REVIEW

Opportunities for Improved Mechanical Weed Management in India

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Abstract

India is an agricultural country, with more than 40% of its population engaged in agriculture and allied sectors. About 62.9% of the people involved in agriculture-related activities are females, who perform the majority of the most arduous activities. Most of these operations are time-consuming drudgeries that require much energy. Weeds are one of the significant constraints in crop production in India and can cause up to 37% of yield losses. Timely weed management is essential to reduce crop-weed competition, especially during critical periods, to ensure the quantity and quality of the produce. In India, most farmers (more than 86%) are smallholders and farm on fragmented and marginal lands with low-cost production methods. Most still rely mainly on hand weeding with simple, traditional tools for weed management in all major crops.

Manual weeding is one of the most tedious and laborious jobs in agriculture. It has been estimated to consume up to 25% of the total labour requirement in agricultural production. The use of traditional tools still results in the loss of 10-15% of crop productivity in Indian agriculture. India has an estimated farm power availability of 3.045 kW/ha and weed management mechanization of around 32% across all crops. Our review finds that the adoption of mechanical weeders in India is greatly hindered by smaller land holdings, farmers' economic conditions, high initial cost of machines, high repair and maintenance costs, and non-availability of weeders and repair services at the village level. Other significant obstacles are inadequate awareness of advanced weed management technologies, cropping systems, and patterns.

However, in our view, based on literature and research experience across many regions in India and crops, improved mechanized weed management practices could save one-third of the weed management costs. Therefore, in Indian agriculture, there is tremendous scope for increasing the mechanization level of weed management, focusing on input use efficiency and sharing available tools and equipment at the village level. Increased mechanization would improve farming net profits and reduce the drudgery of labour-intensive field operations.

A critical requirement is the further development of low-cost, ergo-refined weeders, which are suitable for small and marginal land holding sizes. This review finds the Government of India's scheme "Sub-Mission on Agricultural Mechanization (SMAM)" as providing a fresh, single window for improving the mechanization of weed management in India through more innovative designs.

Keywords: mechanical weed management, mechanical weeding tools, mechanized farming

Introduction

India is an agriculture-based country, with more than 40% of its population engaged in agriculture and allied activities. Agriculture provides employment, food security and demand for industrial goods and services. Agriculture and allied sectors are the largest employers in India's workforce (Vemireddy and Choudhary, 2023). While playing a pivotal role in supporting 17% of the global population (Rao, 2024), agriculture contributed 14.45% to India’s gross domestic product (GDP) in 2023-24 (Statistics Times, 2024). About 45.5% of the total workforce (62.9% female and 38.1% male workers) is involved in the agricultural and allied sectors (PIB, 2023).

Among the most significant challenges faced by Indian agriculture are (a) the ever-increasing food demand, (b) labour shortages, (c) inadequate mechanization of agricultural activities and (d) higher input costs. Urbanization, better opportunities available in the non-agricultural sector and uncertainties in agriculture as a vocation are factors that lead the workforce to migrate from the farming sector to non-agricultural industries. A drop in the percentage share of the labour force from the current figure of about 40-45% to 34.6% by 2030 has been estimated (Kapur et al., 2015).

Indian agriculture is mainly characterized by its land holdings (Table 1). The total land holdings increased from 138.35 million in 2010-11 to 146.45 million in 2015-16. However, the operational area has decreased from 159.59 million ha in 2010-11 to 157.82 million ha in 2015-16. The per capita availability of land has decreased from 1.15 ha in 2010-11 to 1.08 ha in 2015-16 (PIB, 2020).

As per Agriculture Census, 2015-16, India had 86.1% of small and marginal farmers (up to 2.0 ha), 13.35% of medium farmers (2.0 to 10.0 ha) and a very small number (0.57%) of large farmers (more than 10.0 ha). The small and marginal farmers cultivated about 47% of the area, medium farmers cultivated 44% of area and large farmers cultivated only about 9% of the total area cultivated during 2015-16.

An increasing population in India has resulted in fragmentation of land and smaller per capita land holding sizes. The smaller size of per capita land holdings affects the economic conditions of the farmers. It limits the suitability of such farms for large-sized machinery. This effect is an obstacle to the effective mechanization of agriculture. Most Indian farmers now own farms that are, on average, less than 1.4 ha. Bringing new technologies and practices and integrating them with a large population of poor farmers scattered over a large country is also a hugely challenging task for profitable agriculture.

Table 1 Classification of land holdings in India

Category	Size class
1. Marginal	< 1.0 ha
2. Small	1.0 - 2.0 ha
3. Semi- Medium	2.0 - 4.0 ha
4. Medium	4.0 - 10.0 ha
5. Large	> 10.0 ha

(Source: PIB, 2019)

Besides affecting agro-biodiversity and natural water bodies, weeds are a significant biotic constraint in crop production. They compete with crops for nutrients, moisture, sunlight and space, reducing crop yields by as much as 37% (Tewari and Chethan, 2018). In 2018, Gharde et al. estimated crop yield loss due to weeds in 10 major crops in India and reported that yield losses due to weeds varied depending on the crops, soil type, geographical location, cropping condition, and weed management practices followed.

