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REVIEW ARTICLE

Mechanical weed management technology to manage inter- and intra-row weeds in agroecosystems - A review

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ABSTRACT

Traditional manual weed management is one of the tedious and costly operations in the complete cycle of crop production, reasons being high labor costs, time and tedium. The herbicide use contributes to environmental pollution in addition to other disadvantages of concern. The increasing demand for toxicant free food has become a challenge for weed control. Hence, the mechanical weeding is gaining importance. Automation in agriculture has also improved the mechanization input in weed management. The rapid entry of sensors, microcontroller and computing technologies in the field has formed a foundation of agricultural autonomous guidance systems. An automated system is time effective for field operations, avoids huge labor requirement and health drudgery issues to provide an efficient farm operation. Generally manual tools such as khurpi (hand operated small hoe), grubber, spade, wheel hoe, push pull type of weeder are used by farmers for the removal of inter- and intra-row weeds with higher weeding efficiency in the range of 72 to 99% but field capacity is very low in the range of 0.001 to 0.033 ha/h. This review deliberates on the latest work being done on mechanical weed management such as tractor operated finger weeder, torsion weeder, ECO weeder, flame weeder, harrow and sensor-based technologies for management of inter- and intra-row weeds in crops with wider rows.

Key words: Automation, Crops, Inter- and intra-row weeder, Mechanical weed management, Microcontroller, Sensors

INTRODUCTION

Weed infestation is a major concern in agriculture worldwide. Weeds germinate and grow substantially in a random and ununiform manner across the crop field and compete with main crops for water, nutrients and sunlight, resulting in a significant deterioration of production quality and quantity (Berge *et al.* 2008, Slaughter *et al.* 2008, Hamuda *et al.* 2016). The weed management in India, involves an average expense of ₹ 6000/ha for rainy *(Kharif)* season crops and ₹ 4000/ha for winter *(Rabi)* season crops amounting to 33% and 22% of the total production costs, respectively (Yaduraju and Mishra 2018). Several studies have also demonstrated a strong impact of weed infestations on crop yield loss (Slaughter *et al.* 2008, McCarthy *et al.* 2010). Even with traditional methods of weed control, an average yield loss of 15-20% occur and thus weed management remains critical for effective crop loss management and quality production (Chethan *et al.* 2022).

Weeds that emerged with the crop should be controlled during critical period (Rao and Nagamani 2010). Weed management is a strategy for ensuring the success of a targeted weed population in a crop area by employing weed ecology and management technical knowledge (Ghersa *et al.* 2000). An integrated approach for weed management is required evolving (i) Cultural methods, (ii) Physical methods, (iii) Chemical methods and (iv) Biological methods (Buhler 2002, Rao and Nagamani 2010). Even though soil steaming, laser radiation, and flame are among intra-row weed management techniques (Raffaelli *et al.* 2013, Fontanelli *et al.* 2015) are available, they are successful under certain soil and plant conditions and they necessitate additional steam and flame generation systems, which result in excessive fuel consumption and are costly (Melander and Kristensen 2011, Marx *et al.* 2012).

Physical force either manual, animal, or mechanical strength is used to tug out or kill weeds under physical strategies of weed management. One or combinations of these methods are employed to

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control the weed population depending on weed and crop. Major operations of physical control are hand weeding, hand hoeing, digging, mowing, cutting, tillage, burning, inter cultivation, and use of mulches. Hand weeding is also very popular amongst the farmers in India where weeds are pulled out by hand or uprooted by small hand tools. The weeds are eliminated through digging it in deeper layers to remove the underground storage organs. Nowadays, physical weed control techniques are compelling very quick and effective solution which does not leave any chemical deposits on crop or plants. The objective of the current review is to review the research efforts on mechanical weed management to provide a synthesis and some thoughts on weed management tactics that could be useful in developing sustainable solutions.

OVERVIEW OF MECHANICAL WEED MANAGEMENT TECHNOLOGY

Conventional methods of weed control system

The weeding tools basically can be categorized based on power sources such as manual, animal-drawn, and power or tractor operated. Popular weeding tools are khurpi (hand hoe), spades, and long handle tools. Animal drawn equipment or implements are suitable for intercultural and weeding operations. They may be accomplished weeding fast and successfully by way of the advanced mechanism. A wider row spacing (above 30 cm) is provided for the movement of animal-drawn weeders which preserve proper row spacing and that are beneficial for successful weeding operation. The cost of operation and time can be reduced by animal-drawn tools. Animal weeding tools are single and multi-row hoes. The farmers of various states in India have extensively used the animal-drawn single row hoes. The blade shape like straight or slightly curved is typically used in animal-drawn single row hoes. According to crop spacing, the size of the blade can be modified. Multi-row units are famous for weeding operations in Gujarat and other states for more coverage and timely operation. Some new designs in animal-drawn weeders are three tine cultivators (Triphali), Akola hoe, Bardoli hoe and animal-drawn sweeps of different designs (Singh *et al.* 2018). A power-operated weeder for inter-row cultivation is costlier for small farm operations compared with the push-pull type weeder. The work rate of different weeding implements varies due to variation in a row and plant spacing, crop canopy size, weeding depth, soil conditions and other different factors. The typical work rate might vary from 300-500 man-h/ha with the use of a hand hoe (khurpi). But, a khurpi demanded much less energy expenditure than a three-time hoe accompanied with the aid of a spade (Tewari *et al.* 1991). The labor requirement in hand hoeing varies from 200-300 man-h/ha within rows using chopping hoe. Push-pull type weeder requires 100-125 man-h/ha along the row in typical conditions. The labor requirement varies from 6-20 man-h/ha for animal-drawn weeding tools (blade hoe and blade harrow) (Anonymous 2017). Some advanced weeding tools are suitable for the reduction in the human attempt, reduction in time, compared to manual weeding and effectiveness in operation.

