An autonomous system with fuzzy logic algorithm was integrated for weed control in the intra-row crop[121]. A mechanical linkage actuator system and different electrical sensing and control systems have been incorporated to develop a prototype of an intra-row weeder[125,126]. Various parameters such as variety of soil compaction, forward speed, depth of operation, and plant spacing conditions were used in the soil bin laboratory test of the intra-row weeding method. Plant damage considerably increased with greater forward speeds and closer plant spacings. When assessed using various plant spacings, the overall operational efficiency ranged from 80% to 96%. Table 8 depicts various sensor-guided systems and the accuracy of intra-row weeding systems. Saber[127] developed an automated mechanical intra-row weed control machine for vegetable crops (Figure 6i). The weeding mechanism works upward and downward instead of sliding in and out sideways. The upward and downward movement helps to improve weed control operation and also minimizes wear on the pinch-roller rubber. The developed weeders work on crop height up to 29 cm. The weeder was powered by a hydraulic system of tractor. To detect the accurate location of crop plants, a proximity ultrasonic sensor was used. The forward speed and roller rotational speed of the weeder were 0.19 m/s and 400 r/min, respectively. The weed removal efficiency of the developed weeder was 41.7%. The weeds that were left (not uprooted) were either too tall to be forced horizontally onto the soil surface, which was positioned farther from the active pulling surface of the pinch roller, or they were too short to be used by the rollers.

Table 8 Sensor-guided system for intra-row weeding operations

Machine	Guidance type	Accuracy/Limitation	References
Hoe	Laser guidance steering system Ultrasonic Real-Time Kinematic (RTK)	± 6 99% over range 0.1-10 m ± 20 mm and ± 60 mm	[101,106,110,121,122]
Cycloid hoe	Hydraulic side-shift device	Geo-positioning, expensive maintenance	[113]
Field robot or Autonomous weeder	Machine vision guidance system	± 12 mm and ± 45 mm	[50,118,123,124]
Vertical rotating disc weeder	Rotating disc with cut-out sector	Angular error < 10°	[80]
Rotating disc type	Infrared	Error of identifying plant and weed	[113,114,115]
Radius moving tine	Light sensor	Error due to natural light interference	[116,117]

Conventional weed management tactics have been revolutionized, including by the use of robotics and sensors. Robotic weed management can reduce herbicide consumption by 5%-10% compared to blanket spraying[128]. The introduction of autonomous robots capable of performing various agricultural activities has led to much study on the roboticization of the agricultural environment. As robots become more economical and sophisticated, their capacity to eradicate weeds will increase.

6 Precision weed management

The most commonly used method for weed management is pesticide spraying, although it has a detrimental impact on the ecosystem[129]. As a result, it is essential to develop a weeding method that requires fewer pesticides. Precision agriculture, which integrates sensors, information systems, and management[130], may be used to maximize agricultural yield while minimizing the impact on the environment.

To help in improving agricultural productivity and reducing waste and costs, smart farming technologies such as smart sensors, remote sensing, UAV, satellites, internet of things (IoT) technology, etc. are becoming popular in modern agriculture[131] (Figure 7). Variable rate technology (VRT), which is a component of sensing, provides an efficient way to protect the environment and increase the economic benefits of precision farming[132]. This method applies fertilizer, pesticides, or herbicides by combining a sprayer with a variable rate control system. The application may fundamentally be based on maps or sensors with varying rates[133]. The use of precision farming technologies can significantly improve weed control methods. Since weeds are a consistent problem, weed control technology must constantly improve to keep up with weed growth and adaptability[134].

