

Chapter 2

Biology and Management of Weeds in India



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Abstract Agriculture serves as the backbone of India's economy, playing a pivotal role in ensuring food security, providing employment, and contributing to overall economic development. The largest Indian population is engaged in agricultural activities growing a wide range of cereals, pulses, oilseeds, fruits, vegetables, and non-food crops. In this chapter, six crops, namely rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), pulses, cotton (*Gossypium* spp.) and sugarcane (*Saccharum officinarum* L.), are included for their weed management aspect. Weed infestation poses a significant threat to crop production, leading to substantial yield losses and economic challenges for farmers. By delving into weed biology and management techniques, farmers may be empowered with the knowledge and tools necessary to mitigate weed-related risks, optimize crop productivity, and promote sustainable agricultural practices. Traditionally, manual weeding and intercultural operations have been used to manage weeds, but changing rainfall pat-

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terns, rising labor costs, and increasing agricultural expenses have made weed management more difficult. Though herbicides are the easiest, cheapest, and timely weed management approach, it is helpful and effective only for a short period. Majority of the research in India is based on herbicides, and very limited studies on weed biology and IWM are carried out on problematic weeds. The shift toward integrated weed management (IWM) highlights the growing need for more sustainable and effective weed control methods in crop production. Therefore, IWM research must focus on weed biology and ecology, combination of mechanical, cultural, and chemical methods, and potential benefits of weeds. New cutting-edge futuristic technologies such as machine learning, drones, and robotics may aid in the development of innovative and environmentally friendly weed management approaches.

Keywords Cotton · Corn · Pulses · Rice · Sugarcane · Integrated weed management · Wheat

2.1 Introduction

Agriculture, with its allied sectors, is unquestionably the largest livelihood provider in India, and remains vital to India's socioeconomic fabric, more so in the vast rural areas. India has diverse agroclimatic zones ranging from temperate to tropical and humid to arid regions (Anonymous 2025a). It is the seventh largest country by area and has only 2.4% of global land. Further, it is the most populous country in the world with over 1.42 billion population that is 17.76% (one sixth) of total world population. About 18% of Indian farmers own 1–2 ha of land, while over 67% own less than 1 ha. With an average land holding of less than 1.1 ha, small and marginal farmers made up approximately 86% of the population (Kareemulla et al. 2021). Moreover, there are different soil types, climatic conditions, and traditional cultivation methods in the nation's agricultural landscape, which produces crops that support livelihood of millions of people.

Major crops grown in India are rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L. emend. Fiori and Paol.), corn (*Zea mays* L.), cotton (*Gossypium* spp.), sugarcane (*Saccharum officinarum* L.), tea (*Camellia sinensis* (L.) Kuntze), coffee (*Coffea arabica* L.), jute (*Corchorus capsularis* L.), pulses, oilseeds, and millets. Among cereal crops, rice, wheat, and corn are the first three important food crops (Anonymous 2025a). Pulses and corn seeds are very important dietary sources for humans and animals in the world. Particularly, pulses are consumed as the world's second-most food, which is an important source of proteins, whereas, corn is mostly consumed as an animal dietary system and is an important source of carbohydrates and proteins. The rice-wheat cropping system is the most dominant and profitable system in the Indo-Gangetic Plain region of north-west India. Corn-wheat is the third most important cropping system in India after rice-wheat and rice-rice that contributes about 3% in the national food basket.

In 2030, the population is expected to increase to 1.5 billion people, and around 345 million tons of food grains will be required to feed (NITI Aayog 2018). It would be an arduous task to produce food in the current agricultural scenario of shrinking agricultural land due to alternate land use, increasing threats of climate change, water scarcity, rapid urbanization, etc. to feed the burgeoning population (Kaur and Chauhan 2023). In India, per capita agricultural land is shrinking due to continued fragmentation (population pressure and inheritance laws), urbanization, and alternate land use. Targeting the yield gaps caused by weed competition is one approach to achieve this target.

Globally, in crop production, weeds cause great yield losses and are considered a major biotic stress in crop production. In economic terms, approximately 1800 weed species not only caused a 31.5% reduction in crop production but also amounted to \$USD 32 billion per year in economic losses (Kubiak et al. 2022). Weeds compete with crops for light, water, and nutrients and can drastically reduce crop yields and quality. In a recent study, a total economic loss of about USD 11 billion was estimated due to weeds in 10 major field crops from 18 states in India (Gharde et al. 2018). Estimates of actual economic losses were the highest in the case of rice (worth \$USD 4420 million), followed by wheat (worth \$USD 3376 million) and soybean (*Glycine max* (L.) Merr.) (worth \$USD 1559 million), respectively. Yaduraju (2012) also estimated the economic losses as approximately USD 13 billion when losses due to weeds were taken as 10%, which would amount to a loss of about 25 mt of total food grains in India. The density and duration of weed species are critical factors that define the intensity of crop-weed competition and the resultant losses in crop yield.

Weed flora in cropped fields is highly diverse, encompassing grasses, sedges, and broadleaved weeds. Weed species and its floristic composition present in any agricultural field reflect the history of crop production and/or protection activities in the field (Hofmeijer et al. 2021). Weed floristic composition in a particular crop is a function of agronomic practices such as cropping rotation, tillage systems, residue management, fertilization, crop density, geometry, water management, and herbicide use history, along with environmental and edaphic conditions. For example, rice was not the major crop of northwestern India before the green revolution, and perennial weeds like *Cynodon dactylon* (L.) Pers., *Sorghum halepense* (L.) Pers., *Cyperus rotundus* L., *Convolvulus arvensis* L. and *Cirsium arvense* (L.) Scop. were predominant during the summer season under such situations (Kaur et al. 2022). Change in tillage practices (puddling) for rice cultivation has resulted in a major shift in weed flora from aerobic summer-annual weeds to water-loving, semi-aquatic, and aquatic weeds viz.; *Echinochloa crus-galli* (L.) P. Beauv., *Paspalum distichum* L., *Cyperus iria* L., *Ischaemum rugosum* Salisb., *Cyperus difformis* L., *Fimbristylis miliacea* (L.) Vahl, *Leptochloa chinensis* (L.) Nees, *Ammannia bac-cifera* L., *Caesulia axillaris* Roxb., *Sphenoclea zeylanica* Gaertn., *Sagittaria guayanaensis* Kunth., *Scirpus juncooides* Roxb., *Eleocharis acicularis* (L.) Roem & Schult., *Najas arguta* Kunth., *Hydrilla verticillata* (L. f.) Royle, and *Ipomoea aquatica* Forssk. Further due to canal irrigation system, typical weeds of hilly areas like

Ageratum conyzoides L. invaded the rice fields, watercourses, and bunds of the fields in the state.

2.2 Biology of Problematic Weeds

Phalaris minor Retz. is a self-pollinated, winter annual grass and is a satellite weed of wheat crops. It reproduces mainly through seeds, and at maturity, seed dispersal takes place after caryopses shatter from their glumes (Matus-Cádiz and Hucl 2002). During winter months, its emergence starts in November, and multiple cohorts emerge with subsequent irrigation given throughout the cropping season depending upon the available space (Singh 2007). During the initial 60 days, its dry biomass accumulates at slower speed, and it is faster between 60 and 90 days after sowing (DAS) (Malik and Singh 1995). Plant invests 27% of aboveground biomass in seed production, irrespective of plant size (Franke et al. 2007). The aboveground biomass failed to influence the thousand seed weight, and even small plants also produced seeds of equal individual seed weights; but, the numbers of seeds were reduced. The thousand seed weight of *P. minor* varies from 1.5 to 2.1 g (Bhan and Choudary 1976). Singh et al. (2025) observed that seed production per panicle was 309.1 ± 7.5 , and almost 74% of seeds were retained on the panicle at the harvest, thus indicating the potential for use of harvest weed seed control tactics.

Avena spp. is one of the troublesome winter annual grass weeds of temperate agricultural landscapes and is a naturalized species in the Indian subcontinent (Holm et al. 1979). It is an annual grass with fibrous roots that reaches up to 150 cm high with profuse tillering (Tidemann et al. 2021). Like *P. minor*, the initial morphology similarities of this weed to wheat plant make it difficult to control with mechanical methods. Further, its seeds exhibit multiple dormancy mechanisms in the soil after shedding, which help in the enriched weed seed bank for several years (Holm et al. 2000). Singh et al. (2025) observed that the total number of seeds per panicle ranged from 52 to 61, and most of seeds were shed (only 10%–11% retention) by the time of wheat harvest.

Echinochloa colona (L.) Link, a C_4 plant native to tropical and subtropical Asia, now spreads across warm regions of Asia, Africa, and Australia, growing as a prostrate to erect, shallow-rooted annual or occasionally perennial plant up to 100 cm tall (Rao 2021). However, *E. crus-galli* is robust, tufted annual grass with an erect to decumbent 150 cm tall stem that is often branched at the base. *E. colona* can germinate throughout the growing season in several upland summer crops, but it is a less vigorous competitor than *E. crus-galli* (Zhang and Watson 1997). Many of the growth characteristics of *E. crus-galli* are like those of rice, making it a strong competitor to rice in fields across the world (Rao et al. 2007).

Digitaria sanguinalis (L.) Scop., features sparse tufts and weak, spreading stems, reaching up to 100 cm in length, with soft, flat leaf blades and spikelets occurring in pairs. *Digitaria* spp. are summer annuals; however, they can begin to exhibit growth of a perennial species due to extended durations of favorable growing conditions

(Jones et al. 2021). This is a C_4 plant, and vegetative growth is invariably dictated by light and temperature (Shetty et al. 1982). *Digitaria* spp. are determinate plants, monoecious, and mainly self-pollinated and can produce up to 150,000 seeds per plant.

Commelina benghalensis L., a perennial, succulent, and sprawling herb found in tropical Asia and Africa, produces aerial and underground flowers (Walker and Evenson 1985). It can form new roots when leaf nodes encounter soil. Moreover, rhizomes and underground flowers start developing 6 weeks after emergence, before the development of aerial flowers. This weed represents floral dimorphism and seed polymorphism (Maheshwari and Singh 1934).

Trianthema portulacastrum L. is an annual broadleaf weed belonging to the Aizoaceae family and is a widely distributed weed in summer and rainy season fields and horticultural crops in India. It is a strong competitor, reducing significant losses in corn and soybean yield (Kaur and Aggarwal 2017). It has high acclimatization capacity and produced more growth under elevated temperatures up to 4 °C (Mandal et al. 2017). The invasion hotspots for *T. portulacastrum* will be shifted towards the south and east of the country, including a few western parts like Gujarat, in future climatic scenarios (Singh et al. 2024a).

Parthenium hysterophorus L., considered one of the most aggressive invasive and problematic weeds, germinates in spring, produces flowers and seeds throughout its life cycle, and dies in late autumn, with optimal seed germination observed at 21/16 °C (day/night). The ability of *P. hysterophorus* to perpetuate in diverse climatic regimes, soil types, and disturbed environments enhances its potential to occupy a wide array of habitat ranges (Annapurna and Singh 2003). The phytotoxic ability of the weed has been proved against many agricultural crops. It exhibits diverse characteristics and adaptations, posing significant challenges to agriculture and biodiversity conservation efforts worldwide (Kaur et al. 2021). Ahmad et al. (2019) mapped current and potential distribution of *P. hysterophorus* in India and observed a significant shift in niche in response to climate changes.