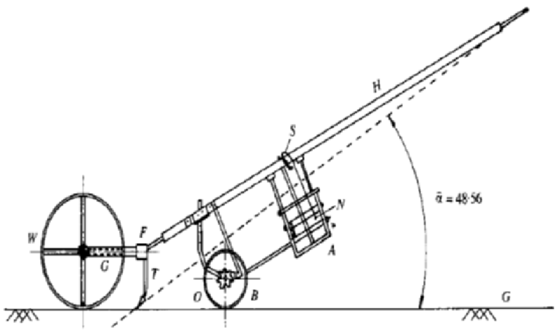
The manual weed management technique has been taken into consideration because of the smoothest and earliest among all techniques. Farmers with their bare hands used to uproot the weeds earlier without the use of hand tools including khurpi (hand-hoe). The manual method which is the simple but it is labour and cost intensive and consumes a huge human effort and energy (Cloutier *et al.* 2007). Humans work in a bending posture for longer durations with this practice, which poses health hazards and has thus been abandoned (Tewari *et al.* 1993, Tu *et al.* 2001, Weide *et al.* 2008, Tewari *et al.* 2014a and b, Chandel *et al.* 2018). Slaughter *et al.* (2008) reported that around 65 – 85% of the weeds only were removed from cotton field by hand-weeding, due to human inaccuracy or missing. It was also stated that, the usage of long-treated hoes would damage the crops and leaving behind some weeds in the field (Gianessi and Reigner 2007). A manually operated weeder, was developed and tested ergonomically for relative weeding performance, consisted of a pull-push recorder to measure the force of five different blades during the weeding operation (**Figure 1**) (Tewari *et al.* 1993). Each of the blades has width of cut 20 cm, cutting angle 20° and sharpness angle 15°. The quality of work of B_1 was superior (84%) compared to all other blades. Another manual weeder was developed and when its performance was studied in the groundnut field by operating at 30 mm depth had field capacity of 0.048 ha/h with weeding performance up to 92.5% (Yadav *et al.* 2007). Another manual weeder developed and ergonomically evaluated in groundnut crop (Goel *et al.* 2008) had the highest performance index (3690) at 11.63% moisture content with the lowest plant damage (2.46 to 7.96%) and the lower energy consumption rate (8.34 to 40.05 kJ/min) when compared with other weeders such as wheel finger weeder, wheel hoe, and traditional weeding. Manual weeding has always faced a problem during cultivation in a timely manner. Different manual weeding tools with its performance parameters is shown in **Table 1.**

Mechanical weed management systems for inter-row weed management

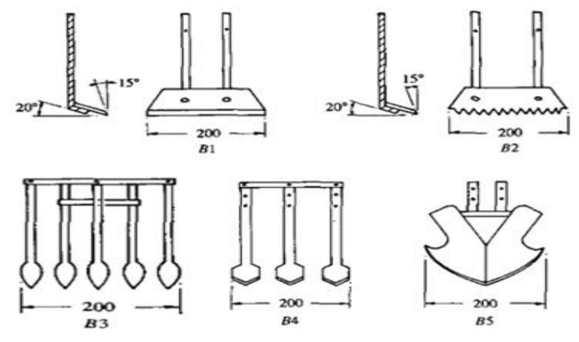
Mechanical inter-row weeders can remove weeds completely or partially. Many mechanical weeders have been developed for cutting, uprooting and burying the weeds in soil. The weeding equipment developed earlier had been pulled by draft animals, which include bullocks and buffaloes. As time progressed, the shift to tractors as the power source was observed (Gianessi and Sankula 2003). Mechanical weed management, alone, is practiced mostly by farmers who avoid usage of herbicides. Inter-row weeding eliminates weeds within the inter-row region without adverse the crop. Mechanical weed management is effective only at the initial stage of crop growth. At a later stage, tractors and cultivators damage the crop foliage due to less ground clearance compared to crop plant height (Cloutier *et al.* 2007). The basket weeder, that consisted of rolling rectangular-shaped round baskets (Bowman *et al.* 1997), is ground driven and did not require any power other than a draft from the tractor. It is capable of removing weeds from the top surface of the soil with the least amount of soil sport into the crop row and is suitable only for soil with high moisture content and a speed range of 6.4 to 12.9 km/h.

A three-row tractor-mounted rotary weeder, with four "L" shaped blades per flange, was developed at TNAU, Coimbatore, under the ICAR- AICRP on Farm Implement and Machinery (FIM) Scheme (Anonymous 2006). In a sugarcane field (at 2-4 km/h speed of operation, 2-2.4 m width of machine, row spacing of 67.5-90 cm) its weeding efficiency was 61-82% with damage of less than 3% with labour saving of > 70% and cost-saving > 50%. Another weeder, with three rows coil spring full sweep tine (Sutthiwaree *et al.* 2015), had the field capacity, weeding efficiency, and fuel consumption were 0.54 ha/h, 94.66% and 5.58 L/ha, respectively, when tested in sugarcane field. A tractor-mounted rotary weeder designed and developed at PAU, Ludhiana under ICAR-AICRP on FIM scheme. (Anonymous 2018), had the field capacity of the machine was 0.24 ha/h with a weeding efficiency of 83-87%. Three commercially available power weeders for weeding operation and inter cultivation were evaluated in the sweet sorghum crop in Andhra Pradesh (Srinivas *et al.* 2010). Power weeder consisted of three types of blades *i.e.*, C, L and Sweep type of blades. The weeding efficiency of C, L and Sweep type of blades was found to be 91, 87 and 84%, respectively. The performance index with C, L and Sweep type of blades was observed as 169.84, 153.23 and 114.30, respectively.