The highest yield loss of around 35.8% was recorded in groundnut (*Arachis hypogaea* L.). This was followed by losses of 31.4% in soybean [*Glycine max* (L.) Merr.], 30.8% in green gram [*Vigna radiata* (L.) Wilczek], 27.6% in pearl millet (*Pennisetum glaucum* L.), 25.3% in maize (*Zea mays* L.), 25.1% in sorghum [*Sorghum bicolor* (L.) Moench], 23.7% in sesame (*Sesamum indicum* L.), 21.4% in mustard [*Brassica juncea* (L.) Czern.], 21.4% in direct-seeded rice (*Oryza sativa* L.), 18.6% in wheat (*Triticum aestivum* L.) and 13.8% in transplanted rice (*Oryza sativa* L.).

Most Indian farmers still use traditional and age-old weed control practices despite losing 15-20% of crop yield to weeds (Chethan et al., 2018). In India, on average, weed control costs are around INR 6000 ha^{-1} in the *kharif* (rainy) season and INR 4000 ha^{-1} in the *rabi* (winter) season, accounting for 33% and 22% of the total cost of cultivation, respectively (Yaduraju and Mishra, 2017).

Among the standard weed control methods, biological and cultural methods have limitations concerning managing a significant diversity of weeds under most cropping conditions. Chemical weed management is biologically productive and economically superior, but herbicide use has an environmental cost (Slaughter et al., 2008). On the other hand, mechanical weed management is very effective in controlling weeds without negative impacts on the environment (Tewari and Chethan, 2018).

Mechanical Weed Control and Tillage Operations

Mechanical weed control involves the physical removal of weeds using mechanical tools and implements. Weed control is an integral part of primary and secondary tillage, which are the initial steps taken to prepare a field for cropping (ASAE, 2004; 2005). The choice of tools and implements used in tillage, as well as the time and frequency of their use, depend on the type of crop to be sown and the weeds encountered in the land that need to be prepared for cropping. Further, the soil type, soil moisture, agro-climatic condition, field size and shape also influence the type of tillage and weeding equipment (Rueda-Ayala et al., 2010).

Primary and Secondary Tillage

In simple terms, primary tillage is the first breaking of the soil, which loosens the soil but leaves it with a rough texture in large lumps. Primary tillage can effectively control the weeds by burying their seeds or propagules to a depth from which they cannot emerge (Cloutier and Leblanc, 2001; Mohler, 2001; Cloutier et al., 2007). For example, problematic perennial weeds in Indian farming, such as purple nutsedge (*Cyperus rotundus* L.), creeping thistle (*Cirsium arvense* (L.) Scop.], coltsfoot (*Tussilago farfara* L.) and wild wormwood (*Artemisia vulgaris* L.), can be effectively controlled by burying their bulbous or rhizomatous propagules deep, preventing or slowing emergence. Some of the implements used for primary tillage are mouldboard ploughs, disc ploughs, rotary ploughs, diggers and chisel ploughs (ASAE, 2004; 2005).

Secondary tillage is the second breaking of the soil, producing finer soil and sometimes shaping the rows, preparing the seed bed for planting. Secondary tillage may also involve mixing fertilizers, lime, manure or any other soil amendments. Seedbed preparation is the final secondary tillage operation except when used in the stale or false seedbed technique for controlling weeds (ASAE, 2004). Secondary tillage tools include the rotatory plough and various types of harrows (e.g., disc, spring-tyne, radial blade and rolling harrows).

Both primary and secondary tillage, undertaken before crops are sown or planted, improve the surface area of soil such that the roots of germinating seeds or juvenile plant roots can easily take up water and nutrients from it. Weed control is an integral part of these activities. During these tillage operations, weeds are uprooted and mixed with soil. Tilling increases soil aeration and the soil's water-holding capacity while killing and burying weeds (Kurstjens and Perdok, 2000; Kurstjens and Kropff, 2001).

Cultivation tillage (tertiary tillage)

Cultivation tillage refers to activities that are undertaken after the planting and emergence of a crop. The primary objective of cultivation tillage is to control emerging weed species at early development stages. Cultivation tillage aims to create a non-competitive environment and conditions for crop growth (Vanhala et al., 2004; Rueda-Ayala et al., 2010). The depth of operation in cultivation tillage varies from 2 to 6 cm and can destroy the weeds in several ways.

The passage of a cultivator over a field wholly or partially buries and uproots the weeds and breaks weed roots encountered by the cultivator (Rasmussen, 1991; Kurstjens and Perdok, 2000). Cultivation tillage is more effective in dry soils than wet soils, as weeds often die by desiccation. However, death and decay and the mortality rate of weeds decrease under moist conditions. Cultivating the soil when it is too wet will also damage the soil structure and may possibly spread perennial weeds (Cloutier and Leblanc, 2001).

Cultivation tillage includes whole-crop cultivation (full surface), inter-row cultivation (between crop rows) and intra-row cultivation (between crops). Depending on the severity and condition of the weeds, cultivation tillage may be carried out during the early emergence of crops. Weeds, such as the use of microwave weeders, which kill weed seeds. However, cultivation tillage is by and large an activity that targets weeds after the emergence of the crop and needs to be done with care to not disturb crop plants.

Broadcast (Full-width) Cultivation

Broadcast cultivation involves cultivating the soil with the same intensity, both on the rows and in between the crop rows. It is done before or after crop emergence, depending on the requirements. Common implements used for this purpose are implements, such as chain harrows and flex-tyne harrows.

Inter-row cultivation

Inter-row cultivation refers to the cultivation of soil between the crop rows to loosen the soil and kill weeds at the same time. This method ensures minimal risk to the crop and usually provides excellent weed control. The major limitations are the growth stages of the crop and weeds. Inter-row cultivation weeding should be done within the critical period of crop-weed competition. Otherwise, the luxurious growth of weeds may clog the cultivators and lead to poor weeding.