Cyperus rotundus, native to India, is widely naturalized across Africa, America, South Asia, and southern/central Europe, significantly impacting subtropical and tropical agroecosystems in both hemispheres. This erect, glabrous, grass-like perennial sedge can reach heights of 7–40 cm, with prolific production of rhizomes and tubers. It germinates in warm seasons, has prolific rhizome and tuber production, and flowering is favored by favorable conditions. *C. rotundus*, a perennial weed, has been stated to be 60%–80% of total weed flora in sugarcane, causing more than 40% yield reduction (Chand et al. 2014; Giraldeli et al. 2021). It is a rapidly spreading perennial C_4 sedge reproducing extensively through underground tubers and rhizomes and rarely by seeds. More than 80% of tubers of *C. rotundus* occur in the upper 15 cm of soil. Rhizome penetration of *C. rotundus* will be more in light textured soils than heavy-textured soils. Under ideal soil conditions, a single tuber can produce more than 100 tubers within 90 days. This sedge can propagate best under high soil moisture, high fertility, and high temperature, making it a serious weed of sugarcane (Stoller and Sweet 1987).

Cynodon dactylon is a warm-season perennial known for its rapid spread via rhizomes and stolons, forming dense turf resilient to foot traffic and environmental challenges. Thriving in diverse soils, it favors heavy clay and alkaline conditions but tolerates varying pH levels. Its growth peaks in spring and summer, persisting year-round due to its ability to regenerate vegetatively. Its robust growth and adaptability allow it to outcompete crops for nutrients, water, and light, severely affecting agricultural productivity. While primarily spreading vegetatively, it also reproduces through seeds, germinating in warm, moist conditions. This weed thrives in fertile, moisture-retentive deep black cotton soils (vertisols, found in central India), where it establishes extensive underground rhizomes and stolons, making mechanical or manual control methods largely ineffective. It is a persistent and aggressive perennial grass weed, and a comprehensive approach involving integrated weed management strategies is required to achieve effective long-term control (Satao et al. 1995). Its robust growth and adaptability allow it to outcompete crops for nutrients, water, and light, severely affecting agricultural productivity. The infestation of *C. dactylon* in sugarcane reduces the cane yield as well as the number of subsequent ratoons (Dalley et al. 2013). *Cynodon dactylon* is a troublesome perennial stoloniferous and rhizomatous creeping C₄ grass with long runners. It is a serious weed of sugarcane throughout Asia due to its wide ecological tolerance and effective vegetative propagation through rhizomes and stolon fragments in addition to seed production (Ramakrishnan and Kumar 1971). It responds positively to high light intensities, and it is adversely affected by shading. Hence, competition of *C. dactylon* is more severe in the initial growing stages of sugarcane than in later stages with dense canopy (Horowitz 1972).

Rottboellia cochinchinensis (Lour.) Clayton is a noxious grass weed infesting sugarcane both in tropics and subtropics causing yield losses of 50%–70% in sugarcane (Millholon 1992). This weed is also a major problem in corn crop fields. It is a fast-growing annual or perennial C₄ grass reaching up to 4 m in height, and a single plant can produce 100 tillers with over 15,000 seeds (Correia 2016). These seeds germinate throughout the growing season, making it difficult to control. These seeds can remain dormant in the soil for up to 4 years. Manual removal of *R. cochinchinensis* from the infested field is very difficult due to the presence of rigid trichomes in leaf sheaths (Chauhan 2013).

Ipomoea spp. are the most bothersome broadleaved weeds in sugarcane cultivation in many countries, including India. Sugarcane crops can be badly damaged due to twining of this weed around sugarcane clumps, which can cause yield loss up to 25% (Singh et al. 2018). These weeds also interfere with harvesting operations. With the extension of sugarcane cultivation to rice fields, twining weeds, or creeper weeds, or binding weeds, have become a major problem. Management of creeper weeds poses serious problems, as they germinate after the earthing up, and it is difficult to use mechanical methods. Seeds of *Ipomoea* spp. buried under the soil during sugarcane planting exhibit very poor germination. These seeds will be scarified and brought to soil surface during earthing-up operations (Bhullar et al. 2012). Binding weeds like *Ipomoea* spp. germinate in sugarcane fields 120 days after cane planting and occupy the top plane of the cane, compete for sunlight, and also hinder cane harvesting (Kathiresan et al. 2004).

2.3 Weed Infestation in Major Crops

Rice For rice production, India ranks second in the world after China. India is the largest exporter of rice globally. Rice is the staple food crop in India and is grown over the largest area. It requires warm temperatures (above 25 °C) with high humidity and annual rainfall of above 100 cm. In rice, production agronomy affected the distribution of weed species comprising a population. Changes in tillage and crop establishment methods significantly affected the weed flora infestation level and its composition. The crop-weed competition is influenced by i. rice production systems (transplanting versus direct seeding); ii. relative heights of rice and weed; iii. Cropping density; iv. rice cultivar; and v. soil moisture and nutrient availability (Rao et al. 2007). Rice is mainly grown with the puddling and transplanting technique. In transplanted production systems, 25–30-day-old rice seedlings are transplanted (manually or mechanically) into puddled soil, and that plant height difference gives rice a significant head start on weeds. Furthermore, water in the ponded fields (paddies) itself acts as herbicide, leading to minimal competition in the initial crop growth phase. Crop-weed competition intensifies as growth progresses. The crop-weed competition is comparatively more in upland dry direct-seeded rice (DSR), as both crop and weeds emerge at the same time and compete for nutrients, light, and space with the rice seedlings. Weeds caused 10%–15%, 35%–45%, and 20%–25% reduction in yield in transplanted rice (TPR), DSR, and wet-seeded rice, respectively (Rao et al. 2007).

DSR is gaining popularity as a potential alternative to conventional transplanting with reduced input requirements, reduced methane and CO₂ emissions, increased adaptability to climate change, and increased economic returns. Weed infestation is the major setback in DSR, which is held accountable for the yield loss ranging from 15% to 20%, but in severe cases, it may exceed 50% or even cause complete crop failure (Jabran and Chauhan 2015). Further, dry-DSR rice has more diverse weed floristic composition than TPR. Aerobic weeds such as *Dactyloctenium aegyptium* (L.) Willd. and *C. rotundus* are common in unpuddled DSR but are not found in TPR due to hypoxic edaphic environment (ponded water) that inhibits weed germination. Some weeds, especially red/weedy rice, are a major limitation in dry-DSR > wet-DSR (Johnson Sunder Singh et al. 2024). Recently, there has been a shift toward herbicide-tolerant crops (for example, non-genetically modified basmati crops such as Pusa Basmati 1979 and Pusa Basmati 1985) for reducing area under TPR in favor of DSR. These herbicide-tolerant rice varieties, if cultivated following the stewardship guidelines, could provide an effective solution for weed management (weedy rice in particular) in DSR.

Wheat Wheat is the important staple food and the second cereal crop in terms of area and production after rice in India. Wheat is the most important cereal crop of temperate regions, and it requires a cool climate with moderate rainfall. Yield losses in wheat due to *Phalaris minor* Retz. alone may be up to 50%, and heavy infestations may lead to total crop failure (Malik and Singh 1995; Singh 2007). The crop

biomass was significantly reduced at 200 plants m^{-2} of *P. minor* (Bhan and Froud-Williams 2006). The biology of *P. minor* is already discussed in detail by Chaudhary et al. (2021). Narrowing the crop row width, increasing the crop density, and sowing competitive cultivars can also result in a dense canopy soon after emergence and may considerably reduce the quantity of light reaching the soil surface.

In the rice-wheat cropping system, production systems have changed significantly for wheat and rice. It was demonstrated that though seeds of *P. minor* get distributed in upper 10 cm soil depth during the intensive tillage and puddling performed during the preceding rice crop, there was 50% reduction in the emergence of the first cohort of *P. minor* in zero-till wheat compared to conventional-till sown wheat, irrespective of the texture of soil (Singh et al. 1999; Franke et al. 2007). Further, TPR-wheat cropping system has *P. minor* as predominant weed in wheat. However, DSR/cotton/corn-wheat cropping systems have *Avena* spp. along with *P. minor* (Kaur et al. 2022). Recently, adoption of zero/conservation tillage with or without residue mulching and dry-direct seeding (without puddling) in wheat and rice, respectively, has significantly modified the weed flora and management strategies. In conservation agriculture systems of rice-wheat, where residue of the previous crop is retained on the soil surface as mulch (e.g., Happy Seeder, Surface Seeder, and Smart Seeder-sown wheat), light exposure of *P. minor* seeds is prohibited, which leads to reduction in germination of *P. minor*. The presence of residue as mulch moderates soil temperature and moisture along with its effect on weed germination and emergence that ultimately enhances the crop vigor. Thus, sustainable weed control is achieved with Integrated Weed Management (IWM), combining conservation tillage practices with residue as mulch on the soil surface (Chauhan et al. 2012). Crop residues may help in weed control through allelopathic effects and/or by blocking light transmission. However, the amount of crop residue has a differential effect on weed germination, and a smaller residue load may not be sufficient for covering the soil surface in even and uniform way, and may rather trigger weed germination and pose challenges for weed management under zero tillage. The efficacy of pre-emergence herbicide in residue-retained fields may be lowered.

Corn Corn, being a C_4 plant, is one of the most vibrant food grain crops having wider adaptability under diverse soil and climatic conditions. In India, corn is the third most important cereal crop after rice and wheat, being used both as grain and fodder crop. Along with the main use of corn as food crop and animal feed, it is a major raw material for diverse industrial uses. Corn production steadily increased to 33.7 million tons during 2021–2022, with a targeted production of 35.5 million tons projected for 2023–2024.

Weeds pose a significant economic challenge to corn cultivation, jeopardizing crop quality by contaminating seeds and vying for essential resources such as light, water, and nutrients (Table 2.1). Studies by Mukhtar et al. (2007) have demonstrated that uncontrolled weed growth can lead to staggering yield reductions of 58%–62% in winter and 67%–79% in summer, accompanied by a substantial 65% decrease in plant height under similar weedy conditions. The first 20–60 days in the rainy

season and 30–45 DAS in winter corn are the most critical periods of weed competition for the crop. The presence of weeds reduces the corn yields by 27%–60%, depending upon the season, floristic composition, and weed growth.

Pulses There are eleven types of pulses as identified by the United Nations Food and Agriculture Organization, including *Phaseolus vulgaris* L. (common bean), *Vicia faba* L. (broad bean), *Pisum sativum* L. (field pea), *Cicer arietinum* L. (chickpea), *Vigna unguiculata* (L.) Walp. (cowpea), *Cajanus cajan* (L.) Millsp. (pigeon pea), *Lens culinaris* Medik. (lentil), *Vigna subterranea* (L.) Verdc. (Bambara bean), *Vicia sativa* L. (common vetch), and *Lupinus albus* L. (lupin). India is the largest producer (25% of global production), consumer (27% of world consumption), and importer (14%) of pulses in the world. Pulses production surged to a peak of 27.3 million tonnes in India during 2021–2022. India leads the charge as the world's top producer of pigeon pea. Chickpea, the world's third-most cultivated legume, holds a position of immense significance in the semi-arid tropics, as it exhibits remarkable resilience in harsh environmental conditions, including heat and drought.