Inter-row weeding using precision hoe showed good results for vegetable farming in Italy (Peruzzi *et al.* 2007, Fontanelli *et al.* 2009, Raffaelli *et al.* 2009). The developed machine is a modular machine which was constructed for different working depths



(a) Push-Pull weeder



(b) Different type of weeding blades

B1: A straight flat blade, B2: A straight flat blade with a serrated edge, B3: A five tines blade, B4: A sweep type blades, and B5: A double plough type blade

Figure 1. Manual operated push-pull weeder and different types of blades

Table 1. Manual weeding tools

Device	Width of cut (mm)	Field capacity (ha/h)	Weeding efficiency (%)	Work rate (man-h/ha)	Energy requirement (MJ/ha)
Khurpi	80	0.001-0.002	92-99	300-500	567.62
Grubber		0.004-0.008	82-96	109	212.62
Spade	220	0.0002	75.7-92	120-226	326.62
Wheel hoe	230	0.008-0.009	72-94	86	167.30
Push-pull type weeder (V shape blade)	150-250	0.026-0.033	80-90	100-125	140.5

Ref: Tewari *et al.* 1993, Mandal *et al.* 2002, Yadav *et al.* 2007, Shekhar *et al.* 2010, Sarkar *et al.* 2017, Chethan *et al.* 2018 adapting to the distinct soil conditions (Raffaelli *et al.* 2009). The working width is adjustable as every device is fixed on an articulated parallelogram ready with a small wheel that allows adjustments. The precision hoe working equipment, mounted on a rectangular draw frame, comprises of rigid elements that include a 9 cm wide triangular horizontal blade each, pairs of concave discs, and two types of elastic tines- vibrating and torsion). The steering is manually completed by way of a back-seated operator. This system can provide a more selective weed control inside the rows for vegetable plants such as cabbage, cauliflower and tomato. The rolling harrow for weed control was utilized for the shallow tillage and performed efficient weed control methods.

Split-hoe is used to control weeds in the inter-row area of herbaceous, horticultural, and greenhouse plants in Germany (Asperg Gartnereibedarf, Germany) (Pannacci and Tei 2014). Split-hoe has the advantages of hoe, rotary tilling cultivator and brush weeder, while it does not have their negative aspects. Weeds present in the inter-row area ranging from 0.4 - 0.5 m to 0.2- 0.25 m can be removed using a split-hoe. A shield is provided for covering the crop plants. As a result, an uncultivated soil band of 80 mm gets left. Weeding was achieved by the gangs of spike-wheels mounted on a horizontal axis that gets power from the tractor PTO (Power take off) . A spike wheels system was provided for the cutting and pulling of the weed plants simultaneously at the same time (Pannacci *et al.* 2017).

The majority of previous weeders have been horizontal, and there has been little investigation into vertical axis rotating weeders and weeding unit energy considerations. A non-powered self-propelling vertical axis rotary weeder was designed to eliminate the external powering mechanism that delivers the energy to remove the weeds and soil (Kumar *et al.* 2019). The designed weeder was tested in a maize crop, with operational depths of 2 and 4 cm and crop growth stages of 15 and 30 DAS. The invented weeder functioned well at all stages of crop development, with weeding efficiency ranging from 65 to 70% and plant damage from 1.98 to 5.88%.

The evaluation of self-propelled rotary weeder and a tractor-operated sweep weeder for weed management in cotton (Dixit *et al.* 2011) recorded weeding efficiency of 94 - 95% and plant damage 1-4 % with the field capacity 0.11 ha/h to 0.13 ha/h for self-propelled weeder and 0.2 ha/h to 0.4 ha/h for tractor operated weeder. Several mechanical weeders capable of removing inter-row weeds at different depths and speeds with high weeding efficiency were developed and demonstrated **(Table 2)**.

Mechanical weed management systems for intra-row weed management

The intra-row weeds remain uncontrolled after the management of the inter-row weeds with mechanical weeders. Hence, intra-row weeders were also developed from time to time. The spring-tine harrow weeder could be worked at a speed of around 6 to 8 km/h and at a working width of 6 to 24 m (Kouwenhoven 1997). The level of weed control relies on weed types and crops. The duration of operation, forward speed, angle of the tines, weed composition, difference between growth phases, and plant height differential between the crop and weeds all had an impact on the weed/crop (Rasmussen 1990).

A brush weeder was developed (Kouwenhoven 1997, Melander *et al.* 1997**)** which was manually directed and consisted of flexible brushes made of fiberglass or nylon that revolved around vertical or horizontal axes (**Figure 2a**). This weeder is capable of uprooting weeds, besides, to bury and destroy them. A protecting guard was provided to avoid the crop from damage. An operator was preferred to manually guide the brushes to eliminate weeds closest to crop plants without detrimental them. The torsion weeder is a gadget for weed management inside vegetable rows and is frequently used along with any other inter-row cultivation blade (Weide *et al.* 2008). Torsion weeder was fabricated that consisted of pair of spring tines linked to a rigid frame angled downward or backward within the row so that the two quick segments can work very close to each other and parallel to the soil surface (**Figure 2b**). The tines control the intra-row weeds. However, any imprecision in steering distracts the output and damages the main crop. The work is also supposed to perform on relatively low forward velocities, and hence it has a very low working capacity (Bleeker *et al.* 2002, Melander 2004, Cloutier *et al.* 2007, Weide *et al.* 2008).