The weeders used for inter-row cultivation are khurpi, wheelhoes, rotary weeders, wetland weeders, engine-operated weeders, tractor-operated weeders, self-propelled weeders and robotic weeders.

Intra-row cultivation

Intra-row weeding refers to the cultivation of soil within crop rows. There are increased risks of intra-row weeders damaging crops while performing weeding. Therefore, intra-row cultivation requires both precision and accuracy and experienced operators to perform a weeding operation. The weeders used for intra-row cultivation are finger weeders, torsion weeders, air blow grit weeders, cycloid weeders and brush weeders.

Types of Mechanical Weeders

Mechanical weeders are classified on the basis of soil type, cropping condition, power source, sensor system for detection, weed removal, etc. (Table 2). It is well known that the efficacy of mechanical weeding declines as the weeds develop. Weeds are more vulnerable when they are in their young growth stages. However, weeding efficiency also varies significantly with the type of device used.

Table 2 Types of Mechanical Weeders

Criteria	Classification	Tools
Power source	Manual weeding tools	Khurpi, grubber, straight blade hoe, wheel hoe and cono weeders.
	Animal drawn weeders	Sweeps, duck foot cultivator and harrows.
	Power operated weeders	Self-propelled rotary weeders, tractor-operated rotary weeders, cultivators and brush cutters.
Crop condition	Broadcast weeders	Spring tyne, rolling, chain harrows and rotary hoes.
	Inter-row weeders	All types of sweeps, including hoes and shovels, rotary weeders and brush weeders.
	Intra-row weeders	Rotary weeders, brush weeders, torsion weeders, finger weeders and sensor-based robotic weeders.
Soil engagement	Soil engaging type	All cultivating tools.
	Non-soil engaging type	All weed-cutting tools, e.g. mowers and brush cutters.
Sensing system	Sensor-based system	Sensor and robotic weeders. These include mechanical actuators/ optical/ ultrasonic/ infrared red/ laser/ thermal, and microwave weeders.
Weeding system	Thermal weeders	Various types of Microwave/ laser/ infrared/ steam/ hot air blown/ electric/ flame weeder
	Non-thermal weeders	All conventional weeding tools

(Source: Tewari and Chethan, 2018)

The control of weeds by mechanical means depends on the degree of soil disturbance caused by the weeding implements. The mechanical weeders simultaneously uproot, cut and bury weeds during the weeding operation (Melander et al., 2017). If soils are dry, uprooting weeds reduces their root anchorage and increases the desiccation rate. Burying weeds in the soil destroys them effectively (Rasmussen, 1991).

A soil burial depth of six cm will kill most of the weeds, regardless of species and growth (Merfield et al., 2020). Therefore, soil tillage needs to be performed to achieve a soil cover of six cm to kill weeds if they have surpassed the seedling stage (Melander and McCollough, 2021). The above mechanism holds true for tyne-type weeders. However, blade-type and share-type hoes can also cut weeds with several mature leaves and uproot them at relatively advanced growth stages (Melander et al., 2005).

Weeding activities in India are the most laborious and costly operations. They involve a great deal of energy-intensive activities compared to other agricultural operations (Chethan et al., 2020). The majority of Indian farmers still use small-capacity, less efficient, manually-operated weeders, such as kodali, khurpi, powrah, sickle, locally made hoes and hand-held forks. Only a small proportion of farmers are able to afford tractor-operated weeders (Appendix 1).

Manual weeding accounts for up to 25% of the total labour requirement, depending on the condition of the field (Nag and Dutta, 1979; Chethan and Krishnan, 2017). If conducted well, manual weeding provides a near 'weed-free' environment. Undertaking one- to two-hand weeding operations during the critical period of crop-weed competition usually results in satisfactory weed control. However, the non-availability of experienced workers during this crucial period limits the success of manual weeding operations in most crops. The resulting inadequacy of weed control greatly affects crop yields and quality.

In recent times, engine-operated weeders, suitable for small landholdings, have gained increasing popularity among Indian farming communities. The cost of these machines is cheaper. They also require fewer repairs and maintenance compared to tractor-operated and other bigger machines.

Problems with Mechanical Weed Management

Several recommendations were made to adopt mechanical weed management in different crops (Appendix 2). However, the lack of awareness about mechanical weeders, higher initial cost and non-availability of machines, fragmentation of lands, requirement of highly skilled operators, rural landscape, migration of labourers from the agricultural sector, etc, makes it difficult to adopt mechanical weed management under the Indian scenario.

More than 86% of Indian farmers have fragmented lands with a land size of less than 2 ha. These farmers are economically poor compared to large farmers and totally dependent on inefficient, drudgery-prone and time-consuming traditional weeding tools. On average, the khurpi requires 500-600 man-h/ha, the grubber requires 330-500 man-/ha, manually operated hoes require 50-100 man-h/ha, and animal-drawn weeders require 6-20 man-h/ha of manpower to perform the weeding operations (Tewari and Chethan, 2018).

The operation of most of these tools requires bending and squatting postures, which require 30-50 % higher energy compared to weeding operations performed in standing or sitting posture (Chethan et al., 2018). Thus, manual weeding using small tools is a costly affair in India.

In India, two to three mechanical weeding operations have been recommended for most crops. Generally, mechanical weeding is done 15-20 days after the sowing of the crop. It needs to be repeated depending on the severity of the weed infestations. The time available to perform weeding operations in most crops is limited. If weeding is not conducted within this window, it could result in the luxurious growth of weeds and adverse effects on the crops.