Table 2.1 Distribution of corn-associated weeds in India

Predominant weeds	Distribution	References
<i>Echinochloa colona</i> , <i>Trianthema portulacastrum</i> , <i>Cyperus rotundus</i> , <i>Eleusine indica</i>	Banswara, Rajasthan	Porwal (2000)
<i>Echinochloa colona</i> , <i>Brachiaria ramosa</i> , <i>Digitaria sanguinalis</i> , <i>Dactyloctenium aegyptium</i> , <i>Eleusine indica</i> , <i>Setaria glauca</i> , <i>Sorghum halepense</i> , <i>Panicum</i> spp., <i>Ageratum conyzoides</i> , <i>Galinsoga parviflora</i> , <i>Commelina benghalensis</i> , <i>Lindernia ciliata</i> , <i>Polygonum hydropiper</i> , <i>Euphorbia geniculata</i> , <i>Oxalis latifolia</i> , <i>Cyperus rotundus</i>	Pantnagar, Uttaranchal	Pandey et al. (2001)
<i>Cynodon dactylon</i> , <i>Cyperus rotundus</i> , <i>Echinochloa crus-galli</i> , <i>Echinochloa colona</i> , <i>Agropyron repens</i> , <i>Parthenium hysterophorus</i> , <i>Digitaria sanguinalis</i> , <i>Eclipta alba</i> , <i>Euphorbia hirta</i> , <i>Commelina benghalensis</i>	Pantnagar	Sarma and Gautam (2006)
<i>Cyperus rotundus</i> , <i>Digera arvensis</i> , <i>Commelina benghalensis</i> , <i>Euphorbia hirta</i> , <i>Parthenium hysterophorus</i> , <i>Cleome viscosa</i>	Bihar	Jat et al. (2012)
<i>Commelina benghalensis</i> , <i>Ageratum conyzoides</i> , <i>Echinochloa colona</i> , <i>Panicum dichotomiflorum</i> , <i>Cyperus iria</i> , <i>Digitaria sanguinalis</i> , <i>Polygonum alatum</i> , <i>Aeschynomene indica</i>	Palampur, Himachal Pradesh	Kumar et al. (2012)
<i>Echinochloa colona</i> , <i>Digitaria sanguinalis</i> , <i>Cyperus rotundus</i> , <i>Commelina communis</i> , <i>Phyllanthus niruri</i> , <i>Eclipta alba</i>	Hyderabad	Sanodiya et al. (2013)
<i>Celosia argentea</i> , <i>Commelina benghalensis</i> , <i>Dactyloctenium aegyptium</i> , <i>Digera arvensis</i> , <i>Eleusine indica</i> , <i>Echinochloa colona</i> , <i>Corchorus trilocularis</i> , <i>Leptochloa chinensis</i> , <i>Rumex acetosella</i>	New Delhi	Singh et al. (2015a)
<i>Parthenium hysterophorus</i> , <i>Melilotus alba</i> , <i>Cyperus rotundus</i> , <i>Trianthema portulacastrum</i> , <i>Dactyloctenium aegyptium</i> , <i>Cynodon dactylon</i> , <i>Digera muricata</i> , <i>Amaranthus viridis</i> , <i>Commelina benghalensis</i> , <i>Eragrostis cilianensis</i> , <i>Chenopodium album</i> , <i>Trichodesma indicum</i> , <i>Digitaria sanguinalis</i> , <i>Euphorbia geniculata</i> , <i>Echinochloa colona</i>	Hyderabad	Ram et al. (2017)

Table 2.2 Weed flora associated with pulse crops

Season	Weed type	Common weed species
Winter	Broadleaved weeds	<i>Chenopodium album</i> , <i>Fumaria parviflora</i> , <i>lathyrus</i> spp., <i>Melilotus alba</i> , <i>Vicia sativa</i> , <i>Cirsium arvense</i> , <i>Rumex dentatus</i> , <i>Rumex spinosus</i> , <i>Anagallis arvensis</i> , <i>Veronica agrestis</i> , <i>Medicago denticulata</i> , <i>Ageratum conyzoides</i> , <i>Argemone mexicana</i> , <i>Asphodelus tenuifolius</i> , <i>Carthamus oxyacantha</i> , <i>Coronopus didymus</i> , <i>Gnaphalium indicum</i> , <i>Lathyrus aphaca</i> , <i>Launaea nudicaulis</i> , <i>Solanum nigrum</i> , <i>Spergula arvensis</i> , <i>Vicia hirsuta</i> , <i>Amaranthus viridis</i> , <i>Physalis minima</i>
	Grasses	<i>Phalaris minor</i> , <i>Avena ludoviciana</i> , <i>Poa annua</i> , <i>Polypogon monspiliensis</i> , <i>Lolium temulentum</i> , <i>Echinochloa colonum</i> , <i>Cynodon dactylon</i> , <i>Eleusine indica</i> , <i>Dactyloctenium aegyptium</i> , <i>Digitaria sanguinalis</i> , <i>Echinochloa crus-galli</i> , <i>Setaria glauca</i> , <i>Saccharum spontaneum</i> , <i>Sorghum halepense</i> , <i>Eragrostis tenella</i>
Summer	Annual grasses	<i>Echinochloa colona</i> , <i>Dactyloctenium aegyptium</i> , <i>Eleusine indica</i> , <i>Digitaria sanguinalis</i> , <i>Commelina benghalensis</i> , <i>Eragrostis</i> spp.
	Broadleaved weeds	<i>Trianthema portulacastrum</i> , <i>Digera arvensis</i> , <i>Phyllanthus niruri</i> , <i>Celosia argentea</i> , <i>Cleome viscosa</i> , <i>Cucumis trigonus</i> , <i>Eclipta alba</i> , <i>Euphorbia hirta</i> , <i>Trianthema monogyna</i> , <i>Convolvulus arvensis</i>
	Perennials	<i>Cyperus rotundus</i> , <i>Cyperus difformis</i> , <i>Cyperus iria</i>

Adapted from Kaur and Kaur (2021)

Weed infestation poses a significant threat to pulse cultivation in India, leading to substantial yield losses and economic challenges for farmers (Table 2.2). In India, pulses are mainly cultivated (84%) under rainfed conditions alongside non-legume crops, exacerbating the competition between crops and weeds. Significant losses were reported in *Vigna radiata* L. (green gram), common bean, and *Vigna aconitifolia* (Jacq.) Maréchal (moth bean) crops by Pramanick et al. (2014) and Kumar et al. (2016).

Cotton Cotton, known as “White Gold,” is a key commercial crop in India and globally, with India being the largest producer, cultivating 13 million ha. India is the only country in the world that cultivates all four species of cotton. These species are *Gossypium arboreum* (Asian Cotton), *Gossypium herbaceum* (Asian Cotton), *Gossypium barbadense* (Egyptian Cotton), and *Gossypium hirsutum* L. (American Upland Cotton). Cotton is a crucial fiber crop, and its seeds are used in the vegetable oil industry and as fodder for milch cattle. Cotton crop is a long-duration crop, with its life cycle spanning 150–180 days depending on the variety, soil type, and climatic conditions.

Cotton crop faces significant challenges from abiotic and biotic stresses, particularly weed competition during the early stages of growth. The pervasive weed infestation in cotton cultivation is a critical challenge in all major cotton-growing regions in India, including the north, central, and south zones. Despite regional variations in cotton cultivation, these zones exhibit a comparable pattern of yield reduction due to the relentless competition from weeds. Weeds compete for moisture, nutrients, light, and space, leading to substantial yield losses of cotton up to 45%–85%. For

instance, Pagar et al. (1995) reported from Nagpur that weed-free plots produced a seed cotton yield of 987 kg/ha, while unweeded plots yielded only 226 kg/ha, resulting in a yield reduction of 77%. The first 15–60 DAS are crucial for cotton growth, as weeds compete intensely during this period, making the crop particularly vulnerable to weed competition. If timely weed control is not implemented, grass weeds can aggressively rob essential nutrients and moisture from the soil, significantly reducing the resources available for cotton plants. This nutrient competition can hinder the growth and development of cotton, leading to reduced crop yield and quality. Effective weed management is crucial to prevent these invasive weeds from outcompeting cotton, ensuring that the crop receives adequate nutrients for optimal growth (Deshpande et al. 2006). Manual weeding is typically carried out 15–20 DAS, during the early leaf stage of the cotton crop. It is then repeated after 35–40 days, just before square formation, and finally after 55–60 days, prior to flowering. It helps in keeping the plot weed free and maintains soil moisture.

In the central zone, Raju and Tayade (2013) observed that cotton fields in gravelly soils are predominantly dominated by annual grasses and perennial weeds, particularly *Cyperus rotundus*, *Cynodon dactylon*, *Digitaria ciliaris* Retz. Koeler, and *Dinebra retroflexa* Vahl. Panzer. Furthermore, broadleaved weeds such as *Celosia argentea* (L.) and *Euphorbia hirta* (L.) are also prevalent in these cotton fields. In the North zone, Nayak et al. (2024) observed the predominance of several weed species in cotton fields. The most prevalent weed was *Cyperus rotundus* (57%), followed by *E. colona* (13%), *Parthenium hysterophorus* L. (11%), *T. portulacastrum* (7%), *Cynodon dactylon* (7%), and *Phyllanthus niruri* L. (6%). In southern Indian conditions at Madurai, Tamil Nadu, Chandrasekaran (2019) observed the dominance of *T. portulacastrum* (42%), *Cyperus rotundus* (34%), *Cynodon dactylon* (14%), and *Phyllanthus niruri* L. (3%), along with minor weed flora in cotton.

Sugarcane Sugarcane, a native of India, is widely cultivated in tropical and subtropical agroecosystems of the world as main and ratoon crop to produce sugar as well as bioenergy. In India, it is the largest crop in terms of production value amongst the important commercial crops. One-third of the sugarcane production is processed in sugar factory while two-third is used for making jaggery and *khandsari*. Weeds are considered major constraints to higher yields in sugarcane production. Weeds can reduce potential sugarcane yield by 12%–72% depending on the severity of infestation by competing for moisture, nutrients, and light during the growing season (Kanwar et al. 1992). Weeds remove 4 times more nitrogen and 2.5 times of potassium than that of sugarcane crops during the first 7 weeks' period. The duration of crop-weed competition in sugarcane is much greater than in other short season row crops due to long duration, wider row spacing, slow initial growth phase, and abundant supply of irrigation water and fertilizers (Shyam and Singh 2015). Weed problem is also very serious in the ratoon crop of sugarcane due to its little preparatory cultivation. Weed-free environment during initial stage after planting or ratooning is essential for realizing higher cane yield. Effective weed management should provide weed-free environment for the sugarcane from planting or ratoon onward as the case may be, up to at least 90–120 days (Singh et al. 2011). Owing to

the initial slow growth of sugarcane, the inter-row spaces that is not covered by sugarcane canopy provide a promising microclimate for profuse growth of weeds under wide row planting.

More than 200 weed species comprising annuals, perennials, and parasitic weeds have been reported to invade the sugarcane fields. A mixed population of grasses, broadleaved weeds, and sedges grows with sugarcane under different agroclimatic conditions, seasons, edaphic conditions, crop rotations, weed management practices, and agronomic practices followed for cultivation of the crop. Weeds such as *Cynodon dactylon*, *Cyperus rotundus*, *Rottboellia cochinchinensis* (Lour.) Clayton, *Ipomoea* spp., and *Striga* sp. are very difficult to control in sugarcane. The infestation of binding weeds like *Ipomoea* spp., is a serious menace in many sugarcane-growing areas after final earthing up and causes a 15%–25% reduction in cane yield (Sarala et al. 2011). These binding weeds take support from cane stalk, spread, and wrap on the top plane, and exerts their weight resulting in lodging of cane and reduced cane and sugar yield (Marimuthu et al. 2002).

Striga spp., an obligate parasitic weed, is adversely affecting cane cultivation in some sugarcane-growing districts of tropical zone like Belgaum, Bagalkot, and Vijayapura (Manjunatha et al. 2018). *Striga* (three species, *Striga asiatica*, *S. gesnerioides*, and *S. hermonthica*) becomes a serious problem when sugarcane cultivation is done in the poor fertile soils along with the moisture deficit conditions. *Striga* spp. are annual, photosynthetically active, obligate root parasites that depend on host plant for their growth. A single *Striga* plant produces numerous miniature seeds, which remain viable in soil for several years and will not germinate until host plant like sugarcane grows near to them and produces chemical signals called strigolactones. *Striga* is completely dependent on sugarcane for survival for nutrients and water and invades sugarcane host through root system. This eventually results in chlorosis, stunting growth and death of sugarcane crop. Infestation of *Striga* spp. is more common in low input, dry, infertile, and marginal soils with poor management practices (Dafaallah 2019). *Striga* management practices involve improvement of soil fertility, which has to be improved, and moisture stress should be avoided.