A finger weeder is a basic mechanical intra-row weeder that consists of two pairs of truncated metal cones that are ground-driven by metallic tines oriented vertically. The cone has rubber spikes, or

Table 2. The inter-row weed control devices developed and their features

Devices	Depth of operation (mm)	Speed of operation (Km/h)	Field capacity (ha/h)	Weeding efficiency (%)
Rotary weeder	40-50	2-4	0.24-0.5	61-87
Sweep cultivator	20-40	2-4	0.54	84-94
Chemical weeding	On surface	2.9-9.7	2 -5	90
Self-propelled rotary power weeder	20-50	1.3-2.5	0.08-0.09	91-95

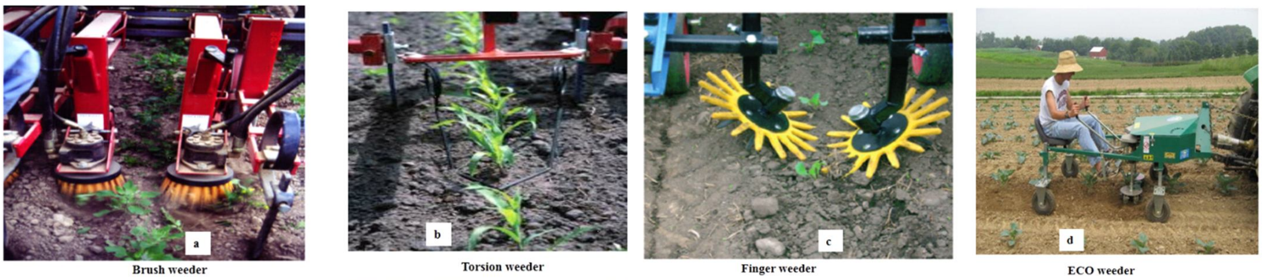
weeder fingers pointed horizontally outwards while the crop row is in between the cones **(Figure 2c)**. Finger weeder is a great performer in loose soils; however, it performs poorly incrusted or compacted soils or while the long-stemmed residue is present in the area (Van der Schans *et al.* 2006, Weide *et al.* 2008). Small weeds near the fingers are removed by the rubber fingers that penetrate below the soil surface.

An ECO-weeder is a mechanical intra-row weeding equipment with a three-point hitch system that was operated behind a tractor (**Figure 2d**). The weeding unit was powered by tractor Power take-off (PTO). The ECO-weeder could reduce the weeding costs by up to 60% compared to manual weeding. The field performance of intra-row weed management devices and effect of speed on weed control is shown in **Table 3** and **Table 4** respectively. A mechanical inter- and intra-row weeding system for row crops was developed at ICAR-Central Institute of Agricultural Engineering, and was evaluated in field grown crops (Chandel *et al.* 202). The optimal intra-row tine rotary speed to forward speed (u/v) ratios were in the range of 0.8–1.3, resulting in weed mortality of 88.4% (Buried: 8.5%, Uprooted: 79.9%), negligible intact weeds, and plant damage (Pd) of less than 6%. At recommended operating speeds of 0.50–0.56 m/s, the machine's field capacity was found to be 0.22–0.26 ha/h.

Automated technology for intra-row weeding

Manual guidance is the most common techniques, either by the input of a second operator seated on the hoe or by highly accurate tractor steering, both demand high levels of concentration. Weed management can overcome the limitation in manual and mechanical methods through automation which helps in differentiating crop plants and weeds and remove the weeds precisely by mechanical device in an automotive mode without intervention of human and without causing plant damage (Bakker 2009). Automation incorporates major innovations such as guidance, detection and identification, in-row precise weed control and mapping (Slaughter *et al.* 2008). It helps to reduce the operator stress and restricts operators from continuous steering of agricultural equipment. It allows in focusing on implement performance and reduce resources through use of electronic hardware, sensors, actuators and software (Kocher *et al.* 2000).

Enormous importance was given to vision systems and image processing techniques for weed identification based on plant characteristics and visual structure (Gonzales *et al.* 2004). A computer vision guiding system can detect the location of a tool, the center of the seed line, the ridge edges, and calculate the offset distance from the crop's center line. Slaughter *et al.* (1999) built up a machine vision guidance framework utilizing an ongoing color segmentation of direct-seeded crops in seed lines



(**Source:** Dedousis *et al.* 2006, Dedousis 2007, Weide *et al.* 2008, Anonymous 2011, Ahmad 2012)

Figure 2. Mechanical intra-row weeders

Table 3. Field performance of intra-row weed management devices

Devices	Weed control	Depth of operation (mm)	Field capacity (ha/h)	Weeding efficiency (%)
Finger weeder	Intra-row	10-40	0.3-0.6	55-60
Torsion weeder	Intra-row	10-25	0.1-1.4	60-80
ECO weeder	Intra-row	25-50	0.05-0.15	60-80
Flame weeder	Intra-row	On surface	0.1-0.5	80-90

Table 4. Effect of speed on intra-row weeds management

Devices	Weed control	Depth of operation (mm)	Speed (km/h)	Weeding efficiency (%)
Brush weeder	Inter-/Intra-row	20-30	<3.5	60-80
Harrow	Inter-/Intra-row	20-30	7	70-80
Hoe ridger	Inter-/Intra-row	25-40	7	80-90
Sensor based vertical axis rotor weeder	Inter-/Intra-row	20-60	1-2.58	75-90

where the crop is missing because of poor germination. They utilized two cameras and a framework was tried in the field at a speed of 16 km/h. The general RMS position error was from 4.2 mm (no weed condition) to 12 mm (under high weed condition). A row guidance system dependent on machine vision just as global positioning systems (GPS) for crop row recognition was described (Slaughter *et al.* 2008). The machine can identify crop rows with minimal errors from 12 to 27 mm at travel speeds of 2.5 to 10 km/h and GPS precision with RMS error at 6 cm and 13 cm maximum error in horizontal direction. Simultaneously, the lateral movement of the electromechanical/hydraulic steering system was controlled in this system (Tillett *et al.* 2008, Sogaard and Olsen 2003, Bakker *et al.* 2008).