The non-availability of gender-friendly weeding tools and implements is also a major drawback for not adopting mechanical weed management. In India, more than 62% of the agricultural labourers who perform the majority of the weeding operations are females. However, the implements and machines developed in India are largely based on the anthropometric parameters of male workers. These weeders are not suitable for female workers, most of whom have less muscle mass than male workers. As a result, female labourers are often handicapped in the use of existing machines for weeding operations. Further, the non-availability of weeder sale centres, custom hiring centres, repair and maintenance centres, and farm machinery banks also greatly influences the non-adoption of mechanical weeders.

Other issues, mainly faced at village levels, include the difficulty of finding a skilled operator, inefficiency of unskilled operators, inappropriate way of handling the machines, delays or lack of repair services and high fuel consumption. All such factors contribute to the non-adoption of mechanical weeders.

A survey has been conducted to study the reasons for non-adopting mechanical weeders at the farmers' level (Figure 1). It showed that 22% of the respondents did not adopt the weeders because of the machine cost. About 20% of them did not adopt because of the non-availability of hiring facilities, and 8% of them did not adopt because of the higher hiring cost (Vemireddy and Choudhary, 2023).

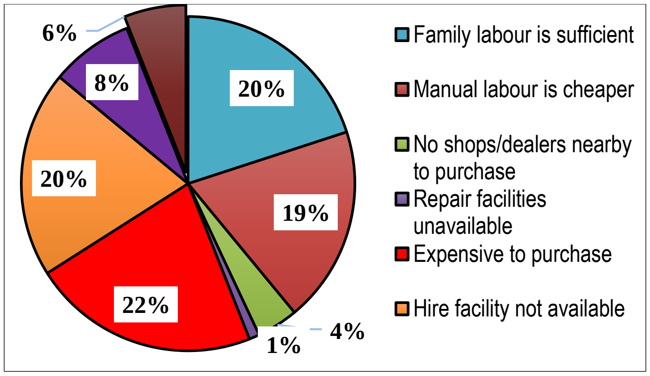

Figure 1. Response of the labourers for adopting mechanical weeders

Adopting advanced weeders, incorporating a global positioning system (GPS)-guided tractor-operated weeders, sensor-based weeders, robotic weeders, laser weeders and microwave weeders, may not be possible in the present-day situation in India. The farmers' economic conditions and capacity to afford the high-cost machines are very poor compared with the farmers of developed nations. Therefore, Indian farmers are in great need of low-cost, cost-effective, ergo-refined weeding tools that are suitable for both small-to-medium-sized and larger landholdings.

The data compiled by the ICAR-Directorate of Weed Research, Jabalpur and AICRP-Weed Management (a network-coordinated research programme) shows a tremendous scope for adopting improvised mechanical weeders, which are cost-effective and efficient for controlling the weeds. Improving and mechanizing weed management practices could save one-third of the weed control cost (Chethan et al., 2020). Given that small and marginal farmers comprise the largest portion of the Indian farming community, priority research should focus on developing weeding machines and implements that such farmers can afford.

Opportunities for Mechanized Weed Management

Mechanized weed management attempts to increase the farm power availability to perform the different weed control operations. It is our experience that mechanized weed management greatly enhances the quality of weed control work, timeliness of operation, operator productivity and comfort.

The level of agriculture mechanization in India is about 40 to 47%, with an average farm power availability of 3.045 kW/ha during 2021-22 (Mehta et al., 2023). This mechanization level is lower compared to other countries such as the USA (95%), Western Europe (95%), Soviet Union (80%), Argentina (75%), Brazil (75%) and China (59.5%) (Vemireddy and Choudhary, 2023).

The mechanization level of weeding operations, interculture and plant protection operations is just about 30 to 32% during 2020-21, which is less than the overall agricultural mechanization in India.

The adoption of various types of weeders, discussed herein and the mechanization of weeding operations are greatly influenced by factors including the crops grown, soil conditions, the agro-ecological zone and the cropping season.

Thus, a huge variation in mechanization levels for weed management practices for different crops has been observed (Figure 2). The wheat crop had the highest mechanization of 50%, and oil seeds and millet crops had the lowest mechanization of around 20% for weed control operations (Mehta et al., 2023).

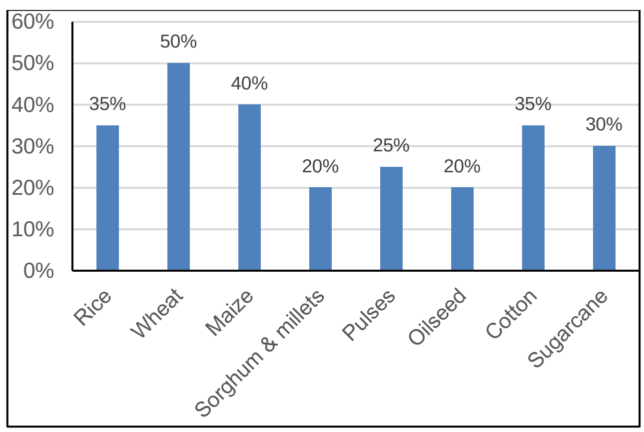

Figure 2. Mechanization level for weed management in major crops

Agricultural mechanization has been identified as a critically important area crucial for India's agricultural development to achieve the second green revolution.