2.4 Evolution of Herbicide Resistance in Weeds

In India, *P. minor* was the first weed to evolve herbicide resistance against isoproturon during 1991 (Malik and Singh 1995). To date, 7 unique cases of 4 weeds, namely *Phalaris minor* (4 cases), *Rumex dentatus* (1 case), *Cyperus difformis* (1 case) and *Echinochloa crus-galli* var *crus-galli* (1 case), have evolved herbicide resistance in India (Table 2.3). There are 11 and 4 unique cases of herbicide resistance in *P. minor* that are confirmed globally and in India, respectively (Heap 2025). Globally, there is only one unique case of *Rumex dentatus* that has evolved herbicide resistance (Dhanda et al. 2022). Globally, there are 12 and 54 confirmed unique cases of *Cyperus difformis* and *Echinochloa crus-galli* var *crus-galli*, respectively.

Table 2.3 Confirmed unique cases of weeds resistant to different herbicide modes of actions in India

Year	Situation	Sites of action	Candidate herbicide(s)
<i>Phalaris minor</i>			
1991	Wheat	PSII inhibitors—serine 264 binders, HRAC group 5 (legacy C1 C2)	Isoproturon
1994		Inhibition of acetyl CoA carboxylase, HRAC group 1 (legacy A)	Diclofop-methyl, pinoxaden
2006		Multiple resistance: Three sites of action Inhibition of acetolactate synthase, HRAC group 2 (legacy B); Inhibition of acetyl CoA carboxylase, HRAC group 1 (legacy A); PSII inhibitors—serine 264 binders, HRAC group 5 (legacy C1 C2)	Clodinafop-propargyl, fenoxaprop-ethyl, sulfosulfuron, isoproturon, mesosulfuron-methyl, pinoxaden, pyroxsulam
2013		Inhibition of acetolactate synthase, HRAC group 2 (legacy B)	Iodosulfuron-methyl-Na, mesosulfuron-methyl
<i>Rumex dentatus</i>			
2014	Wheat	Inhibition of acetolactate synthase, HRAC group 2 (legacy B)	Florasulam, iodosulfuron-methyl-Na, mesosulfuron-methyl, pyroxsulam
<i>Cyperus difformis</i>			
2017	Rice	Inhibition of acetolactate synthase, HRAC group 2 (legacy B)	Bispyribac-sodium
<i>Echinochloa crus-galli var. crus-galli</i>			
2017	Rice	Inhibition of acetolactate synthase, HRAC group 2 (legacy B)	Bispyribac-sodium

Adapted from Heap (2025)

Note: PSII inhibitors: herbicides belonging to the Photosystem II inhibitors group; ACCase inhibitors: herbicides belonging to the acetyl-CoA Carboxylase inhibitors group; ALS inhibitors: herbicides belonging to the acetolactate synthase inhibitors group

Recently, herbicide resistance was also characterized in *Commelina communis* against imazethapyr in soybean. Amongst these unique cases, evolution of herbicide resistance against isoproturon in *Phalaris minor* was devastating, which affected about 0.8–1.0 million ha of wheat-growing regions (Malik and Singh 1995; Franke et al. 2007). Due to resistance evolution in *P. minor*, crop yield decreased by 25%–50% and farmers were forced to plow their fields under heavy infestations, during late 1990s (Kaur et al. 2022). In isoproturon-resistant *P. minor*, metabolic detoxification of the herbicide was the reason for evolution of resistance (Singh et al. 1998; Kumar and Guru 2016).

2.5 Strategies for Weed Management

The extent of crop-weed competition is influenced by crop, cultivar being grown, agronomic practices, and climatic factors. “Prevention is better than cure,” and in this context, maintaining clean cultivation practices is crucial for abating weed menace in crops. Prevention is a cornerstone of integrated pest management, considered the most cost-effective strategy for growers (Norris et al. 2003). Preventive management is highly efficient regardless of property size, applicable from small vegetable crop seedbeds to extensive areas dedicated to major field crops (Christoffoleti et al. 2007). This accentuates the importance of keeping the field, its boundaries, water channels, farm roads, and the entire farm area free from weeds. It also highlights the use of clean (weed-seed free) seed, water, organic manure, and chemical fertilizers as prominent preventive weed control techniques. Farmyard manure should be well-decomposed to ensure that weed seeds are destroyed, and farm machinery must be thoroughly cleaned before use.

Cultural weed management techniques play a crucial role in weed control by completely removing weeds and providing competitive advantages to crops, as they reduce weed establishment. Cultural methods of weed control include planting the crop in right time with optimum planting density, raised bed sowing, residue mulching, earthing up, and applying plant nutrients in bands to boost the early growth of the crop for early canopy cover. Angiras et al. (2010) found that raised seedbeds had the lowest seed numbers of certain weeds at shallow depths (e.g., *D. sanguinalis*, *E. colona*, *Panicum dichotomiflorum* Michx.), while zero tillage had the lowest numbers at deeper depths. Growing trap crops like sorghum, corn, and cowpea to stimulate suicidal germination and reducing soil seed bank of *Striga*. Application of adequate farmyard manure or organic manure improves soil fertility, enhances soil moisture retention, and increases the competitive ability of sugarcane over *Striga*. Application of extra doses of nitrogen, split application of fertilizers, and light and frequent irrigations are also recommended in the *Striga*-infested areas (Singh et al. 2018).

Cultural weed management in pulses encompasses a range of strategies vital for mitigating weed competition and optimizing crop productivity. Timing of sowing is a critical factor, as evidenced by the research of Malik and Yadav (2014), who found that sowing pigeon peas in May resulted in reduced weed density and biomass, ultimately leading to higher yields compared to later sowings in June. Additionally, selecting appropriate planting methods can further suppress weed growth, as demonstrated by Muhammad et al. (2007), who showed that flat planting methods were more effective than ridge planting in reducing weed density and biomass.

An effective weed management program necessitates an in-depth understanding of weed species identification, their biology, associated weed communities, and their seed dispersal capabilities. Greater understanding of the factors influencing the germination of weed seeds could facilitate the development of more effective cultural weed management practices (Chauhan and Johnson 2010). Since weed communities are shaped by climatic conditions and soil characteristics, it is imperative

to comprehend the location-specific critical periods of crop-weed competition. Moreover, understanding the traits of crop varieties, including their cross-resistance and multiple resistances to herbicides, is essential for optimizing weed control strategies and ensuring sustainable crop production. Some weed management options are discussed below.

Land Preparation Proper seedbed preparation significantly reduces weed problems, while neglected fields can lead to persistent issues that last for years until the weed seed bank is depleted. Conservation tillage affects weed dynamics through its effect on seed germination and emergence behavior (Chauhan et al. 2012). Deep plowing and collection and destruction of vegetative/asexual parts of weeds while preparing the field for planting crops would reduce their infestation in the crop. Deep summer plowing every 2–3 years immediately after harvest using subsoiler or moldboard plow, followed by two crosswise harrowings before the pre-monsoon showers eliminates the perennial weed seed propagules of *Saccharum spontaneum* L., *Ischaemum pilosum* Klein ex Willd. Wight, *C. rotundus*, and *C. dactylon*. Deep summer plowing effectively exposes the rhizomes and vegetative propagules of these perennial weeds to intense summer heat, thereby mitigating weed proliferation in succeeding crops.

Soil solarization with a 0.05 mm transparent polyethylene cover in April–May after irrigation effectively suppressed weeds and boosted baby corn yields compared to non-solarized soil. Proper land preparation and irrigation before solarization maximize its weed control efficacy and increase yields of baby corn and peanut (Thimmegowda et al. 2007). Further, puddling in rice fields is helpful in reducing the infestation of *C. dactylon* and *C. rotundus*. Most terrestrial cropped field weeds cannot survive in ponded fields; thus, water management is an excellent method to control diverse weed flora.

Blind tillage, a non-selective tillage technique usually followed in sugarcane, can be employed prior to crop sowing to manage early-season weeds. This practice disrupts the soil surface indiscriminately, without targeting specific crop rows, uprooting, and burying the newly emerged weed seedlings. By diminishing the competition for vital resources such as nutrients, water, and light, blind tillage significantly reduces weed pressure, thereby fostering an environment conducive to robust crop growth.

Stale Seedbed Technique The stale seedbed technique involves the removal of initial flushes of weeds before the sowing of rice, cotton, corn, and pulses. This method permits the germination of weed seeds situated just beneath the soil surface, which are then eliminated prior to crop sowing. By depleting the weed seed bank before sowing the crop, this technique mitigates competition between the crop and weeds during critical growth phases. The technique entails thoroughly moistening a meticulously prepared field through irrigation or rainfall, encouraging weed seeds to germinate. Subsequently, a shallow tillage operation or the application of non-residual herbicides can be utilized to destroy the dense flush of weed seedlings.

The stale/false seedbed technique aims to diminish the weed seed bank by leveraging seed germination biology. Its effectiveness hinges on various factors influencing weed seed germination and seedling emergence, such as soil temperature, diurnal temperature fluctuations, soil moisture, light exposure, soil nitrate levels, and soil gaseous conditions (Merfield 2017). Leguminous cover crops such as cowpea or *Crotalaria juncea* L. (sunn hemp) are highly effective in suppressing weed growth and can be judiciously combined with the stale seedbed technique to provide a sustainable weed management strategy. Further, weedy rice and volunteer rice plants can easily be controlled with this eco-friendly technique.

Crop Rotation Cultivation of diverse crops in rotation affects weed floristic composition present in a field, primarily due to different agronomic practices. Crop rotation involves the sequential cultivation of diverse crops within the same field. Effective rotations include crops that mitigate the prevalence of troublesome weeds in subsequent seasons. Crop-bound (*Striga*) and crop-associated weeds (*Echinochloa* spp. in rice, *P. minor* in wheat) can easily be controlled following the crop rotation. The strategic integration of crop and herbicide rotations has proven highly effective in weed management. By incorporating diverse crops into rotations, one can utilize herbicides with different modes of action, thereby mitigating the risk of the evolution of herbicide resistance (Norsworthy et al. 2012).

Monocultures significantly influence floristic composition, potentially exacerbating the spread of resistant and detrimental weed species. Crop rotation exerts a profound influence on the soil weed seed bank, facilitating the management of both weed species and their seeds and seedlings (Cardina et al. 2009). Such diversity in rotational crops offers multiple advantages for soil health and subsequent crops in terms of pest management. For example, the fibrous root systems of cereals help alleviate soil compaction, nitrogen-fixing legumes bolster soil fertility, and rotating crops with vegetable crops ensures a high level of fertilizer residual carryover. Consequently, crop rotations emerge as highly efficacious strategies, providing incremental yield benefits compared to monoculture systems.

Rotating cotton with alternative crops can effectively diminish the prevalence of established cotton-associated weeds. Implementing a cotton-cereal rotation, for instance, is instrumental in controlling various broadleaf weeds. The practice of rotating cotton with corn not only enhances soil organic carbon content, primarily due to the substantial biomass produced by corn (Mitchell and Entry 1998), but also benefits from corn's rapid growth and extensive canopy coverage, which effectively suppresses weeds that could otherwise impact cotton in subsequent crops. Cotton-based rotation systems can significantly impact both the cotton crop and its environment, potentially resulting in a 2.6%–4.5% increase in seed cotton yield when legumes are incorporated into the rotation, as opposed to conventional cotton monoculture. This yield enhancement is attributed to improved macroaggregate formation, stemming from deeper root systems, leaf drop, augmented rhizosphere activity, and root exudates. In central India, a biennial rotation of cotton and soybean has been shown to enhance both cotton productivity and nitrogen use efficiency relative to continuous cotton cultivation. Conversely, in the irrigated regions of northern

India, rotations involving cotton with wheat, chickpea, or barley have proven to be the most advantageous.