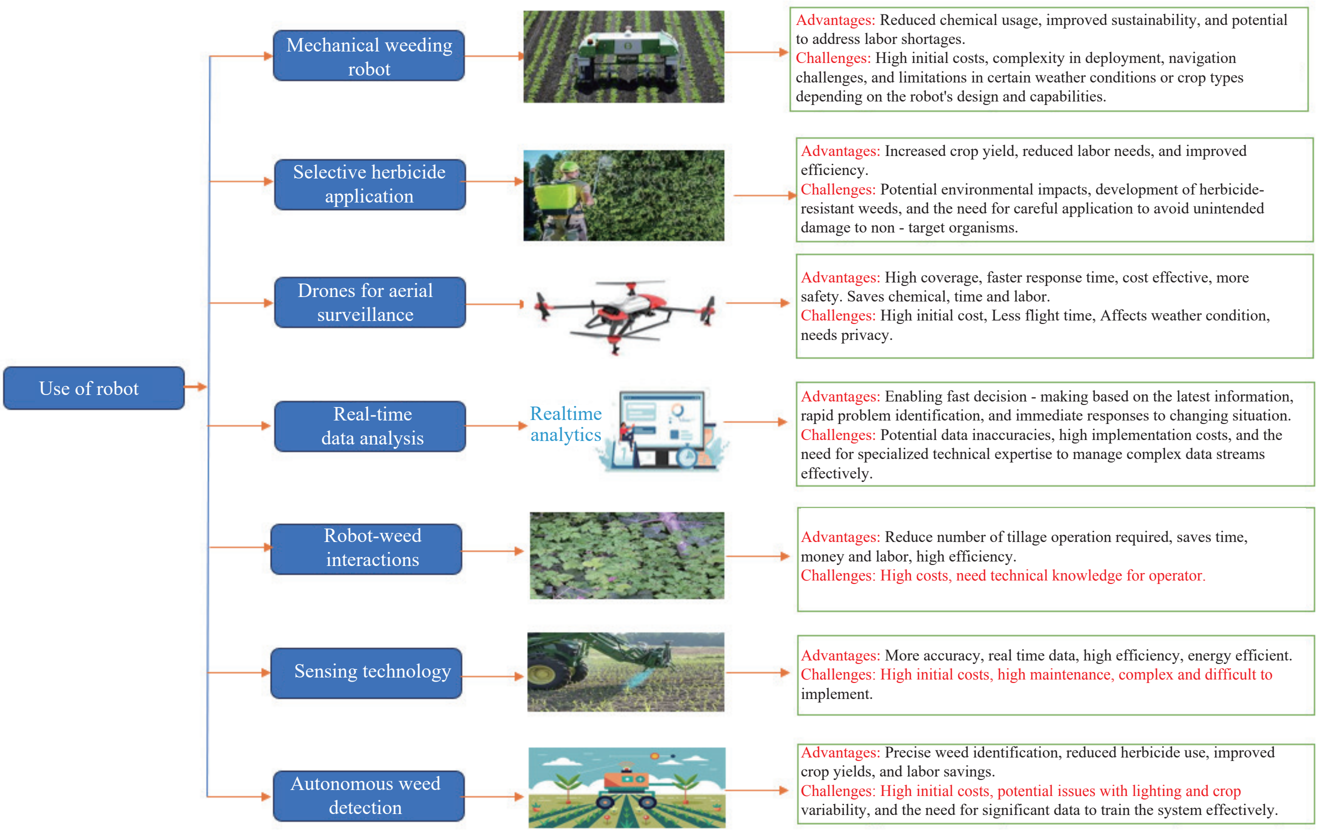


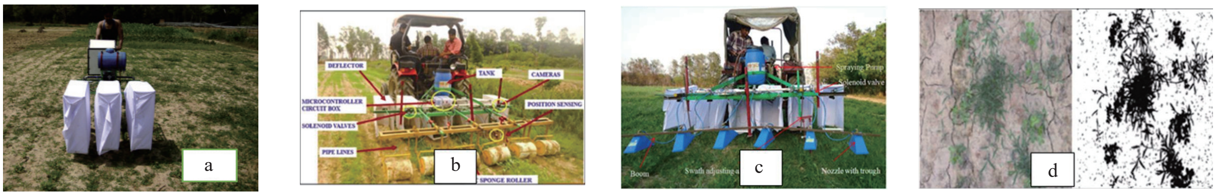
Figure 7 Different precision weed management techniques

Since the beginning of this century, various weed sensing methods have been studied. Remote sensing may be the most economical method for large areas to provide a farm, or a broad area covering numerous farms, with maps of weed presence. Data collection for remote sensing includes satellites and manned or unmanned aerial vehicles. Large-scale crop yield monitoring and area surveying are both made easier by satellite-based remote sensing. High-resolution imaging is required for these operations, which is normally obtained through closer inspections made with manned or unmanned aircraft or ground vehicles[135].