There are numerous guidance systems proposed for weed control in agriculture (Tillett 1991, Hague *et al.* 2000) using which high-level accuracy is expected for intra-row cultivation. The most appropriate guidance techniques are to sense the crop directly and operate the weeding system on time. Sukefeld *et al.* (2000) utilized Fourier descriptors and shape parameters to distinguish more than 20 weed species. About 69.5% of weeds with only cotyledons were correctly identified, while 75.4% of weeds with one or two pairs of leaves were correctly identified. In wider row crops, this detecting system distinguishes between crop and weeds by working constantly with a camera image and under uncontrolled illumination and movement conditions (Guerrero *et al.* 2017).

High-level accuracy is expected for intra-row cultivation. There are numerous guidance systems proposed for weed control in agriculture (Tillett 1991, Hague *et al.* 2000). The most appropriate guidance techniques are to sense the crop directly and operate the weeding system on time. Manual guidance is also the most common techniques, either by the input of a second operator seated on the hoe or by highly accurate tractor steering, both demand high levels of concentration.

For detection of weed and subsequent control, Astrand and Baerveldt (2002) developed an autonomous mobile agricultural robot using a system that includes two cameras: one gray-scale camera for distinguishing crop rows and another for weeds rows. The robot works along with the columns, and the subsequent camera utilize a color-based vision system to recognize a single crop among weeds and thus it focuses on a perceptual system for crop row recognition rather than weed management specifically. The weeding device was guided with the assistance of a pneumatic chamber for some tilling action in inter row plant area. At a speed of 0.2 m/s and a camera error of +2 cm, machine performance was acceptable. Using picture segmentation algorithms, the color-based camera effectively spotted crops. It uses colour and shape characteristics to classify weeds and crops. The machine's weed-control effectiveness, however, was not reported.

A robotic weed control machine was developed for transplanted lettuce (Blasco *et al.* 2002) by which weeding was done using a high voltage electric current (15 kV electrical current discharge). Two vision-based machines were used, one to detect the weeds in the field based on size and another to position the electrical probe to destroy those weeds. The autonomous platform and record device was capable of gathering pix automatically. Maps and images of weeds and crops were also acquired. The detection accuracy of the system was 84% for the weeds and 99% for the lettuce plants.

For the guidance of an implement at the side of a pre-stored electronic area map through satellite, Real-Time Kinematics (RTK) DGPS (Differential Global Positioning gadget) was inspected by Zuydam (1999). The field map was based on a coordinate system that describes the path of an implement. It was observed that the real direction of the implement deviated using less than ± 20 mm from a straight line. A rover and a base DGPS were used for the guidance of the weeding machine. This base station must stay close to the rover unit for best results. The implement was guided through GPS the use of a side-shift mechanism to control lateral position.

An intra-row weeder, developed by Griepentrog *et al.* (2006) on the RTK base, used crop seed maps created at the time of sowing to remove the weeds. This rotary weeder consisted of eight tines rotated with the help of an electro-hydraulic motor describing cycloid curves. The rotary tine cultivator (the cycloid hoe) can be guided within the crop rows by RTK-GPS (Norremark 2008). It was tested in the field for its accuracy. By using a plastic stick, instead of crop, a violation of the uncultivated region (10 mm from the center of sticks) by tines was seen in less than 2% of the observations. The effectiveness of weed eradication and crop–weed discrimination, on the other hand, was not assessed. The research findings highlight that the rotor weeding mechanism could control weeds and cut the soil without destructive crop plants. The weeding mechanism can uproot and cut weeds and cover them with soil. The cycloid pattern is visible in the hoeing system. The novel idea is that, the tines may be retracted to the interior of the cylinder, causing the tine tip to trace a smaller cycloid. Griepentrog *et al.* (2007) examined the identical machine at a speed of 1.44 km/h; they mentioned that it induced immoderate damage to the crop and resulted in very low weed control efficacy. Moreover, cycle hoe has some disadvantages that make it unsuitable for mechanical weed control. One of the most reported constraints is its design complexity, which causes the increased maintenance and capital price. An undisturbed circle around the plant (18 mm) also makes the system difficult to adapt. The soil type is another crucial factor. When soil clods engage with crops, it will become tough to control crop damage. In cotyledons plants (at the true leaf stage), the mechanical design of the system is tough for use due to potential damage.

The rotary tine cultivator (the cycloid hoe) guided within the crop rows by RTK-GPS was tested in the field for its accuracy (Norremark 2008). by using a plastic stick, instead of crop. A violation of the uncultivated region (10 mm from the center of sticks) by tines was seen in less than 2% of the observations. The effectiveness of weed eradication and crop–weed discrimination was not assessed.

Zuydam and Sonneveld (1994) explored the accuracy of a laser directing system that is guided to a tool to control the weed. A side moving unit, a transmitter, and a second operator with a hand-held receiver made up the guidance system. An electro-hydraulic valve was used to convert a lateral error indication into hydraulic cylinder activation. It assists with moving the laser guidance system towards an exact side. The maximum distance for the selected laser can work at 500 m with an average steering accuracy of ± 6 mm over a length of 250 m. The maximum deviation was no longer exceeded 19 mm. An alternative non-contact system was developed by Andersen (2003). To measure the furrow's extreme value points, he used a vertically placed laser light source. Following that, the implement was guided to produce the proper lateral alignment. Kise *et al.* (2005) created a weed-free detection system using near-infrared stereovision. The system represented an error of 30–50 mm RMSE relying on speed and row arc. Astrand and Baerveldt (2002) developed a machine based on vision steering to distinguish between direct-seeded crop plantings, crop plant length and the presence of weeds at densities up to 200 weeds/m^2. This machine was primarily based on the Hough transform, which uses a couple of rectangular regions for crop size to estimate the row position.