In India, the level of mechanization in weed management could be increased by the following:

- Introducing improvised, highly efficient animal-drawn and small engine-operated power weeders for small holdings.
- Developing multi-task, operator-friendly, refined power weeders suitable for small-to-medium holdings.

- Improving accessibility to tractor-drawn-implements, power tillers and small tractors for medium-sized holdings.
- Improving access to high-power tractors and machines, sensor-based weeders and advanced machines like GPS-guided vehicles for large holdings.

Recognizing the importance and need for agricultural mechanization, the Government of India initiated a scheme called “Sub Mission on Agricultural Mechanization (SMAM) under the National Mission on Agricultural Extension and Technology (NMAET) during 2014-15. The main objective of this scheme is to provide a “single window” for all the activities related to agricultural mechanization for accelerated agricultural growth (PIB, 2023).

Under the scheme, various activities, such as establishing a Farm Machinery Bank (FMB), High-tech Hubs, Custom Hiring Centres (CHC) and the distribution of agricultural machines, have been conducted. In addition, the scheme provides financial assistance to farmers, rural youths, FPOs, Village Panchayats, Cooperative societies and farmer-registered societies.

The main aim is to increase the mechanization level in small and marginal land holdings and reach areas where the mechanization level is lower. These activities have resulted in expanding the cropped area, increasing the cropping intensity and production and increasing the average farm power availability from 2.02 kW/ha in 2016-17 to 3.045 kW/ha in 2021-22 (Vemireddy and Choudhary, 2023; Mehta et al., 2023).

Conclusion

Indian agriculture is mainly defined by small and marginal farmers. Mechanical weed management in Indian agriculture is limited by the fragmentation of land, smaller land holdings, farmers’ economic conditions, their education level, awareness about advanced technologies, seasonal variations and cropping patterns.

Nevertheless, mechanical weed management is a critically important tool that has a tremendous scope for improvisation within the existing technologies. A low-cost, ergo-refined, operator-friendly weeding tool that is best suited to small and marginal farmers can be developed. It is expected that most farmers will be able to afford to purchase or hire such a tool.

There is also tremendous scope for improving the average farm power availability to 4.0 kW/ha by the end of 2030. The activities under the “Sub Mission on Agricultural Mechanization (SMAM)” scheme enhanced the mechanization level at the small and marginal farmers' level and are the best possible solution to increase India’s mechanization level for weed management.

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Appendix 1

Table 3 The popular mechanical weeders used in India

Khurpi: Mode of use: A sharp, straight tool operated in sitting and squatting positions. Used for: Inter and intra-row weeding. Suitable crops: all types of crops cultivated in dryland. Field capacity: 0.0016 - 0.002 ha/h Approximate cost: INR 150 – 500 **https://www.indiamart.com**	
Straight Blade Hoe: Mode of Use: it is a long-handled hand tool operated in a standing position by pulling action. Used for: Inter and intra-row weeding. Suitable crops: all types of crops cultivated in dryland. Field capacity: 0.002 - 0.003 ha/h Approximate cost: INR 300 - 400 **https://www.walmart.com/ip/1-2-Inch-Shank-Cotton-Hoe-W-60-Inch-Handle/261045508**	
Grubber weeder: Mode of Use: it is a hand tool operated in sitting and squatting positions by pulling action. Used for: Inter and intra-row weeding. Suitable crops: all types of crops cultivated in both wetland and dryland. Field capacity: 0.002 - 0.02 ha/h Approximate cost: INR 300 – 2000 **https://www.indiamart.com**	
Twin wheel hoe: Mode of Use: it is a push-pull type weeder operated in a standing position. Used for: Inter row weeding. Suitable crops: all types of crops cultivated in dryland. Field capacity: 0.015 – 0.019 ha/h Approximate cost: INR 1500 – 3000 **https://www.desertcart.in/products/39567254-hoss-double-wheel-hoe**	
Cycle wheel hoe: Mode of Use: it is a push-pull type weeder operated in a standing position. Used for: Inter row weeding. Suitable crops: all types of crops cultivated in dryland. Field capacity: 0.017 – 0.019 ha/h Approximate cost: ₹ 1500 – 2500 **https://www.amazon.in/Attachments-Loosening-Digging-Weeding-Agriculture/dp/B0BM6F4KY5**	

Peg type hoe: Mode of Use: it is a push-pull type weeder operated in a standing position. Used for: Inter row weeding. Suitable crops: all types of crops cultivated in dryland. Field capacity: 0.005 – 0.006 ha/h Approximate cost: ₹ 800 – 1200 **https://www.farmech.dac.gov.in**	
CRIJAF Nail weeder: Mode of Use: it is a push-pull type weeder operated in a standing position. Used for: Inter row weeding. Suitable crops: Jute and other crops in sandy and sandy loam soil. Field capacity: 0.013 - 0.015 ha/h Approximate cost: ₹ 1500 – 2000 **https://www.moglix.com/unison-uei-1174-dry-land-weeder/mp/msnpkep4dr6q9g**	
Brush cutter (Weed cutter): Mode of Use: It is a non-soil-engaging type of weeding tool that cuts weeds above the ground by rotating fibre wire or cutting blades at higher speeds parallel to the ground. The weeding operation is performed in a standing position. Used for: Inter and intra-row weeding. Suitable crops: all types of crops irrespective of soil type. Field capacity: 0.2 - 0.3 ha/h Approximate cost: ₹ 15,000 - 25,000 **https://www.machinemart.co.uk/p/einhell-gc-bc-36-4-s-377-cc-petrol-brush-cutte/**	
Cono weeder: Mode of Use: it is a push-pull type weeder operated in a standing position. Used for: Inter row weeding. Suitable crops: Transplanted rice and SRI method. Field capacity: 0.012 – 0.015 ha/h Approximate cost: INR 1800 – 2000 **https://www.indiamart.com**	
Mandava Weeder: Mode of Use: it is a push-pull type weeder operated in a standing position. Used for: Inter row weeding. Suitable crops: Transplanted rice and SRI method. Field capacity: 0.012 – 0.015 ha/h Approximate cost: INR 500 - 1200	 (Source: WASSAN, 2006)