7 Machine vision system to control inter- and intra-row weeds

A sensing device based on machine vision was integrated with an existing sprayer for precise herbicide management. The device's spatial application effectiveness was evaluated in the field using artificial targets. There is no statistical evidence that the mean pattern length was impacted by vehicle speed, and the system had a 91% overall impact accuracy. Weeds were controlled using a customized device for spatially variable rate application of herbicides[136]. A transportable machine specifically developed software, a DGPS, and a mechanism that applies rates proportionate to the machine's forward velocity make up this system. Grain production across the entire field was essentially uniform due to the herbicide application, which was done at a pace that varied spatially. The method saved 29% on herbicides compared to the amounts usually employed in conventional farming. A real-time robotic weed management system beneficial for cotton fields was able to differentiate between weeds and cotton plants, enabling precise chemical spray management[137]. The system effectively sprayed 88.8% of the weeds at the targeted travel speed of 0.45 m/s.

Tewari et al.[138] designed a three-row contact-type herbicide applicator to manage the number of weeds from the inter-row crop based on a microcontroller (Figure 8a). Real-time image processing served as the system's foundation. Field tests showed that there was a 40% herbicide decrease with 90% application efficiency. A microcontroller-based position sensor and an integrated digital image processing platform were deployed by Chandel et al.[49] to develop a tractor-operated contact-type weed eradicator for row crops (Figures 8b and 8c). A graphic user interface was also developed for the image analyzer's customizable changes. To release the chemical over the contacting roller, the microcontroller receives the data from the image analyzer, analyzes the data, and then transmits the signal to the solenoid valve (Figure 8d). The average weeding efficiency was 90%, with plant damage of 5% and 8% for maize and wheat, respectively. An integrated system developed digitally saved 79.5% on herbicide. The excessive use of herbicides results in an increase in health issues, environmental problems, and herbicide-resistant weed species. Each of these is increasing the need for chemical-free production. To study and develop an alternative weed control system, several investigators have been challenged[79,99,104, 108,139].



a. Manual drawn b. Tractor drawn roller-based herbicide applicator c. Herbicide applicator d. Image processing of weeds

Figure 8 Microcontroller and image processing-based herbicide applicator

Machine vision has the potential to be applied to a real-time robotic weed management system to apply herbicides precisely to the target weeds[124]. High-voltage electrical currents (15-60 kV) may also be used to precisely manage weeds by applying them to small plants[105,140]. Infrared sensors and flame nozzle spray can be used to accurately locate and burn weeds[141]. Also used for weeding operations is the flame weeder. Flame weeders can be applied either pre-emergence or before weeding, which is an important point about which to be informed. In addition, they could eradicate weeds that grow on the surface of the soil. Flame weeders accurately destroyed the weeds that were growing in the "in-row" area along a 0.25 m-wide strip. According to Parish[142], this weeder was specifically employed for the onion and maize crops, and plants which can withstand flames. According to references [99,100,143], the lateral movement of the electromechanical/hydraulic steering system was regulated in this system simultaneously.

7.1 Remote sensing

Remote sensing techniques such as thermal infrared (IR) sensors and light detection and ranging (LiDAR) technology have demonstrated astounding results in monitoring vegetation canopy temperatures and heights in order to assess biomass, chlorophyll, and nitrogen contents at a discrete moment[144]. Remote sensing is also commonly used in agriculture to map and detect weeds[145]. In remote sensing photography, the digital reflectance value at each pixel is calculated by integrating spectral contributions from each scene of the element. For example, for weed mapping, the scene component of soil, shadow, and crop species is used[146].