The rotating disk and the cycloid hoe for Intra row weeder was developed (Cavalieri *et al.* 2001) whose working was based on real-time or map-based. The rotating disk, developed at Wageningen University, comprised of a vertical rotating disc with two spring-loaded knives that are actuated by a hydraulic motor. Its speed was controlled by a hydraulic controller. The disc rotates with a steady speed of 850 rev/min, and the knives fold-out due to the significance of both the forces, which is the centrifugal force that is larger than the spring force. The disc decelerates to 700 rev/min when a plant is detected, and because of the inertia forces, the knives fold in, letting the disc to keep away from the plant contact (Bontsema *et al.* 1998, Home 2003). The plant detection sensor, along with three infrared transmitters and three infrared receivers, are placed in front of the disc at a constant height along the crop row (Bontsema *et al.* 1998). Plant detection signals are sent to a digital signal processor. The weeding efficiency is low due to one mode of cutting action above the soil surface. Weed killing efficacy was reduced due to three possibilities *i.e.*, uproot, cut, and cover. Additionally, the detection device couldn't differentiate between the plants and weeds appropriately, hence making it a system suitable only for transplanted crops (Jones *et al.* 1995).

Radis Mechanism developed an intra-row weed management system with blades mounted on a pivoting arm. Light sensors detect the plants, and this information is used to control the disc's position. When no plants are visible, the rotating arm enters the intra-row area through an air pressure chamber, eradicating the intra-row weeds.

Bakker (2003) reported that weeds were removed only up to 20 mm at a driving speed of 5 km/h. Bleeker (2005 and 2007) reported a maximum speed of 3 km/h limited for weeding operation in case of Radis weeder, due to the plant damage by the intra-row hoe mechanical transition. This technique is best suited to vegetables with a wider spacing between rows and a minimum intra-row spacing of 220 mm (Bakker 2003). The system's challenge was detecting the plant in a wide row crop and limiting the speed of the intra row weeding operation.

Tillett (1991) reported that a high accuracy of 99% can be obtained from ultrasonic guidance in the distance range of 100 mm to 10 m. He also said that stray foliage poses issues because the distance is calculated based on the time it takes for the ultrasonic signal to reach, hit, and reflect back off the target, which means that the signals are reflected back from weeds rather than crops.

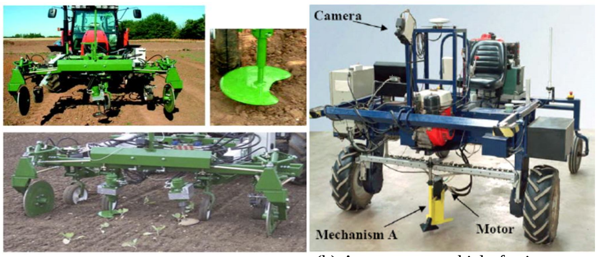
A weeding machine using computer vision was tested to detect plants by Tillett *et al.* (2008). A rotating half circle disc was provided in this automated intra-row weeder to protect the crops at the time of weeding (**Figure 3a**). A digital camera was fixed at mid-position of the weeder for looking forward and down. The camera was vertically above the base of the field of view and it covered the length of about 2.5 m over a time of view. Weeding treatments were conducted at 16, 23, and 33 days after transplanting (DAP). Weeding conducted after

16 and 23 days of planting gave the best results as it resulted in a decrease in the number of weed plants by 77 and 87%, respectively.

Another novel inter and intra-row mechanical weeder can operate at a speed of 1.2 m/s in transplanted intra-row spacing (**Figure 3b**) (Home 2003). It consists of a duck foot and reciprocating blades for inter and intra-row weeding, respectively. The plants are identified by using a camera and differentiated from the weeds based on computer vision. It is possible to operate at a speed of 2.2 m/s. Excessive damage to the plants was reported.

A rotating tine mechanism for an automated mechanical intra-row weeder with rotating tine mechanism powered by a brushless DC (BLDC) motor was developed (Ahmad *et al.* 2012) which detects crop location using a machine vision system. The weeding actuator was controlled using a controller. At travel speeds ranging from 0.8 to 2.4 km/h and working depths of 25.4 mm and 50.8 mm, they discovered a substantial difference in weed canopy area.

A weeding tool developed by Gobor *et al.* (2013), comprised of number of arms holders and integrated on horizontal axis of rotating arms, placed directly above the crop row. A concept of integration of the weeding tool on an autonomous platform, in the form of a prototype was used. The guiding principle was based on the hoeing tool's rotating speed. The tool must be fine-tuned in real time, taking into account the tool carrier's forward speed, the estimated in-row distance between consecutive plants, and the observed angular position of the arms. For the validation of the geometrical equations, a model was built and a virtual prototype of the system was created in Pro/Engineer. For testing the system behaviour for various weeding techniques and considering distances inside adjacent crops, a virtual model of the weeding tool was used. Different weeding approaches were simulated for less plant damage and examined for one, two, and three consecutive trajectories tools inside nearby plant, with and without changing the angular position. The sensor guided system and accuracy of intra row weeding system is shown in **Table 5**.



(a) Disc weeder (b) Autonomous vehicle for intra-row

Source: Home 2003, Tillett *et al.* (2008)

Figure 3. Autonomous hydraulic operated weeder

A weed identifying robot was developed by Sujaritha *et al.* (2017), consisting of a Raspberry Pi microprocessor with appropriate input-output subsystems, such as cameras, small light sources, and motors, as well as an electric device. Raspbian working gadgets and python programming were used for the weed detection mechanism. Among nine different weed species, the built robot prototype was able to correctly locate the sugarcane plantation. The developed system identified the 92.9% weeds correctly and had a handling time of 0.02 s. Jakasania *et al.* (2019) developed an intra row weeding unit and evaluated at soil bin laboratory for determining percentage of plant damage. The minimum plant damage was observed at plant spacing of 35 cm and speed of operation of 1.0 km/h.