Intercropping Intercropping, a practice that involves growing complementary crops in the same field, can significantly suppress weed growth. This method reduces reliance on herbicides, offering an efficient, cost-effective, and environmentally friendly alternative (Gnanavel and Natrajan 2014). Intercropping not only lessens the emergence of secondary weeds that may appear after the intercrops have fully covered the ground, but it also necessitates manual intervention, such as hand weeding, to manage weeds that emerge prior to full canopy cover. In the realm of conservation agriculture, cover crops or mulches are recommended as intercrops or companion crops to aid in weed suppression. Intercropping with legumes and cover crops reduces *C. dactylon* infestation since this weed does not tolerate shade (Singh et al. 2018).

Cotton, a long-duration crop characterized by its wide spacing and slow early growth, often leaves substantial interspaces that are prone to weed infestation, resulting in approximately 45% crop loss. These expansive interspaces present prime opportunities for weed proliferation. In India, short-duration legumes such as clusterbean (*Cyamopsis tetragonoloba* (L.) Taub.), soybean, cowpea, pigeon pea, black gram (*Vigna mungo* (L.) Hepper), and green gram are commonly grown between widely spaced cotton plants to enhance weed suppression and overall system productivity. A 2-year study conducted by Chandrasekaran (2019) demonstrated that intercropping cotton with black gram effectively reduced the density of grass weeds compared to sole cotton. Moreover, black gram was more successful in controlling sedge populations and achieved a notable reduction in broadleaved weeds compared to other systems.

Mulching Mulching involves applying a protective layer of material to the soil surface. The efficacy of weed suppression is intricately linked to the mulch area index, which limits light penetration to newly germinated weed seeds. Mulch inhibits weed seedling growth by preventing light penetration or excluding specific wavelengths crucial for photosynthesis (Kamara et al. 2000). Singh et al. (2015b) observed that mulching significantly decreased mean seasonal soil evaporation compared to areas without mulch. Additionally, mulching enhanced grain yield, yield attributes, and water use efficiency. The literature suggests that mulching improves soil moisture retention, leading to enhanced water-holding capacity (Jabran 2019).

For optimal results, organic mulches should be applied at a thickness of 10–15 cm to ensure sufficient light exclusion. The principle behind mulching is to obstruct sunlight from reaching the photosynthetic portions of weeds, thereby inhibiting their development. Many weed seeds require light to trigger germination; thus, mulches diminish the germination rates of these seeds. Furthermore, emerging weeds may succumb to starvation due to the lack of photosynthesis, or, if allelopathic mulches are used, may die from chemical growth inhibition. In corn cultivation, Pandey et al. (2000) observed that mulching with pine needles improved yield

attributes and water use efficiency compared to areas without mulch. Dry leaves of sugarcane or any other crop can be applied as mulch in the interspaces of sugarcane to check weeds. In addition to weed control, this trash will add nutrients to the soil upon decomposition (Singh et al. 2018).

In cotton cultivation, various types of mulch, such as organic crop residues, dry shredded cotton stalks, or polyethylene film employed to effectively suppress weed growth. According to Nalayini et al. (2009), polyethylene mulch with a thickness of 30 μm achieved complete weed control in cotton, although it was less effective against *C. rotundus*. Wheat straw, when used as mulch at a rate of 10 t/ha, has been shown to significantly diminish weed biomass, enhance growth parameters, and boost seed cotton yield by 38.4% compared to untreated controls (Singh et al. 2021). Ramzan et al. (2012) assessed various organic mulch materials for their efficacy in weed management and revealed that different mulching materials, except plastic mulch, were less effective than manual weeding. Plastic mulch exhibited the lowest weed density, surpassing other materials such as wheat straw, banana leaves, sugarcane trash, and no mulch. Nalayini et al. (2023) reported a marked reduction in weed density in cotton fields under tropical conditions in Coimbatore, Tamil Nadu, when stale seedbed techniques were integrated with leguminous cover crops such as sunn hemp and cowpea. This integrative approach outperformed the conventional practice of pre-emergence application of pendimethalin followed by two manual weedings. The synergy of cover crops and stale seedbed techniques proved highly efficacious in depleting the weed seed bank in cotton cultivation, offering a superior alternative for sustainable weed management.

In addition to traditional mulching, cover crops such as sunn hemp and *Sesbania bispinosa* (Jacq.) W.Wight (spiny sesbania) represent a viable alternative for weed suppression. These fast-growing legumes contribute to nutrient capture, nitrogen fixation, the alleviation of plow pans, water retention, and the provision of organic matter when incorporated into the soil prior to cotton sowing (Sharma and Ghosh 2000). The effectiveness of cover crops is contingent upon timely planting and robust biomass production. Cover crops also offer soil erosion protection and can be cultivated between wide row spaces of cotton or in the field's side rows. Before flowering, typically 45–60 days post-sowing, the cover crops can be cut and applied as mulch. This biomass serves as a physical barrier to weed growth and may also release allelopathic chemicals to further inhibit weed proliferation.

Mechanical Methods Mechanical and physical methods of weed control have been employed since the advent of agriculture and remain integral to weed management strategies in India. These methods encompass a range of practices, including tillage, hoeing, hand weeding, digging, intercultural operations, and mulching. Mechanized weeding entails physically eliminating weeds from the cropping system to diminish competition with crops. Beyond weed management, it can also aerate the soil and enhance its quality, occasionally exerting a greater influence on crop yield than solely focusing on weed control.

Mechanical weeders span from manual weeding to advanced implements propelled by tractors. Tools for mechanical cultivation include hoes, harrows, tines,

brush weeders, and cutting apparatus such as mowers and sickles. The selection of these tools depends on factors like the type of crop, weed species, and the economic circumstances of farmers. Manual weeding with hand tools has long been practiced as a conventional means of weed management. Brush weeding involves uprooting and burying weeds between crop rows, proving effective in wet conditions. Harrowing, a traditional method, is commonly employed before and after corn seedling emergence, especially in hilly regions, to foster corn seedling competitiveness and prepare the land for subsequent weeding. Additionally, heavy machinery like mechanical hoes and mowing machines is utilized for weed control. Manual hand pulling of weeds, removal of weeds by using small hand tools like hand hoes, and control of weeds by using inter-cultivation implements drawn by animals or tractors all constitute mechanical methods of weed control. Hand weeding remains a practical and effective approach for managing both annual and perennial weeds, though it is labor-intensive and particularly challenging during heavy rainfall. These techniques are particularly advantageous in areas where labor is abundant and affordable. The timing of hoeing is critical; it should be neither too early nor too late to ensure effective weed control during the crop's most vulnerable stages of competition. Research indicates that physical methods, such as burying weeds to a depth of 1 cm, are particularly effective, followed by cutting at the soil surface to manage weed populations.

Research indicates that two hand weedings at 21 and 42 DAS in irrigated corn are more effective in reducing weed dry matter and nutrient depletion by weeds (Subramanyam et al. 2001). Various yield parameters were significantly enhanced in weed-free plots managed through hand weeding compared to control plots, contributing to crop development and increased corn grain yield (Shrestha et al. 2018). In corn, Sharma et al. (2010) found that hand weeding at 25 and 45 DAS resulted in higher yields with minimal weed density and dry weight. Similarly, Prasad et al. (2008) reported that manual weeding at 15 and 30 DAS achieved the highest weed control efficiency (70.9%) along with higher grain yield. Though effective, it is labor-intensive and costly, remaining a viable method for weed control in both cropped and uncropped soils (Sharma et al. 2000). Hand hoeing at 25 and 40 DAS resulted in the lowest weed density and dry weight, contributing to 44.22% of yield enhancement over the control in green gram (Kaur et al. 2010).

In cotton fields, weed removal using tools such as the hand hoe or wheel hoe is generally more efficient than hand pulling. Commonly, manual weeding is the major and most effective method of weed control, which demands more labor and is cumbersome. Many times, this operation may not be possible if it rains. In central India, mechanical weed management in cotton typically begins around 30 DAS. This approach includes three to four rounds of hoeing (inter-cultivation) at 15-day intervals, supplemented by two to three rounds of manual hand weeding. Specifically, hoeing and hand weeding conducted at 20, 40, and 60 DAS have been shown to be highly effective in managing weeds and are widely practiced in the cotton-growing regions of Vidarbha, Maharashtra (Patil et al. 1997). Similarly, Kakade et al. (1999) observed that employing manual weed control methods, specifically three rounds of hoeing combined with three rounds of hand weeding, resulted in a significantly

higher number of bolls and increased boll weight, culminating in a 50.8% increase in seed cotton yield compared to the untreated weedy check. *Cyperus rotundus*, one of the world's most problematic perennial weeds, is difficult to control using conventional methods like hand weeding and hoeing.

Timely removal of weeds, particularly before these reach the flowering stage, is crucial; otherwise, they can pose a persistent challenge in subsequent cropping seasons. Incorporating weeds and farm wastes into on-site composting practices can recycle biomass effectively back into the field. Efforts to mechanize the weeding process in cotton have been pursued globally to enhance weed management efficiency and economic viability. In this context, two self-propelled rotary weeders and a tractor-operated sweep weeder have proven to be effective for inter-row weeding in cotton. Dixit et al. (2011) reported a weed control efficiency of 94%–95%, along with cost savings of 50%–60% and labor savings of 70% compared to manual weeding.

Mechanical weeding is a popular method of weed control in sugarcane. Weeds are generally removed by blind hoeing operations within 20–35 days after planting, and weeding/interculture is done from rows of standing crop with the help of power tillers or bullock-/tractor-drawn tillers. Earthing up operation after fertilizer application, either manually or by using ridge plows, incidentally controls weeds to some extent. Mechanical weeding at 30, 60, and 90 days after planting is an effective practice for weed management in sugarcane (Patel et al. 2024). Though interculture is not efficient for controlling weeds (as weeds within crop row are not removed), it is less costly.

In recent advancements, robotic weeding has shown significant potential in enhancing the efficiency of mechanical weed management in corn. Recent advancements in robotic systems have significantly improved mechanical weed management in corn. Robotic weeding, guided by precise navigation data, has been shown to enhance weed control efficiency by targeting specific areas with minimal soil disturbance (Bakker et al. 2010). Furthermore, innovative approaches to weed detection, such as the use of unmanned aerial vehicles (UAVs) combined with improved machine learning models like the enhanced YOLO v5n, offer promising results in mapping and identifying weed infestations with high accuracy. Chen et al. (2024) demonstrated that their novel weed detection strategy achieved a high R^2 value of 0.96 and a root mean square error of 3.08% in detecting weeds across various coverage levels. Building on this, Zhu et al. (2022) introduced a YOLOX-based weeding robot with a blue light laser, reducing weed dry weight by 85% and maintaining low seedling injury. These innovations collectively enhance weeding efficiency and contribute to sustainable agricultural practices by reducing herbicide usage.

Chemical Method Herbicides have been pivotal in weed management strategies for the past half-century, with their utilization increasing notably in recent years. Prolonged rainfall often renders soils unmanageable, obstructing timely weed control measures and coinciding with acute labor shortages during critical early growth stages. Under these challenging conditions, precise chemical weed control stands

out as an efficient and economically viable solution. Herbicides contribute significantly to weed control, environmental preservation, and the conservation of labor required for weed management practices.

In this, herbicides are applied either as pre-emergence or post-emergence. Amongst herbicide application timings, pre-plant or pre-emergence applications offer initial advantages in weed suppression. The effectiveness of pre-emergence herbicides is contingent upon sufficient soil moisture to activate weed suppression. Meanwhile, advanced formulations of post-emergence herbicides offer broad-spectrum control, proving invaluable during labor-deficient periods for targeted weed management. The application rate and timing of herbicides are intricately tied to specific environmental and crop conditions, necessitating precise, site-specific application methodologies to maximize their efficacy. According to the Central Insecticide Board & Registration Committee, there are many herbicides recommended for weed control in rice and wheat crops, as given in Tables 2.4 and 2.5, respectively (Anonymous 2025b).