7.2 Applications of hyperspectral and multispectral remote sensing satellite imagery

Variable rate equipment, GPS, and GIS are examples of precision agricultural farming technology innovations that make it possible to use data from multi-spectral photographs to handle challenges[147]. Sensors that identify reflected energy in a variety of different electromagnetic spectrum bands generate multi-spectral images. Transforming weed management methods requires multispectral cameras and advanced imaging capabilities. These cameras allow for a thorough analysis of vegetation since they record information beyond human vision using a range of electromagnetic spectra. It is useful to manage weeds because multispectral cameras are excellent at detecting variations in the reflectance and absorption of light by different plants. By collecting information in certain bands, such as red, green, blue, and near infrared, multispectral cameras enable the creation of accurate maps of vegetation. A normalized difference vegetation index (NDVI) was used for crop health identification and mapping of weed infestations. The spectral characteristics of various plants aid in distinguishing undesirable weeds from crops[148].

In addition to identification, multispectral imaging helps guide targeted intervention strategies. Multi-sensor information fusion is a cutting-edge, multidisciplinary technology; thus, its development in agriculture must meet the demands of contemporary agricultural machinery[149]. By employing this method, farmers may generate prescription maps for focused herbicide application, increasing resource efficiency and mitigating environmental impacts. Furthermore, by facilitating the early detection of stress, multispectral cameras help monitor the overall health of crops. When paired with precision agricultural tools like GPS and GIS, multispectral cameras give farmers pertinent data, promoting a more environmentally friendly and successful method of weed control in agriculture[148]. There are currently several low-cost, high-performance, unique sensors being developed; the Intel D435 stereo camera and the StereoLabs ZED stereo camera are two examples. Comprising two camera modules, these cameras mimic human stereovision and provide the path for agricultural machines to recognize targets using depth and stereovision[147,149].

This strategy increases the precision of environmental detection while optimizing the performance of agricultural machinery and environmental perception systems. Thus, by ensuring the stability and safety of unmanned agricultural machinery while in operation, it successfully fosters the development of intelligence and information within the agricultural machinery sector[149].

Target detection and categorization are the primary responsibilities of hyperspectral remote sensing imaging, which varies from multispectral photography in that it has higher resolution and more interesting targets[150]. Hyperspectral data helps in understanding vegetation's physiological condition, including stress, nutritional deficits, and general health. Early detection of such indications enables proactive weed control measures, which reduce the influence of invasive species on agricultural productivity. Yang et al.[151] used hyperspectral remote sensing to detect weeds in a soybean field. They explored picture segmentation and found that this approach could differentiate between soil and plant with excellent accuracy (99.9%).

Remote sensing uses satellites or unmanned aerial vehicles to collect data. Large-scale crop production monitoring and area surveys are also excellent uses for satellite-based remote sensing[152]. Satellite pictures provide imperfect evaluations of small areas, including spatial distribution, weed identification, and chemical damage assessment (Table 9). High-resolution imagery is necessary for these activities, which are frequently obtained by closer examinations with human or unmanned aircraft or ground vehicles[153].

Table 9 Different cameras used for weed patch recognition

Camera type	Type of crop	Weed	Finding	References
RGB camera	Triticum spp., Hordeum Vulgare	Cirsium arvense Cirsium arvense	Distinguish between crop and weeds	[154] [155,156]
Multispectral camera	Zea mays, Triticum durum, Beta vulgaris	Amaranthus spp., Sorghum halepense Chenopodium album, Phalaris canariensis, Avena sterilis, Cirsium arvense	Distinguish between crop and weeds	[157,158] [159] [160]
Hyperspectral camera	Triticum spp., Zea mays, Hordeum Vulgare Sorghum spp	Conzya canadensis, Chenopodium album, Amaranthus macrocapus, Echinachloa colona, Cyperus rotundus, Malva spp.	Distinguish between crop and weeds	[161,162] [163]
Hyperspectral+ Multispectral camera	Triticum durum, Cicer arietinum	Avena fatua, Phalaris canariensis, Cirsium arvense	Distinguish between crop and weeds	[164] [159]
RGB + Multispectral camera	Glycine max, Helianthus annus	Amaranthus palmeri, Echinachloa crusgalli, Digitaria sanguinalis, Amaranthus blitoides, Sinapis arvensis, Chenopodium album	Crop injury assessment from Dicamba; Distinguish between crop and weeds	[165] [164]