Three-row Raichur weeder: Mode of Use: it is a push-pull type weeder operated in a standing position. Used for: Inter row weeding. Suitable crops: Transplanted rice and SRI method. Field capacity: 0.036 – 0.06 ha/h Approximate cost: INR 1000 - 3000	 (Source: : WASSAN, 2006)
Finger weeder: Mode of Use: it is a push-pull type weeder operated in a standing position. Used for: Inter row weeding. Suitable crops: Transplanted rice and SRI method. Field capacity: 0.012 – 0.016 ha/h Approximate cost: INR 1000 – 1200 **https://ksnmdrip.com/products/drum-seeder/finger-weeder-wetland-weeder**	
Japanese weeder: Mode of Use: it is a push-pull type weeder operated in a standing position. Used for: Inter row weeding. Suitable crops: Transplanted rice and SRI method. Field capacity: 0.03 – 0.05 ha/h Approximate cost: INR 1500 – 3000 **https://www.indiamart.com**	
Animal-drawn hoes: Mode of Use: The hoe or sweeps are attached to the mainframe and pulled by a pair of animals. The number of rows varies from single row to multiple rows. Used for: Inter row weeding. Suitable crops: crops cultivated in dryland. Field capacity: 0.15 – 0.35 ha/h Approximate cost: INR 3000 – 6000 **https://www. economictimes.indiatimes.com**	

Brush cutter- rotary weeder: Mode of Use: It is a soil-engaging weeding tool. A separate rotary tiller is attached to the brush cutter in place of the fibre wire/cutting blade. The rotary tiller tills the soil and cuts weeds. The weeding operation is performed in a standing position. Used for: Inter and intra-row weeding. Suitable crops: all types of crops irrespective of soil type. Field capacity: 0.1 - 0.2 ha/h Approximate cost: INR 15,000 - 30,000/- **https://transvilleagrong.com/shop/agricultural-equipments/agro-handheld-power-weeder/**	 
Lowland paddy power weeder: Mode of Use: It is a soil-engaging weeding tool. A rotary tiller attachment is made to cut the soil and weeds. The weeding operation is performed in a standing position. Used for: Inter-row weeding. Suitable crops: crops cultivated in wetland conditions (transplanted rice and direct seeded rice). Field capacity: 0.1 - 0.2 ha/h Approximate cost: INR 15,000 - 30,000 **https://m.indiamart.com/proddetail/sharp-garuda-paddy-weeder-22668721997.html**	
Engine-operated rotary weeder: Mode of Use: It is a soil-engaging weeding tool. A rotary tiller attachment is made to cut the soil and weeds. The weeding operation is performed in a standing position. Used for: Inter-row weeding. Suitable crops: crops cultivated in both wetland and dryland. Field capacity: 0.1 - 0.4 ha/h Approximate cost: INR 20,000 - 50,000 **https://www.amazon.in**	
Self-propelled rotary weeder: Mode of Use: Weeding elements are a self-propelled type and are operated by an engine. A rotary tiller attachment is made to cut the soil and weeds. The weeding operation is performed in a standing position. Used for: Inter-row weeding. Suitable crops: crops cultivated in dryland. Field capacity: 0.18 - 0.45 ha/h Approximate cost: INR 50,000 - 75,000 **https://www.indiamart.com**	

Power cultivator: Mode of Use: Weeding elements are a self-propelled type and are operated by an engine. Sweep blades are attached to the mainframe to cut and uproot the weeds. The weeding operation is performed in a standing position. Used for: Inter-row weeding. Suitable crops: crops cultivated in dryland. Field capacity: 0.20 - 0.50 ha/h Approximate cost: INR 30,000 – 2,50,000 **https://www.indiamart.com**	
Tractor-operated sweeps/ earthing-up bund former: Mode of Use: the weeding unit (duck foot sweeps/ earthing-up unit, etc.) is mounted on a three-point linkage of the tractor and operated by tractor drawbar power. Used for: Inter-row weeding. Suitable crops: crops cultivated in dryland, especially suited to crops like potato (*Solanum tuberosum* L.), sugarcane (*Saccharum officinarum* L.), pigeon pea [*Cajanus cajan* (L.) Millsp.], maize, soybean, etc. Field capacity: 0.25 - 0.50 ha/h Approximate cost: INR 30,000 - 80,000 https://www.indiamart.com	
Tractor-operated inter-row rotary weeder: Mode of Use: the rotary weeding unit is mounted on a three-point linkage and operated by tractor P.T.O. Used for: Inter-row weeding. Suitable crops: crops cultivated in dryland, especially suited to crops sown in larger row spacing. Field capacity: 0.25 - 0.6 ha/h Approximate cost: INR 50,000 - 1, 00,000	 (Source: Singh, 2022)
Tractor-operated inter-row cultivator: Mode of Use: the cultivator unit is mounted on a three-point linkage and operated by tractor drawbar power. Used for: Inter-row weeding. Suitable crops: crops cultivated in dryland, especially suited to crops sown in larger row spacing. Field capacity: 0.25 - 0.6 ha/h Approximate cost: INR 30,000 - 70,000 **https://www.youtube.com/watch?app=desktop&v=TGEa3sC6SZ8** (Cotton Inter-cultivation)	
Riding type weeders: Mode of Use: it is a developed version of walk-behind type weeders. A weeding element is attached to the rare side of a base frame, and sitting arrangements are made for the operator. Used for: Inter-row weeding. Suitable crops: crops cultivated in dryland. Field capacity: 0.15-0.20 ha/h Approximate cost: INR 40,000 - 60,000 **https://www.amazon.in**	