Earlier, there were recommendations of pre-emergence herbicides such as atrazine, alachlor and simazine in corn. Further, post-emergence herbicides are included in the package of this crop for weed control (Table 2.6). The highest stover and grain yield, as well as other parameters such as grain weight and grains per cob, were achieved with the sequential application of atrazine at 750 g a.i./ha with tembotrione at 100 g a.i./ha at 15–20 DAS (Bhagat et al. 2019; Lukangila et al. 2024). Chhokar et al. (2019) investigated combinations of mesotrione and atrazine for managing diverse weed flora and observed higher weed control efficiency with the application of mesotrione + atrazine at 91 + 909 g a.i./ha, leading to significant grain yield. Maximum weed control efficiency (98%) was attained with the pre-emergence application of atrazine at 500 g a.i./ha along with pendimethalin at 250 g a.i./ha in corn grown on sandy loam soils (Patel et al. 2006). Brankov et al. (2024) investigated post-emergence herbicides for controlling weedy sunflower in corn, highlighting the effectiveness of tembotrione, bentazone, mesotrione, and ALS inhibitors such as rimsulfuron and nicosulfuron.

Chemical weed control is crucial for enhancing yield in pulse crops like green gram, black gram, soybean, and clusterbean (Table 2.7). Pratap et al. (2024) demonstrated that post-emergence application of fomesafen 11.1% w/w + fluazifop-p-butyl 11.1% w/w (25% SL) at 250–312.5 g a.i./ha effectively controlled diverse weeds in green gram, achieving the highest grain yield of 1220 kg/ha with no phytotoxic effects. Similarly, Ciontu et al. (2024) found that combining pre-emergence herbicides, such as acifluorfen and s-metolachlor, with post-emergence treatments in chickpea effectively managed weeds, though challenges remained with perennial species like *Convolvulus arvensis*. These findings underscore the importance of strategic herbicide application in pulse crop management.

In cotton, herbicides like fluchloralin and pendimethalin are effective against both grass and broadleaf weeds. Table 2.8 outlines the optimal timing and dosages of these herbicides to manage annual grass weeds effectively when they reach 3–4 inches in height or are 20–25 days old. Notably, pendimethalin is a potent

Table 2.4 Herbicides approved for use in rice in India

Herbicide name	Dosage (g a.i./ha)	Waiting period before harvest (days)
Rice nursery		
Bispyribac sodium 10% SC	20–25	–
Penoxsulam 21.7% SC	22.5	60
Pyribenzoxim 5% EC w/w	30	–
Direct seeded rice		
Azimsulfuron 50% DF	35	59
Bispyribac sodium 10% SC	20–25	78
Carfentrazone ethyl 40% DF	25	102
Cyhalofop butyl 10% EC	75–80	90
Fenoxaprop-p-ethyl 6.7% w/w EC	56.6–60.38	61
Florpyrauxifen-benzyl 2.7% w/w EC	31.25–37.5	85
Imazethapyr	100	75
Metamifop 10% EC	100	87
Oxyfluorfen 0.35% GR	100–150	–
Oxyfluorfen 23.5% EC	150–240	–
Paraquat dichloride 24% SL	300–800	–
Pendimethalin 30% EC	1000–1500	–
Pendimethalin 5% G	1000–1500	–
Penoxsulam 2.67% OD	25	85
Pretilachlor 30.7% EC	450–600	110
Propanil 80% w/w DF	2000–3000	84
Pyribenzoxim 5% EC w/w	30	89
Bispyribac sodium 2% + 2,4-D sodium salt 54.3% w/w SP	25.0 + 678.75	79
Bispyribac sodium 38% + Chlorimuron ethyl 2.5% + Metsulfuron methyl 2.5% (w/w) WG	43	64
Florpyrauxifen-benzyl 1.31% w/w + Penoxsulam 2.1% w/w OD	15.63 + 25	83
Florpyrauxifen-benzyl 2.13% w/w + Cyhalofop-butyl 10.64% w/w EC	150–180	92
Penoxsulam 1% + Pendimethalin 24% w/w SE	22.5–25.0 + 540–600	100
Penoxsulam 1.02% + Cyhalofop-butyl 5.1% OD	120–135	60
Pretilachlor 30.0% + Pyrazosulfuron ethyl 0.75% WG	600 + 15	113
Triafamone 20% + Ethoxysulfuron 10% WG	44 + 22.5	83
Pretilachlor 27.4% w/w + Florpyrauxifen-benzyl 0.91% w/w EC	600 + 20	95
Pyribenzoxim 5% EC w/w	30	89
Direct seeded imazethapyr-herbicide tolerant rice		
Imazethapyr 10% SL	100	75

(continued)

Table 2.4 (continued)

Herbicide name	Dosage (g a.i./ha)	Waiting period before harvest (days)
Puddled transplanted rice		
Anilophos 2% G	400–500	30
Azimsulfuron 50% DF	35	59
Bensulfuron methyl 60% DF (pre-emergence)	60	88
Bensulfuron methyl 60% DF (post emergence)	60	71
Bentazone 480 g/l SL	960	71
Bispyribac sodium 10% SC	20–25	78
Butachlor 5% GR	125–187	90–105
Butachlor 50% EW	125–150	–
Chlorimuron ethyl 25% WP + surfactant	6	60
Cinmethylin 10% EC	75–100	110
Clomazone 50% EC	400–500	90
2,4-D Ethyl ester 4.5% GR (having 2,4-D acid 4% w/w)	1000	–
Ethoxysulfuron 15% WDG	12.5–15	110
Fenoxaprop-p-ethyl 9% w/w DF	56.25	65
Fenoxaprop-p-ethyl 9.3% w/w EC (9% w/v)	56.25	70
Fenoxaprop-p-ethyl 6.7% w/w EC	56.6–60.38	61
Florpyrauxifen-benzyl 2.7% w/w EC	25–31.25	73
Flucetosulfuron 10% WG	25	90
Ipfencarbazone 25% SC (22.81% w/w)	125	91
MCPA, amine salt 40% WSC	800–2000	–
Metsulfuron methyl 20% WP	4	60
Metsulfuron methyl 20% WG	4	71
Orthosulfamuron 50% WG	60–75	65
Oxadiargyl 80% WP	100	97
Oxadiargyl 6% EC	100	97
Oxadiazon 25% EC	500	–
Oxyfluorfen 0.35% GR	100–150	–
Paraquat dichloride 24% SL	300–800	–
Pendimethalin 30% EC	1000–1500	–
Pendimethalin 5% G	1000–1500	–
Penoxsulam 21.7% SC	20–22.5 to 22.5–25	60
Penoxsulam 2.67% OD	22.5–25	60
Pretilachlor 50% EC	500–750	75–90
Propanil 35% EC	2000–3000	90
Pyribenzoxim 5% EC w/w	30	79
Pyrazosulfuron ethyl 10% WP	10–15	95
Pyrazosulfuron ethyl 70% WDG	21	43

(continued)

Table 2.4 (continued)

Herbicide name	Dosage (g a.i./ha)	Waiting period before harvest (days)
Quinclorac 250 g/l SC	187.5–250	78
Anilofos 24% + 2,4-D ethyl Ester 32% EC	240 + 320 to 360 + 480	90
Bensulfuron methyl 0.6% + Pretilachlor 6% GR	60 + 600	88
Bensulfuron-methyl 4.8% + Pretilachlor 48% OD	60 + 600	102
Bispyribac sodium 0.25% + Penoxsulam 0.25% + Pyrazosulfuron ethyl 0.20% GR	25 + 25 + 20	73
Bispyribac sodium 2% + 2,4-D sodium salt 54.3% w/w SP	25.0 + 678.75	79
Bispyribac sodium 7.6% + Fenoxaprop-p-ethyl 11.4% w/w WG	37.8 + 56.8	54
Bispyribac sodium 9.5% + Penoxsulam 7.8% w/v SC	23.75 + 19.5	78
Bispyribac sodium 20% + Pyrazosulfuron ethyl 15% WDG	20 + 15	130
Bispyribac-sodium 15% + Metsulfuron-methyl 2.4% + chlorimuron ethyl 3.6% OD	26.25 + 4.2 + 6.3	81
Bispyribac sodium 38% + chlorimuron ethyl 2.5% + Metsulfuron methyl 2.5% (w/w) WG	43	64
Clomazone 20% + 2,4-D Ethyl Ester 30% EC	250–375	100–110
Florpyrauxifen-benzyl 1.31% w/w + Penoxsulam 2.1% w/w OD	15.63 + 25	83
Florpyrauxifen-benzyl 2.13% w/w + Cyhalofop-butyl 10.64% w/w EC	150	67
Metsulfuron methyl 10% + Chlorimuron ethyl 10% WP	4	90
Pendimethalin 38.4% + Pyrazosulfuron ethyl 0.85% ZC	900 + 20	86
Penoxsulam 0.97% w/w + Butachlor 38.8% w/w SE	820	60
Penoxsulam 1.02% + Cyhalofop-butyl 5.1% OD	120–135	60
Penoxsulam 2% + oxadiazon 21% w/w SC	20 + 210	78
Pyriftalid 31.0% w/w + Bensulfuron methyl 15.7% w/w SC	116.1 + 58.9	99
Triafamone 20% + Ethoxysulfuron 10% WG	44 + 22.5	83
Bispyribac sodium 0.25% + Penoxsulam 0.25% + Pyrazosulfuron ethyl 0.20% GR	25 + 25 + 20	73
Bispyribac sodium 9.5% + Penoxsulam 7.8% w/v SC	23.75 + 19.5	78
Pretilachlor 27.4% w/w + Florpyrauxifen-benzyl 0.91% w/w EC	600 + 20	72
Pyribenzoxim 5% EC w/w	30	79
Butachlor 50% EC	1250–2000	90–120

(continued)

Table 2.4 (continued)

Herbicide name	Dosage (g a.i./ha)	Waiting period before harvest (days)
2,4-D Ethyl Ester 38% EC (having 2,4-D acid 34% w/w)	850	–
2,4-D Ethyl Ester 20% WP	900	–
Fenoxaprop-p-ethyl 9% w/w DF	56.25	65
Flufenacet 60% DF	120	90–110
Fenoxaprop-p-ethyl 5% + chlorimuron ethyl 0.6% + pretilachlor 50% ME	50 + 6 + 500	76
Oxadiargyl 1% + Pretilachlor 6% GR	100 + 600	85
Pretilachlor 6% + Pyrazosulfuron ethyl 0.15% (H)	600 + 15	83
Pretilachlor 6.0% + Pyrazosulfuron ethyl 0.15% GR	600 + 15	83

Adapted from Anonymous (2025b)

Table 2.5 Herbicides approved for use in wheat in India

Herbicide name	Dosage (g a.i./ha)	Waiting period before harvest (days)
Carfentrazone ethyl 40% DF	20	80
Clodinafop-propargyl 15% WP	60	110
Clodinafop-propargyl 15% w/w DF	60	70
2,4-D Dimethyl amine salt 58% SL	500–750	–
2,4-D Sodium salt technical (having 2,4-D acid 80% w/w) (earlier registered as 80% WP)	500–840	90
2,4-D Ethyl Ester 38% EC (having 2,4-D acid 34% w/w)	450–750	–
2,4-D Ethyl Ester 20% WP	900	–
2,4-D Sodium salt 50% (w/w) + Metribuzin 15% (w/w) WP	400 + 120	120
Dicamba 48% w/v SL	240	91
Diclofop methyl 28% EC	700–1000	90
Fenoxaprop-p-ethyl 10% EC	100–120	110
Flumioxazin 50% SC	125	137
Isoproturon 50% WP	1000	–
Isoproturon 75% WP	1000	60
MCPA, amine salt 40% WSC	1000	–
Methabenzthiazuron 70% WP (PE –2DAS)	1050–1400	100
Methabenzthiazuron 70% WP (post –EM 30 DAS)	1050–1750	100
Methabenzthiazuron 70% WP (early POE.16–18 DAS)	700–870	100
Metribuzin 70% WP	350–525	30
Metsulfuron methyl 20% WP	4	80
Metsulfuron methyl 20% WG	4	76