7.3 Unmanned aerial vehicles (UAVs)

UAVs enable site-specific weed management, an improved weed management strategy for the highly effective and environmentally safe control of weed populations, allowing accurate and continuous monitoring and mapping of weed infestations. Also, problems regarding soil compaction can be avoided by using UAVs for spraying and planting operations[166]. Due to the excessive use of fertilizers, this technology also has the potential to reduce the amount of soil degradation, soil fertility loss, and subsequent water contamination. It can also potentially save time by significantly lowering inspection times[82]. UAVs with advanced cameras and sensors that can identify specific weeds and GNSS or GPS technology, which offers geographic data for field mapping, can work together to accurately monitor large areas quickly. UAVs stand out today from the various remote sensing platforms for their ability to hover at low altitudes, capture photographs with precision, and deliver data on demand in emergency circumstances, which are not possible with aerial or satellite platforms[167]. UAVs are quicker to monitor or survey a crop field than unmanned ground vehicles (UGVs), and they have the best control in the presence of any natural barriers, which is important while operating between crop rows[168]. UAVs use three types of cameras to identify weeds accurately and precisely during weeding operations, such as RGB (red, blue, and green), multispectral, and hyperspectral cameras, depending on the operating height, resolution of the camera, and UAV model. To efficiently control various weed species that interfere with crops and thereby have a positive impact on the environment, UAVs and image processing technologies may be used together[40].

UAVs equipped with both multispectral and hyperspectral imaging sensors were used successfully to identify different species of weeds. This kind of technology can provide valuable data that is not acquired by RGB cameras or not visible to the naked eye. Since hyperspectral imaging contains more bands than multispectral sensors, it has been utilized more frequently to categorize agricultural systems and vegetation. Hyperspectral imaging-based techniques are the most effective and, as of now, the only ones that can reliably and automatically distinguish between different plant species in the field. With lettuce (*Lactuca sativa* L.) and tomato (*Lycopersicum esculentum* Mill.) crops, the concept of hyperspectral imaging has been evaluated in the field, with a detection rate between species at the pixel level above 75% and crop vs. weed identification rates exceeding 90%[169]. To manage weeds within the crop rows of early-growing tomatoes, a heated oil application system with a micro-spray system was developed. The hyperspectral imaging technique's identification accuracy for tomatoes, black night shade, and pigweed were 95%, 94%, and 99%, respectively[170].

Studies on the use of UAVs for weed mapping and detection mostly emphasize four challenges: spectral differences in weed detection, different aerial image types from various sensors and platforms, the impact of spatial and spectral resolutions on weed recognition, and algorithms and classification strategies for weed mapping. UAVs have been mainly tested with various crops, including maize, wheat, sugarcane, cultivar, chilli, onion, vineyard, pistachio, baby-leaf red lettuce, barley, and mixed agricultural fields, including pea and strawberry (Table 10). These are frequently grown crops. According to the results, weed detection is most significantly affected by the seedling stage of a crop (27.42%). According to Rydberg et al.[171], crop images could be accurately captured in the early growing season in order to apply color-dependent classification to separate weed areas and increase algorithm efficiency.