Appendix 2

Table 3 Recommended Mechanical Weed Management Practices for Major Crops in India

Weed management practice	Reference
Rice	
Dry-Direct Seeded Rice (D-DSR)	
– One mechanical weeding (MW) by finger weeder at 15-20 days after sowing (DAS) followed by (fb) one round of hand weeding (HW) in rainfed uplands and lowlands	Saha and Patra, 2013
– Two MW by finger weeder at 15 and 30 DAS fb one HW at higher weed infestation conditions in rainfed uplands and lowlands	
– MW thrice at 20, 40 and 60 DAS	Saravanane, 2020
– Cono-weeder twice at 20 and 40 DAS/ days after transplanting (DAT)	Dubey et al., 2017
– One hoeing at 12 DAS fb one HW at 30 DAS	Nagargade et al., 2024
Wet-Direct Seeded Rice (W-DSR)	
– One MW by finger weeder at 15-20 DAS in moist saturated soil fb one HW in rainfed shallow lowlands and irrigated condition	Saha and Patra, 2013
– Cono-weeder twice at 20 and 40 DAS/DAT	Dubey et al., 2017
Transplanted rice (TPR)	
– MW by cono weeder at 22-30 DAS in rainfed shallow lowlands and irrigated condition	Saha and Patra, 2013
– Cono-weeder twice at 20 and 40 DAS/DAT	Dubey et al., 2017
– MW starts from 10 – 12 days after transplanting to till crop permits operation at every 10 days interval	WASSAN, 2006
System of Rice Intensification (SRI)	
– Cono-weeder twice at 20 and 40 DAS/DAT	Dubey et al., 2017
– One hoeing at 12 DAS fb one MW at 30 DAS	Nagargade et al., 2024
– MW starts from 10 – 12 days after transplanting to till crop permits operation at every 10 days interval	WASSAN, 2006
Soybean	
– One hoeing at 15 DAS and HW at 30 DAS	Jadhav and Kashid, 2019
– One hoeing at 20 DAS along with HW twice at 30 and 60 DAS	Shete et al., 2008; Dhaker et al., 2015
– HW at 20 and 30 DAS and hand hoeing at 20 and 30 DAS	Chaudhari et al., 2016
– Inter-cultivation at 20 and 40 DAS	Patel et al., 2015
Maize (Sweet corn)	
– Two manual hoeing at 15 and 30 DAS	ICAR-IIMR, 2024
– Two MW by wheel hoe/ hand grubber at 20 DAS and 40 DAS	Mishra, 2022
– One hoeing	Sharma et al., 2000
– Hoeing at 20 DAS fb by 2 HW at 20 DAS and 40 DAS	Pathak et al., 2015
– Soybean intercropping + 1 MW (20 DAS)	Saini et al., 2013
– Two MW 20 and 40 DAS + mash intercropping	
Wheat	
– One MW by twin wheel hoe/ hoe/grubber/khurpi/sweep type cultivator/ other weeders at 35 – 40 DAS	Mishra, 2021
Chickpea (*Cicer arietinum* L.)	
– One to two MW by twin wheel hoe/ hoe/grubber/khurpi/sweep type cultivator/ other weeders at 35 – 40 DAS, depending on the weed intensity	Mishra, 2021