(continued)

Table 2.5 (continued)

Herbicide name	Dosage (g a.i./ha)	Waiting period before harvest (days)
Paraquat dichloride 24% SL (pre-plant (minimum tillage) before sowing)	1000	120–150
Pendimethalin 30% EC	1000–1500	–
Pinoxaden 5.1% EC	40–45	90
Pyoxasulfone 85% w/w WG	127.5	131
Sulfosulfuron 75% WG	25	110
Triallate 50% EC	1250	150
Triasulfuron 20% WG	20	81
Bixlozone 50% + Metribuzin 10% WG	625 + 125 to 750 + 150	120
Carfentrazone ethyl 20% + Sulfosulfuron 25% WG	20 + 25	110
Clodinafop propargyl 15% + Metsulfuron methyl 1% WP	60 + 4	100
Clodinafop propargyl 9% + Metribuzin 20% WP (w/w)	54 + 120	120
Fenoxaprop-p-ethyl 7.77% w/w + Metribuzin 13.6% w/w EC	100 + 175	110
Halauxifen-methyl 1.21% w/w + Fluroxypyr-meptyl 38.9% w/w EC	6.05 + 194.5	87
Halauxifen-methyl 20.8% + Florasulam 20.0% w/w WG (with surfactant polyglycol 26–2 N)	12.76	71
Mesosulfuron methyl 3% + Iodosulfuron methyl sodium 0.6% WG	12 + 2.4	96
Metribuzin 42% + Clodinafop propargyl 12% WG	210 + 60	92
Metsulfuron methyl 10% + Carfentrazone ethyl 40% DF	5 + 20	100
Pendimethalin 35% + Metribuzin 3.5% w/w SE	875 + 87.5 to 1050 + 105	123
Pendimethalin 40% + Metribuzin 8% EC	1000 + 200	107
Sulfosulfuron 75% + Metsulfuron methyl 5%WG	30 + 2	110

Adapted from Anonymous (2025b)

pre-emergence herbicide that effectively controls up to 75% of weed species, including annual grasses (Raju and Tayade 2013). In India, the prevalent practice for weed management involves the application of pre-emergence herbicides, notably pendimethalin, followed by two to three rounds of inter-cultivation. The efficacy of pre-emergence herbicides, especially fluchloralin is optimized when they are incorporated 1–2 inches into moist soil using a blade harrow (*Bakhar*) subsequent to application. Weed management methodologies utilizing these herbicides typically require additional measures, including 2–3 rounds of inter-cultivation for soil aeration at 21-day intervals, along with a hand weeding operation at 30–35 DAS to eliminate any uncontrolled or resistant weed populations. The efficacy of pre-emergence herbicides is substantially enhanced when integrated into a

Table 2.6 Herbicides approved for use in corn in India

Herbicide name	Dosage (g a.i./ha)	Waiting period before harvest (days)
Atrazine 50% WP	500–1000	–
2,4-D Dimethyl amine salt 58% SL	500	50–60
2,4-D Sodium salt technical (having 2,4-D acid 80% w/w) (earlier registered as 80% WP)	1000	120 (pre-em) 90 (post-em)
2,4-D Ethyl Ester 38% EC (having 2,4-D acid 34% w/w)	900	50–60
2,4-D Ethyl Ester 20% WP	900	–
Dicamba 48% w/v SL	360	69
Diuron 80% WP	800	–
Halosulfuron methyl 75% WG	67.5	45
Paraquat dichloride 24% SL [pre-plant (minimum tillage) before sowing]	200–500	90–120
Paraquat dichloride 24% SL (post emergence directed inter row application at 2–3 leaf stage of weeds)	200–500	90–120
Pyroxasulfone 85% w/w WG	127.5	103
Tembotrione 34.4% SC	120	55
Topramezone 336 g/l w/v SC	25.2 to 33.6	83
Tolpyralate 40% (w/v) SC	50	61
Halosulfuron methyl 5% + Atrazine 48% WG	56.25 + 540	37
Mesotrione 2.27% w/w + Atrazine 22.7% w/w SC	875	42
Saflufenacil 68 g/l + Dimethenamid-p 600 g/l EC	68 + 600 to 85 + 750	98
Topramezone 10 g/l + Atrazine 300 g/l SC	775	90
Topramezone 32 g/l + Dimethenamid-p 538 g/l EC	32 + 538	85
Tembotrione 9% + Atrazine 45% WG	135 + 675	81

Adapted from Anonymous (2025b)

comprehensive weed management strategy. For instance, in cotton cultivation, the pre-emergence application of pendimethalin at 1000 g a.i./ha, followed by quizalofop-ethyl at 50 g a.i./ha at the 2–4 leaf stage of weeds and one subsequent hoeing, resulted in a weed control efficiency of 71%. However, the weed-free check exhibited a superior efficiency of 90.3% (Singh et al. 2016).

Generally, pre-emergence herbicides offer superior weed control during the critical initial 30–40 days of cotton growth. However, as the weed seed bank in the soil continues to contribute to subsequent weed flushes, these emerging weeds begin to compete with cotton crop for essential nutrients and soil moisture. In such scenarios, application of post-emergence herbicides not only curtails hand weeding costs but also mitigates potential crop losses. Post-emergence herbicides are predominantly foliage-active and require a minimum of 1–4 h of rain-free weather to ensure optimal efficacy. These herbicides have increasingly gained the trust of farmers, particularly in recent normal and wet seasons. Commonly used herbicides in cotton include graminicides such as quizalofop ethyl, fenoxaprop methyl, and

Table 2.7 Herbicides recommended for various pulses

Herbicide common name	Pulse crop	Dose (g a.i./ha)	Waiting period before harvest (days)
Pendimethalin 30% EC	Soybean	750–1000	110
	Pigeon pea	700–1000	133
Pendimethalin 38.7% CS	Soybean	580.5–677.25	40
Pendimethalin 30% + Imazethapyr 2% EC	Soybean	750 + 50 to 900 + 60	90
Metribuzin 70% WP	Soybean	350–525	30
Imazethapyr 10% SL	Soybean	75–100	72
	Black gram	75	56
	Green gram	75	46
	Pigeon pea	75	125
Imazethapyr 70% WG + Surfactant	Soybean	70	56
Clodinafop-propargyl 12.5% EC	Green gram	125	75
Metolachlor 50% EC	Soybean	1000	–
Pyroxasulfone 85% w/w WG	Soybean	127.5	94
Quizalofop ethyl 5% EC	Soybean	37.5–50.0	95
	Black gram		52
Quizalofop ethyl 10% EC	Soybean	37.5–45.0	69–103
Quizalofop-p-tefuryl 4.41% EC	Soybean	30–40	30
Quizalofop ethyl 10% EC + Chlorimuron ethyl 25% WP + Surfactant (twin pack)	Soybean	37.5 + 9	75
Quizalofop ethyl 7.5% + Imazethapyr 15% w/w EC	Soybean	32.81 + 65.625	75
Sulfentrazone 39.6% w/w SC	Soybean	360	88
Fenoxaprop-p-ethyl 6% + Chlorimuron ethyl 0.9% + Imazethapyr 10% SC	Soybean	60 + 9 + 100	64
Fluthiacet-methyl 2.5% + Quizalofop-ethyl 10% EC	Soybean	12.5 + 50	67
Fluazifop-p-butyl 11.1% w/w + Fomesafen 11.1% w/w SL	Soybean	250	71
Fomesafen 12.5% + Fenoxaprop-p-ethyl 10% + Chlorimuron ethyl 0.9% ME	Soybean	125 + 100 + 9	78
Fomesafen 12% + Quizalofop ethyl 3% w/w SC	Soybean	180 + 45	71
Fomesafen 12.5% + Quizalofop ethyl 4.68% EC	Soybean	125 + 46.8	77
Fomesafen 17.5% + Clodinafop-propargyl 12.5% w/w ME	Soybean	175 + 125	101
	Green gram		83
Fomesafen 16.8% w/w + Propaquizafop 5.2% w/w ME	Black gram	210 + 65	51
	Green gram		46

(continued)

Table 2.7 (continued)

Herbicide common name	Pulse crop	Dose (g a.i./ha)	Waiting period before harvest (days)
Haloxypfop-R methyl 12.8% + Imazethapyr 10% (w/w) ME	Soybean	105.6 + 82.5	88
Propaquizafop 10% EC	Soybean	50–75	21
	Black gram	75–100	21
Propaquizafop 2.5% + imazethapyr 3.75% w/w ME	Soybean	50 + 75	80
	Black gram		56
	Clusterbean		69
Imazethapyr 35% + imazamox 35% WG	Soybean	70	56
	Clusterbean		64
	Pigeon pea		125
Sodium aciflurofen 16.5% + clodinafop propargyl 8% EC	Soybean	165 + 80	61
	Black gram		54
	Green gram		54
Diclosulam 0.9% + pendimethalin 35% SE	Soybean	22.5 + 875	107
Bentazone 480 g/l SL	Soybean	960	62
Chlorimuron ethyl 25% WP + Surfactant	Soybean	9	45
Clethodim 25% w/w (240 g/L) EC	Soybean	120–180	62
Clomazone 50% EC	Soybean	750–1000	90
Diclosulam 84% WDG	Soybean	22–26	60
Ethalfuralin 35.65% w/w EC (36% EC)	Soybean	720	107
Fenoxaprop-p-ethyl 9.3% w/w EC (9% w/v)	Soybean	100	100
	Black gram	56.25–67.5 g	43
Fluazifop-p-butyl 13.4% EC	Soybean	125–250	90
Fluchloralin 45% EC	Soybean	1000–1500	120–150
Flumioxazin 50% SC	Soybean	125	110
Fluthiacet methyl 10.3% EC	Soybean	13.6	73
Haloxypfop R methyl 10.5% w/w EC	Soybean	108–135	60
	Black gram	108	60
Sulfentrazone 28% + Clomazone 30% WP	Soybean	350 + 375	84

Adapted from Anonymous (2025b)

propaquizafop (Singh et al. 2016; Rao 2018). Notably, pyrithiobac sodium, an early post-emergence herbicide with both soil and foliar activity, demonstrates significant efficacy in controlling *E. hirta*, *C. argentea*, and various other grasses, achieving over 75% weed control even under challenging wet monsoon conditions.