The single-rotor, multi-rotor, and fixed-wing UAV types are employed for weed detection (Figure 9). For the application of outer field weed management, Ahmad et al.[172] used a single-rotor spraying device in the target and off-target zones. Huang et al.[173] collected images on several areas of Cyperus iric, whereas Huang et al.[174] captured the Chinensis, Cyperus iric, Digitaria sanguinalis, Scop, and Barnyard grass in his two studies using the multi-rotor on China's rice fields. In a different investigation, Eleusine indica-infested weeds were imaged using a multi-rotor system by Khan et al.[188] along with two distinct crops, pea and strawberry. In the context of fixed-wing UAVs, Zisi et al.[175] employed this kind of UAV to capture images of S. marianum and areas of different weeds such as *Solanum elaeagnifolium Cav*, *Avena sterilis* L., *Bromus sterilis* L., *Cardaria draba* L., *Conium maculatum* L., and *Rumex sp.* L. in a field that was already planted with cereals in

Greece. *Avena sterilis*, *Rumex sp*., *Bromus sterilis*, *Conium maculatum*, *Cardaria draba*, and *Solanum elaeagnifolium Cav* were mixed with various weed types at a field that had previously been planted with cereals in Greece, according to Tamouridou et al.[176], while Barrero and Perdomo[177] found Gramineae at a rice field in Colombia.

Table 10 UAV imaging application for identifying weeds for various crop types

Type of crop	Research focuses	References
Maize	Deployed a cheap UAV for weed mapping, assessed open-source tools for semi-automatic weed classification, and put a recommended map-based sustainable management paradigm into practice.	[178]
Maize	UAV images used to identify weeds in maize field by using crop row processing and advanced YOLOv4 model.	[179]
Wheat	Developed an advanced residual convolutional neural network (ResNet-18) for weed and crop plant identification in UAV data.	[180]
Sugarcane	Developed a system to classify the defected areas in sugarcane field.	[181]
Cultivar	Evaluated the feasibility of combining satellite and UAV imagery to classify various pistachio cultivars and differentiate weeds from plants more accurately.	[182]
Chilli	Used image processing and machine learning techniques to identify weeds in a field farm.	[183]
Onion	By using an easy off-the-shelf UAV for collecting dry onions, late-season weed mapping was developed. Used numerous methodologies across different spatial resolutions, assessed the amount of weed coverage in the fields, and evaluated the spatial pattern of weeds.	[184]
Vineyard	Supplied FOSS-replicable methodologies to UAV and precision farming users so they may meet operational and management requirements alongside the requirements of agricultural activities.	[185]
Baby-leaf red lettuce bed	Used a UAV to determine the precise amount of weeds present in the baby-sized red lettuce bed.	[186]
Barley	Assessed the spring barley yield loss caused by different C. arvense infestations in large plots in the fields of farmers and provided a unique method to measure C. arvense infestation in large plots.	[187]
Mixed agricultural field	Developed a deep learning system to recognize weeds and crops like peas and strawberries in fields.	[188]

a. Mikrokopter JR11X (attached with multispectral MCA 6)
b. Inspire DJI (attached with Micasense multispectral)
c. DJI Phantom 4 (RGB camera)
d. Fixed wing (attached with RGB/Multispectral)
e. Matrice 600—DJI (attached with Hyperspectral Pika L)
f. Yuneec H520 hexacopter (attached with thermal sensor)
g. Sprayer UAV
h. Uni UAV
i. FDG23 pro vertical takeoff and landing (VTOL) UAV

Figure 9 UAV used for classification of weed or weed and crop

Pei et al.[179] evaluated the performance of weed detection in maize plants by using UAV. A YOLOv4 model was used to detect weeds in inter-row crops. After, the crop row detection model fixed the crop row coordinates, drew the boundary box, and masked the boundary box, which helped to obtain the inter-row weed images. Then, 300 images out of the total of 1000 images were selected for labeling the weed and maize plants, and 700 images from among the masked images were selected to label the weeds (labeled to masked ratio: 3:7) to achieve the sample balance. The average precision of maize, weed, and mean average precision was 87.49%, 86.28%, and 86.89%, respectively. The developed model accurately identifies weed and maize plants.