Kumar *et al.* (2020) developed a fuzzy logic algorithm integrated autonomous system for weed eradication in the intra-row crop zone. The system incorporates time of flight and inductive sensing into a fuzzy logic algorithm for electronic control of a four-bar linkage mechanism (FBLM). A prototype of intra-row weeder was developed as a combined arrangement of mechanical linkage actuator system and various electrical sensing and control systems (Kumar *et al.* 2019a and b). The prototype consisted of an intra-row vertical axis rotor, FBLM, sensor, permanent magnate direct current (PMDC) motor, microcontroller circuit box and virtual plants. Intra row weeding system was evaluated at soil bin laboratory at varied conditions of soil compaction, forward speed, depth of operation and plant spacing. The developed system very well accounted for the numerous parameters that could exist in field operations. With faster forward speeds and smaller plant spacings, plant damage increased significantly (p=0.05). The device's sensing accuracy was also evaluated during preliminary tests, and encountered plant damage. The overall operating efficiency varied within 80 to 96% when evaluated under different plant spacing.

Machine vision-based sensing systems for managing inter- and intra-row weeds by other weed management methods

The machine vision-based sensing system was integrated with an existing sprayer for selective herbicide control (Steward *et al.* 2002). A finite state machine (FSM) model was utilised to construct the controller, and generic design specifications were created to determine the travel distance between states. Artificial targets were used to test the system's spatial application accuracy in the field. The system has a 91% overall hit accuracy with no statistical evidence that the mean pattern length was affected by vehicle speed. Home-made system for spatially

Table 5. Sensor guided system for intra-row weeding operation

Device	Guidance type	Accuracy/limitation	Source
Hoe	Laser guidance steering system	±6 mm	Zuydam & Sonneveld 1994
	Ultrasonic	99% over range 0.1-10 m	Tillett 1991; Kumar *et al.* 2020
	Real Time Kinematics (RTK) DGPS	± 20 mm to ± 60 mm	Zuydam 1999; Griepentrog 2006; Buick 2007; Slaughter *et al.* 2008
Cycloid hoe	Hydraulic side-shift system	Geo-positioning expensive maintenance	Griepentrog 2007; Cavalieri *et al.* 2001
Field Robot or Autonomous vehicle for weeding	Machine Vision guidance system	±12 mm to ± 45 mm	Tillett *et al.* 1999; Keicher and Seufert 2000; Astrand and Baerveldt 2002; Home 2003; Aastrand and Baerveldt 2005; Tillett *et al.* 2008; Lee *et al.* 1999; Slaughter *et al.* 2008
Vertical rotating disk weeder	Rotating disc with a cut-out sector	Angular error of the disc less than 10°	Dedousis *et al.* 2006
Rotating disc tine	Infrared	Error on discrimination between plants and weeds	Cavalieri *et al.* 2001; Bontsema *et al.* 1998; Jones *et al.* 1995 and 1996
Radis moving tine	Light sensors	Error due to natural light interference	Bakker 2003; Bleeker 2007

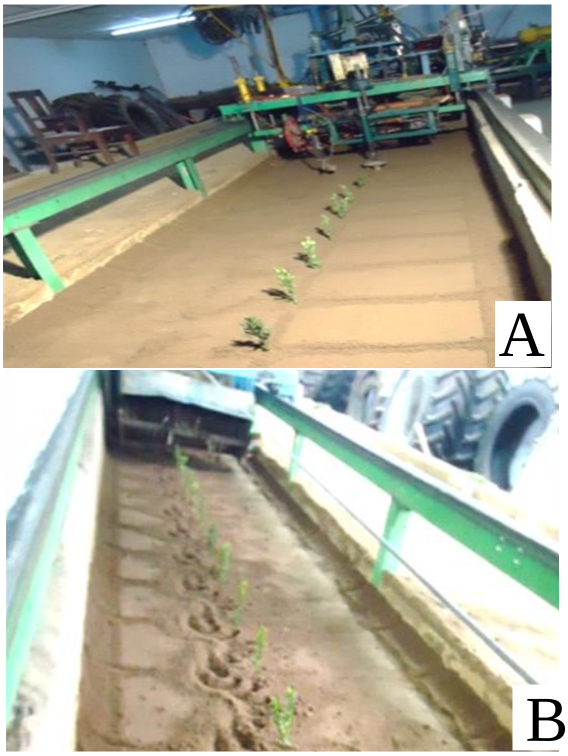
variable rate herbicide applicator was used to weed control (Carrara *et al.* 2004). This system consists of a differential global positioning system (DGPS), a portable computer, custom-developed software, and a device that applies rates proportional to the machine forward speed. The herbicide application at a spatially varying rate allowed for an almost uniform grain production across the entire field. In comparison to the levels generally used in conventional farming, the technique saved 29% of herbicides.

Another real-time robotic weed control system useful for the cotton field (Lamm *et al.* 2002) was able to distinguish between weeds and cotton plants, allowing for precise application of the chemical spray. Weeds were targeted at a travel speed of 0.45 m/s and the system was correctly sprayed at 88.8% weeds at this speed.