In sugarcane, many pre-emergence herbicides such as atrazine, metribuzin, ametryn, diuron, oxyfluorfen, oxadiazon, and pendimethalin have been found to be useful for controlling weeds up to 45–90 days after planting (Patel et al. 2024, Table 2.9). Pre-emergence herbicides must be applied on the soil surface as a blanket spray within 3–4 days of planting. In intercropped sugarcane, chemical weed control is

Table 2.8 Herbicides approved for use in in cotton in India

Herbicide name	Dosage (g a.i./ha)	Waiting period before harvest (days)
Clethodim 13% w/w EC (clethodim 12% w/v EC)	120	135
Diuron 80% WP	750–1500	–
Ethalfuralin 35.65% w/w EC (36% EC)	720	107
Fenoxaprop-p-ethyl 9.3% w/w EC (9% w/v)	67.5	87
Fluazifop-p-butyl 13.4% EC	167	104
Fluchloralin 45% EC	900–1200	180
Glufosinate ammonium 13.5% SL (15% w/v)	375–450	96
Haloxyfop R methyl 10.5% w/w EC	108	86
Paraquat dichloride 24% SL	300–500	150–180
Pendimethalin 30% EC	750–1250	150
Pendimethalin 38.7% CS	580.5–677.25	101
Propaquizafop 10% EC	62.5	115
Pyrithiobac sodium 10% EC	62.5–75	160
Quizalofop-ethyl 5% EC	50.5	94
Pyrithiobac sodium 3.1% w/w + pendimethalin 34.0% w/w ZC	649.25–742	152
Pyrithiobac sodium 6% w/w + Quizalofop-ethyl 4% w/w EC	60 + 40 to 75 + 50	160

Adapted from Anonymous (2025b)

not employed, as most of the intercrops are sensitive to pre-emergence herbicides. In such conditions, pendimethalin (1500 g a.i./ha) can be used as a pre-emergence herbicide (Singh and Lal 2008). However, weeds need to be controlled either through interculture or use of post-emergence herbicides in sugarcane as it is a long duration crop. Post-emergence herbicides such as halosulfuron and 2,4-D are commonly used in sugarcane. Nonselective herbicides such as paraquat, glyphosate, and glufosinate are used for controlling weeds in the inter-row spaces as directed spray in sugarcane and cotton, and the protective hood is used to stop herbicide fluid from falling on the crop stems and leaves (Singh and Kaur 2004). Alternatively, use of topramezone 33.6 g a.i./ha in combination with atrazine 900 g a.i./ha provided excellent control of *C. dactylon* and other broadleaved weeds (Ducca et al. 2020). Application of ethoxysulfuron 15% WG at 60 g a.i./ha effectively controlled *C. rotundus* and some broad-leaved weeds such as *Trianthema* spp., *Digera arvensis*, *Cleome viscosa* L. and *Ipomoea* spp. in sugarcane (Singh et al. 2014). Application of halosulfuron methyl 75% WG at 90 g a.i./ha as foliar spray at 45 DAS was effective for the control of *C. rotundus* in sugarcane without any adverse effects on succeeding black gram crop (Chand et al. 2014). Pre-emergence application of sulfentrazone at 1200 g a.i./ha efficiently killed *C. rotundus* tubers with subsequent reductions in the number of viable tubers (Singh et al. 2018).

In long-duration crops such as cotton and sugarcane, sequential application of herbicides is a requirement for sustainable weed control. Sequential application of atrazine or metribuzin or diuron followed by post emergence application of 2,4-D

Table 2.9 Herbicides approved for use in sugarcane in India

Herbicide name	Dosage (g a.i./ha)	Waiting period before harvest (days)
Ametryn 80% WDG	2000	311
Atrazine 50% WP	500–2000	–
Metribuzin 70% WP	1050–2000	60
Metribuzin 70%WG	1400–2000	309
Clomazone 50% EC	750–1000	296
Halosulfuron methyl 75% WG	60–67.5	294
Sulfentrazone 39.6% w/w SC	720	306
2,4-D Dimethyl amine salt 58% SL	3500	–
2,4-D Na salt technical (with 2,4-D acid 80% w/w)	2000–2600	300
2,4-D Ethyl Ester 38% EC (with 2,4-D acid 34% w/w)	1200–1800	300–330
Diuron 80% WP	1600–3200	–
Metsulfuron methyl 20% WP	6	346
2,4-D Sodium salt 48% + metribuzin 32% + Chlorimuron ethyl 0.85% WDG	2020	315
2,4-D sodium salt 44% + metribuzin 35% + Pyrazosulfuron ethyl 1.0% WDG	1320 + 1050 + 30	249
Ametryn 73.1% w/w + Trifloxysulfuron sodium 1.8% w/w WG	937.5–1125	221
Clomazone 22.5% w/w + metribuzin 21% w/w WP	563 + 525	307
Hexazinone 13.2% + Diuron 46.8% WP	264 + 936	282–306
Mesotrione 2.27% w/w + Atrazine 22.7% w/w SC	875	190
Sulfentrazone 28% + clomazone 30% WP	700 + 750	302
Topramezone 10 g/l + atrazine 300 g/l SC	930	268
Halosulfuron methyl 6% + metribuzin 50%WG	67.5 + 562.5	247
Halosulfuron methyl 12% w/w + Metribuzin 55% WG	54 + 247.5	294
Mesotrione 2.27% w/w + Atrazine 22.7% w/w SC	875	190
Metribuzin 16.8% + 2,4-D Sodium salt 56% WP	525 + 1750	308
Sulfentrazone 28% + Clomazone 30% WP	700 + 750	302
Topramezone 10 g/l + Atrazine 300 g/l SC	930	268

Adapted from Anonymous (2025b)

amine provided the most effective control of *Ipomoea* spp. in Punjab, India (Bhullar et al. 2012). Application of metribuzin at 1250 g a.i./ha + 2,4-D at 1500 g a.i./ha, effectively controlled *Ipomoea* when it is at 45 cm in Lucknow, India (Singh et al. 2018). To control *Striga* after emergence but before it flowers, 2,4-D Na salt can be applied at 1000 g a.i./ha as a directed spray and spray should be repeated two or three times with 15 days intervals. Pendimethalin at 2000 g a.i./ha when applied as a directed spray just before the second irrigation within sugarcane rows after full earthing up may control *Striga* at the emergence stage. Chemical control of *R.*

cochinchinensis is difficult as it is resistant to many herbicide groups like triazines (atrazine) and triazinones (metribuzin). The directed post-emergence application of paraquat and ametryn reduced infestation of *R. cochinchinensis* in sugarcane (Anusha et al. 2023). Clomazone, a triketone, is recommended to control *R. cochinchinensis* infestation in sugarcane both as pre-planting and pre-emergence after planting (Tropaldi et al. 2021).

Integrated Weed Management Traditional weed management methods can be both costly and labor-intensive and herbicides applied at sowing typically do not provide enduring weed control. IWM involves combination of different weed management methods along with agronomic practices (Harker and O'Donovan 2013). The reliance on one weed control technique for controlling weeds is reduced by following stewardship guidelines, and thus its effectiveness is being maintained. The objective of IWM is to maintain weed within manageable limits while taking care of weed shifts and evolution of herbicide resistance. Effective IWM strategies include crop rotation, stale/false seedbed, mulching, cover cropping, competitive cultivars, cropping density, geometry, and time of sowing along with judicious use of herbicides (Kaur et al. 2022).

The periodic weed survey/surveillance showed that the predominance of weeds keeps on shifting from one weed to another weed mainly due to adoption of improved agronomic practices like changes in cropping systems, better irrigation facilities, fertilizer application, sowing time, crop cultivars, and particularly weed management/herbicide use (Hamill et al. 2004). Therefore, weed survey/surveillance in any crop gives an insight into the extent of weed problems and knowledge of associated weed composition, which helps in devising weed management practices before it takes alarming proportions. Continuous application of a particular cropping practice can contribute inadvertently to a shift in dominance and distribution of weeds (Harker and O'Donovan 2013). Weeds readily adapt to practices that are continuously practiced due to selection pressure and weed hardiness. For example, continuous use of herbicides with the same mode of action imposes selection pressure, and there is faster evolution of herbicide resistance in weeds. Therefore, there should be integration of weed management tactics in conservation agriculture systems to prevent over-reliance on herbicides (Chauhan et al. 2012; Singh et al. 2024b). In formulating a weed management program, it is important to systematically manipulate recommended production practices in synchronization with the current location-specific farming activities. A better understanding of the mechanisms of interaction between the different species in an agricultural field population can lead to more effective weed management practices.

Effective weed control is crucial for achieving profitability in cotton cultivation, particularly during the early stages of growth when weeds pose the greatest competition. Pendimethalin application can maintain a weed-free status for 30–40 days; however, if weather conditions allow, hoeing can be performed subsequently, or alternative chemical methods should be utilized in its absence. This holistic strategy not only enhances crop productivity but also ensures effective weed management. Reddy et al. (2023) demonstrated that applying pendimethalin 38.7% CS at 750 g

a.i./ha as a pre-emergence treatment, followed by pyriithiobac sodium 10 EC at 100 g a.i./ha and quizalofop ethyl 5 EC at 50 g a.i./ha as post-emergence treatments at 25 DAS, coupled with inter-cultivation at 55–60 DAS, proved highly effective in controlling weeds and resulted in increased seed cotton yield. For efficient and cost-effective weed management in irrigated cotton, it is recommended to apply pendimethalin at 1000 g a.i./ha as a pre-emergence treatment, followed by one hand weeding at 35–40 DAS and a mixture of pyriithiobac sodium 50 g a.i./ha with quizalofop ethyl 50 g a.i./ha at 60 DAS (Nalayini et al. 2012).

It is very important and necessary to use a combination of different methods, including different herbicides at different times along with mechanical weeding, to effectively control weeds and maximize corn yield. Applying half of the total recommended dose of atrazine as a pre-emergence herbicide, followed by hand weeding at 28 DAS, led to a significant improvement in corn yield by effectively reducing weed infestation compared to the sole application of herbicide at its full recommended dose (Pandey et al. 2002). Ramachandran et al. (2012) observed that a combination of alachlor at 1000 g a.i./ha applied as pre-emergence along with brown manuring resulted in superior yield attributes and the highest grain and stover yield. Further, pre-emergence application of atrazine 1000 g a.i./ha on the third day after planting + hand weeding on 45th day after planting and earthing up on the 60 days after planting combined with post-emergence spraying of 0.5% 2,4-D sodium salt (5 g/l) + 2% urea (20 g/l) on the 90th day after planting is recommended for complete control of *Striga asiatica* in sugarcane.

Seed predation by granivore fauna, including ants and other insects, presents a promising tool for weed management, particularly in zero-till systems where weed seeds accumulate on the soil surface (Chauhan et al. 2012). Encouraging weed seed predators by retaining crop residues in fields can be an effective and cost-efficient approach. These environmentally friendly methods can complement existing weed control practices as part of an integrated weed management (IWM) strategy. However, the abundance of natural enemies needed for effective weed control may be limited in specific agricultural situations.

Unmanned aerial vehicles (UAVs) equipped with various sensors such as optical, multispectral, and hyperspectral play a crucial role in precision agriculture by enabling accurate weed mapping and targeted herbicide application. In addition to UAVs, autonomous laser weeding represents a cutting-edge approach for in-field weed control. Andreasen et al. (2022) describe how these systems utilize artificial intelligence and deep learning to target and destroy weeds with laser beams, achieving significant reductions in weed populations. Laser robots, such as the Laser Weeder, can eliminate up to 200,000 weeds per h, making them highly effective in large-scale operations (Papadopoulos 2022). These technologies not only improve weed management efficiency but also minimize herbicide use, thus reducing environmental impact and preserving biodiversity. Overall, the integration of UAVs and laser weeding into mechanical weed management strategies offers promising advancements for pulse crop cultivation, enhancing both precision and sustainability.

2.6 Conclusions

This chapter elaborates the critical importance of addressing weed challenges to sustain agricultural productivity and ensure food security in India. Weeds, with their diverse species and adaptive strategies, pose significant economic threats, leading to substantial yield losses if left uncontrolled. Therefore, a broader understanding of the influence of chemical and non-chemical weed control treatments on weed population dynamics enables the better prediction of ecological changes. Inter-cultivation has been employed as a weed control strategy, but weather variability and heavy rains often hinder timely weed control. Further, herbicide use in India is only 16% of the total pesticide use compared to 52% use of herbicide on a global scale. Still, there are reports of seven unique cases of herbicide-resistant weeds in rice and wheat crops in India. Weeds must be exposed to constantly changing management methods by exploiting IWM practices to keep them “off balance.” Through a comprehensive exploration of preventive, cultural, mechanical, chemical, and biological management strategies tailored to different crops, this chapter emphasizes the necessity of an integrated approach to weed management. By empowering farmers with knowledge and tools for effective weed control, we can mitigate yield losses, optimize crop productivity, reduce production costs, and promote sustainable agricultural practices that safeguard the future of Indian agriculture.

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