8 Future recommendations

Non-chemical weed control in wide production areas and intensive farming practices is a significant challenge. To accomplish sustainable weed management, an integrated strategy combining agronomic, cultural, physical, and mechanical strategies is necessary. Intensive agriculture centered on the Green Revolution created a number of secondary and tertiary issues, including pesticide resistance and soil and water contamination. Food security is no longer the primary goal of agricultural research and development in India; rather, nutrition, food safety, and diet diversity are. Herbicide-based weed control appears practical for monocropping, but it fails to fulfill the expectations of consumers seeking safe food. Non-chemical weed management using agronomical tools and practices may benefit both environmental health and food quality. Cropping system-based sustainable agriculture methods, such as conservation agriculture, are critical for mitigating the constraints and problems of weed competition in agriculture. Remote sensing, multispectral and hyperspectral cameras, robotics, and UAV are examples of innovative technologies and new ideas that can help to ensure sustainable agriculture. A large reduction in pesticide use may improve food safety, agricultural production, and the quality of life for producers and consumers in an environmentally responsible manner.

9 Conclusions

There is an urgent need for India to improve management of agricultural resources while minimizing negative effects on the environment and ensuring the requirement to maintain the supply of food by increasing agricultural productivity. Sustainable agriculture saves natural resources and promotes cost-effective advancement. Sustainable weed management is required to achieve environmental, social, and economic benefits. Sustainable farming surpasses traditional farming in terms of crop yields, gross and net profits per acre, costs of inputs, and per-farm income. As communities allocate more resources to reconstructing agriculture, living soils, plants, and animals will eventually promote human life. Each acre converted to organic, sustainable methods brings us closer to achieving ecological sustainability and reducing harm. Increasing agricultural productivity leads to a substantial increase in the country's GDP and growth rate. The farming community, particularly the rural poor, will benefit from improved socioeconomic standing. Manual weeding will reduce labor and promote gender equality, freeing up time for rural women and adolescents to pursue other lucrative occupations such as sericulture and beekeeping.

The following conclusions were drawn from the above study:

1) Farmers can substantially improve their income by reducing weed management costs and increasing production.

2) In India, weeds are currently controlled by several methods, such as manual, chemical, and mechanical, which may be advisable to avoid due to their respective limitations, as discussed above.

3) Precision weed control methods help to reduce drudgery and save time and money.

4) Recently, novel technologies such as sensors, microcontrollers, computer vision, robotics, and UAVs have made weed management much easier, which helps to increase food production by reducing labor requirements, using minimal chemicals, operating on time, and posing fewer environmental health hazards.

5) Drone-based remote sensing technology and robotic weed management technology have changed the agricultural business model. Weed mapping is an agricultural technique to identify and count weeds by analyzing remote sensing images of farmland. This technology can help farmers better manage their fields and improve the yield and quality of their crops.

6) In the future, weed management will shift completely towards precision weed methods like UAV or robotics because of increasing wages day by day and unavailability of labor during the peak period.

7) The combined use of drones and image processing technology may help to effectively control different weed species that disturb crops, with associated environmental benefits.

8) UAVs, variable rate spraying, etc. offer precise and adaptable alternative strategies to overcome these challenges.

Authors' contributions

Narayan R. Gatkal: conceptualization, data curation and interpretation, original manuscript writing, manuscript review and editing; Sachin M. Nalawade, Mohini S. Shelke, and Ramesh K. Sahni: visualization, data curation and interpretation, manuscript review and editing; Avdhoot A. Walunj and Pravin B. Kadam: resources; Musrrat Ali: review editing and funding acquisition.

Acknowledgements

The authors are grateful to the Department of Farm Machinery and Power Engineering and the Centre for Advanced Agricultural Science and Technology for Climate Smart Agriculture and Water Management (CAAST-CSAWM), Dr. Annasaheb Shinde College of Agricultural Engineering and Technology, Mahatma Phule Krishi Vidyapeeth, Rahuri-413722, Maharashtra, for providing facilities, and also thankful to Chhatrapati Shahu Maharaj Research, Training and Human Development Institute (SARTHI), India, for providing financial support during Ph.D. work.

Funding

This work was financially supported by the Deanship of Scientific Research, Vice Presidency for Graduate Studies and Scientific Research, King Faisal University, Saudi Arabia (Grant No. KFU250115).

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