Tewari *et al.* (2014a) developed a three-row contact type microcontroller-based herbicides applicator to control the weeds population from the inter-row crop (**Figure 5a**.). The system was based on real-time image processing. The system automatically computes and applies the amount of herbicide through contact sponge rollers depending on the amount of weed estimated by real-time image processing. Field experiments demonstrated that there was a 40% herbicides reduction having an application efficiency of 90%. Chandel *et al.* (2018) developed a tractor-operated contact type weed eradicator for row crops using a microcontroller-based position sensor and an integrated digital image processing system (**Figure 5b** and **c**). The weed density within the crop rows was detected using an image analyzer developed in the Visual Studio Open computer vision platform, which was employed under varied illumination conditions. In addition, a graphic user interface was designed for parametric adjustments of the image analyzer. The micro-controller acquires the data from the image analyzer, processes the data and sends the signal to the solenoid valve to release the chemical over the contacting roller (Figure 5d). They reported an average weeding efficiency of 90% in maize and groundnut crops with plant damage of 5 and 8%, respectively. They observed a saving of 79.5% of herbicides by using the digitally developed embedded system. The use of chemical herbicides in the field is causing an increase in health risks, environmental issues, and herbicide-resistant weed species, all of which are driving demand for low-cost, chemical-free production. Many researchers have been challenged to investigate and develop alternate weed management technologies (Astrand and Baerveldt 2002, Kurstjens 2007, Dedousis *et al*, 2007, Tillett *et al*.2008, Norremark *et al*. 2008).

A real-time robotic weed control system can be utilized for exact application of herbicide applications on weeds utilizing machine vision (Lee *et al.* 1999). Weeds can also be controlled by a high voltage (15-60 kV) electrical current to small weeds utilizing a precise control system (Diprose and Benson, 1984, Blasco *et al.* 2002). Weeds can be detected and burnt precisely using infrared sensors and flame nozzle spray (Merfield 2011). The flame weeder is also used for weeding operation. The important thing to know about flame weeder is it can be used either before weeding or pre-emergence. It can also destroy under soil surface weeds (Kirchoff 1999).

Flame weeders were precisely impacted the weeds growing in the "in-row" space at strip of 0.25 m wide. This weeder was used for onion and maize crop precisely and that plants can tolerate flaming (Parish 1990, Ascard 1990). A computer vision guiding system can detect the location of a tool, the



(Source; Kumar *et al.* 2020)

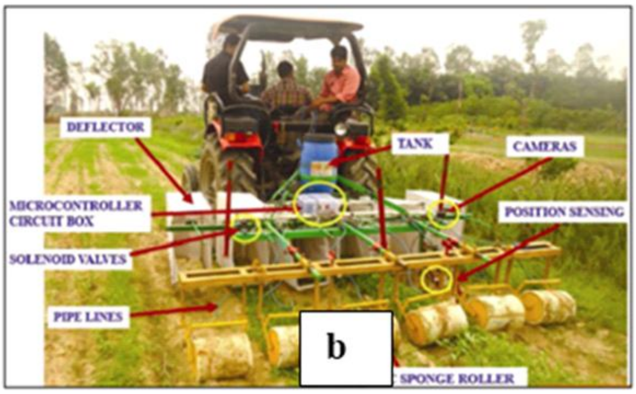
Figure 4. Soil bin profile (a) before and (b) after operation of prototype intra-row weeder

centre of the seed line, the ridge edges, and calculate the offset distance from the crop's centre line. Simultaneously, the lateral movement of the electromechanical/hydraulic steering system was controlled in this system (Tillett *et al.* 2008, Sogaard and Olsen, 2003 and Bakker *et al.* 2008). Sukefeld *et al*. (2000) utilized Fourier descriptors and shape parameters to distinguish more than 20 weed species. About 69.5% of weeds with only cotyledons were correctly identified, while 75.4% of weeds with one or two pairs of leaves were correctly identified. In wider row crops, this detecting system distinguishes between crop and weeds by working constantly with a camera image and under uncontrolled illumination and movement conditions (Guerrero *et al.* 2017).

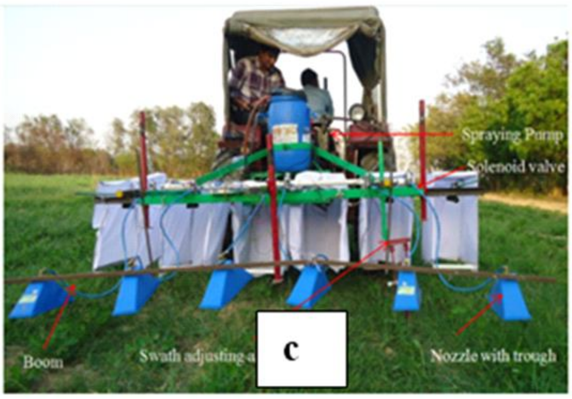
Conclusions

Mechanical weeding has seen a lot of innovation over the previous few decades, but more is needed to develop and use precision agricultural technology for mechanical weed management in India. There are presently no commercial approaches available to effectively control intra-row weeds, and the accuracy of the tool's lateral positioning in intra row is restricted to the guidance system. The challenges for dynamic synchronization of electronic control,

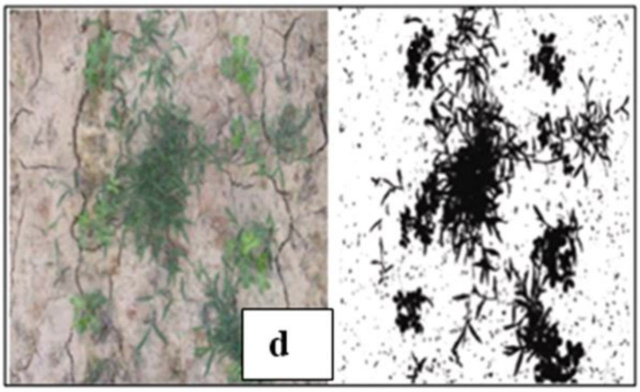
(a) Manual drawn



(b) Tractor drawn roller based herbicides applicator



(c) Herbicideds applicator



(d) Image processing of weeds

Source: Tewari *et al.* 2014a, Chandel *et al.* 2018

Figure 5. Image processing and microcontroller based herbicide applicators

mechanical tool actuations, and plantation characteristics need to be consistently explored and optimized for effective weeding options in row crops.

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