– One hand hoeing 30 DAS	Sahu et al., 2023
– Application of pendimethalin 1.0 kg/ha as pre-emergence (PE) + hand hoeing at 30 DAS	Singh and Jain, 2017
Pigeon pea	
– Two mechanical weed management at 25-30 DAS and at 45-50 DAS	Yaduraju and Mishra, 2005
– Two hoeing at 40 and 70 DAS	Kumar et al., 2019
Green gram	
Hand hoeing at 25 DAS and 40-45 DAS by wheel hoe	Ahmad and Rana, 2016
Application of pendimethalin at 1.0 kg ha-1 as PE *fb* rotary weeding at 15-20 DAS	Muthuram et al., 2017
Black gram (*Vigna mungo* L.)	
– Interculture at 15 DAS *fb* quizalofop-ethyl 50 g/ha 30 DAS	Balyan et al., 2016
– Horse gram	
– Hand hoeing at 25 DAS and 40-45 DAS by wheel hoe	Ahmad and Rana, 2016
– Rice bean	
– Hand hoeing at 25-30 AS and at 40-45 DAS by wheel hoe	Ahmad and Rana, 2016
French bean (*Phaseolus vulgaris* L.)	
Two hoeing	Ahmad and Rana, 2016
Cowpea (*Vigna unguiculata* L.)	
– Application of pendimethalin 0.75 kg/ha as PE *fb* one hoeing at 20-25 DAS	Hanumanthappa et al., 2012
Ground nut	
– Application of pendimethalin @ 2.5 to 3 l/ha or Oxyflourfen @ 1.5 to 2.0 l/ha *fb* one inter-cultivation	ICAR-DGR, 2024
– Inter-cultivation and HW at 15, 30 and 40 DAS	
– Hoeing at 10-15 DAS and at 35-40 DAS (for earthing up)	
Mustard	
– MW at 25 DAS + HW at 50 DAS	Ghasal et al., 2022
– Application of pendimethalin 1.0 kg ha-1 as PE + quizalofop-p-ethyl 0.04 kg ha-1 as PoE + HW and inter-cultivation at 40 DAS	Jangir et al., 2018
– Application of pendimethalin 1 kg/ha *fb* hand hoeing at 35 DAS	Singh and Kumar, 2020
– Application of pendimethalin 30% + imazethapyr 2% EC 1 kg/ha as PE *fb* MW at 30 DAS	Sanketh et al., 2021
Finger millet [*Eleusine coracana* (L.) Gaertn]	
Drill-seeded finger millet cultivation	
– Hoeing twice by wheel hoe between rows + intra-row manual weeding *fb* HW twice at 20 and 40 DAS	Kujur et al., 2018
– Inter-cultivation twice at 20 and 40 DAS *fb* HW once at 35 DAS	Ramamoorthy et al., 2002
– Inter-cultivation once *fb* HW twice at 30 and 45 DAS	Ramamoorthy et al., 2010
– MW at 20 and 40 DAS	Dubey and Mishra, 2023
– Inter-cultivation at 25 DAS + one HW at 45 DAS	
– MW at 20 DAS	
Transplanted finger millet cultivation	
– Hoeing twice at 20 and 35 DAP *fb* HW once at 45 days after planting (DAP)	Patil et al., 2014a
– Hoeing (wheel) thrice at 20, 30 and 40 DAP *fb* HW once at 45 DAP	Patil and Reddy, 2014
– Stale seedbed technique *fb* inter-cultivation twice at 20 and 35 DAP; passing wheel hoe at 20, 30 and 40 DAP + one HW at 45 DAP	Patil et al., 2013

– Stale seedbed technique in combination with inter-cultivation twice at 20 and 35 DAP or passing wheel hoe at 20, 30 and 40 DAP with one hand weeding for weed management	Patil et al*.,* 2014b
– Stale seedbed with inter-cultivation twice at 20 and 35 DAP	Patil et al., 2014b
Pearl millet	
– Deep summer ploughing to control all weeds	Dubey and Mishra, 2023
– Deep summer ploughing *fb* post-emergence application of tembotrione 100 g/ha at 15-20 DAS to control Cyperus rotundus	
– Two MW	
– Inter-culturing *fb* HW at 20 and 40 DAS	Das et al., 2013
– Hand weeding + inter-culturing at 35DAS	Munde et al., 2012
– Two HW/hoeing at 15 and 30 DAS	Chaudhary et al., 2022
Little millet (*Panicum sumatrense* L.)	
– Inter-cultivation twice at 20 and 40 DAS	Dubey and Mishra, 2023
– Two to three inter-cultivations *fb* one hand weeding. The first inter-cultivation should be before 20 DAS and the second before 35 DAS	
Foxtail millet (*Setaria italic* L.)	
– Stale seedbed technique + inter-cultivation twice at 25 and 45 DAS	Dubey and Mishra, 2023
– Inter-cultivation at 25 DAS + 1 hand weeding at 45 DAS	
Potato	
– Hoeing at 20 DAP + hand weeding at 40 DAP	Gupta et al., 2019
– Hand hoeing at 20 and 40 DAP	Bhullar et al., 2015
– Two earthing-up operations at 25 DAP and 55 DAP	Chethan et al., 2022; Chethan et al., 2019
Onion (*Allium cepa* L.)	
– Three MW by duct hoe at 20, 40 and 60 days after transplanting (DAT)	Hembrom et al., 2023; Barla and Upasani, 2019
Sugarcane (*Saccharum officinarum* L.)	
– Three hoeing at 1st, 4th & 7th week after ratoon initiation	Kumar et al., 2014
– Application of metribuzin 1 kg/ha as PE *fb* 1 hoeing at 45 days after ratoon initiation	
– Three hoeing at 30, 60 and 90 days after harvesting (DAH) of the main crop	Krishnaprabu, 2020
– Application of pendimethalin 2.0 kg/ha + Sesbania (brown manuring) + hand hoeing at 90 DAP	Fanish and Ragavan, 2020
– Application of metribuzin at 0.88 kg/ha at 3 DAH *fb* hoeing at 45 DAH *fb* 2,4-D at 1.0 kg/ha at 90 DAH of main crop	Waghmare et al., 2018
– Application of atrazine at 1.0 kg a.i/ha after 2-3 DAP + 2,4-D sodium salt at 1.0 kg a.i/ha at 60 DAP + manual hoeing at 90 DAP	ICAR-IISR, 2024
Cotton (*Gossypium hirsutum* L.)	
– Application of pendimethalin 1.0 kg/ha PE *fb* pyrithiobac sodium 62.5 g/ha PoE at 25 DAS *fb* one hoeing at 45 DAS	Veeraputhiran, 2023
– MW by power tiller at 25 and 45 DAS	
– Application of pendimethalin 1.0 kg/ha PE *fb* weeding by power tiller at 25 and 45 DAS	
– Application of pendimethalin 1 kg/ha *fb* weeding by power weeder	Nalini and Chinnusamy, 2019
– Two MW by power weeder at 25 and 45 DAS	