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REVIEW ARTICLE

Weed management in pulse crops: Challenges and opportunities

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ABSTRACT

Pulses are known for their role in nutritional security, and sustainability of agricultural production systems and agro-ecology. It is a main source of protein to the vegetarian population of the country. India is the largest producer, consumer and importer of pulses. But, the productivity of pulses in India is far below than several countries of the world. The low productivity of pulses in India is mainly due to several biotic and abiotic factors among which weeds are major ones since they severely affect the pulse crops yield. An estimate shows yield losses due to weeds are more than any other pests. The intensity and diversity of weed flora in pulses depends on climatic, edaphic and crop management practices. It has been observed that sedges population in cereal-cereal systems can be minimized through diversification or intensification of cropping systems with pulse crops as components. In addition, most of the pulses are grown as rainfed crops with no or minimal inputs and inadequate weed management. Limited attention was paid in the past by researchers also on development of effective strategies to manage weeds in pulses. Only a few herbicides are registered in India for use in pulses and most of the weed management recommendations in pulses are of pre-emergence herbicide application followed by manual weeding. But, due to shortage of labor for intercultural operations, the need was recognized for development of alternate methods involving post-emergence herbicides too for effective weed management in pulses. The conservation agriculture (CA) adopted acreage is increasing in India with a focus on inclusion of pulses in crop diversification component of CA. Hence, there is need to develop long-term strategies of weed management by inclusion of modern technologies in pulse crops.

Keywords: Allelopathy, Conservation agriculture, Crop-weed competition, Herbicide resistance, Integrated weed management, Soil solarization

INTRODUCTION

Pulses play major role in meeting the global nutrition security. In view of the significance of pulses and to promote the pulses production across the world, United Nations declared the year 2016 as 'International year of Pulses' and 10th February of every year as 'World Pulses Day'. Pulses are an important component of Indian agricultural economy and are next to cereals and oilseeds in terms of acreage, production and economic value. Pulses are an integral part of vegetarian diet of a large population in India. Besides being a rich source of proteins and essential amino acids; they also maintain soil fertility through biological nitrogen fixation in symbiotic association with *Rhizobium* bacteria present in their root nodules. Thus, pulses play a vital role as nitrogen fixing mini-factories, which help in sustaining crop productivity and soil health. Pulses are rich sources of protein and energy but in India, pulses are mostly cultivated under natural resources poor conditions on marginal and sub-marginal lands with more than three-fourth of the area under pulses is rainfed resulting in poor crop productivity.

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India is the largest producer of pulses in the world, with 25% share in the global production. The important pulse crops are chickpea (*Cicer arietinum*), pigeonpea (*Cajanus cajan*), greengram (*Vigna radiata*), blackgram (*Vigna mungo*), field pea (*Pisum sativum*), lentil (*Lens culinaris* ssp. *Culinaris*), cowpea (*V. unguiculata*), lathyrus (*Lathyrus sativus*), frenchbean (*Phaseolus vulgaris*), horsegram (*Macrotyloma uniflorum*) and mothbean (*V. aconitifolium*). In India, production of pulses is around 25.72 million tons with a very low average productivity of 0.892 t/ha (2020-21). Currently, total area under pulses is 828.83 million ha. Among the pulse crops grown in India, chickpea is a leading pulse crop which is grown in 9.85 million ha with annual production of 11.99 million tons registering an average productivity of 1.217 t/ha (2020-21). The productivity of pulses is low due to several factors. In adequate management of weeds is one of the major factors affecting yield of pulses adversely as weeds potentially reduce the pulse crop yield up to 90% (IIPR 2010, Mishra *et al.* 2016). The degree of reduction of yield depends on the density and duration of weed species and fertility status of soil.

Global scenario of pulses area and production

Pulses occupy 96.7 Mha area with total production of 94.9 Mt with an average yield of 0.982 t/ha in the world in 2018. India, Canada, Myanmar, China, Brazil, Ethiopia and Australia are the major pulse producing countries with relative share of 26.7%,6.7%, 6.5%, 5.3%, 3.1, 2.9% and 2.1%, respectively (FAOSTAT 2020). India is the largest producer and consumer of pulses in the world contributing around 24-28% of the total global production. As per FAOSTAT (2020), India's share in the area and production of total pulses in the world is 37.6 and 26.7%, respectively. India along with other developing nations together contributes more than three-fourth of world's pulses production. Canada is the second most important country which contributes 6.6% in global pulses production.

Indian scenario of pulses area and production

During 2010-11 to 2020-21, considerable increase in area (9.20%), production (41.01%) and yield (29.09%) was recorded in pulses that have led to the country's self-sufficiency in pulses production and demand (**Figure 1**). The maximum gain in area (2.6 Mha) and production (3.7 Mt) was recorded in chickpea. Blackgram was the second most important pulse crop with 37.1% gain in area and 95.8% in production followed by greengram with 36.2 and 92.0% increase in area and production, respectively. The considerable gain in area (31.1%) and production (74.4%) occurred with pigeonpea (DAC 2021). The major pulses producing states in India are Madhya Pradesh, Rajasthan, Maharashtra, Uttar Pradesh, Karnataka, Gujarat and Andhra Pradesh which together contribute about 80% of Indian pulse production (**Table 1**). Chickpea continues to be the largest contributor with 46.2% of the total pulses production from 34.2% pulses area with average productivity of 1.217 t/ha (2020-21). Pigeonpea is the second most important pulse crop with total production of 4.28 Mt from 4.8 Mha area and

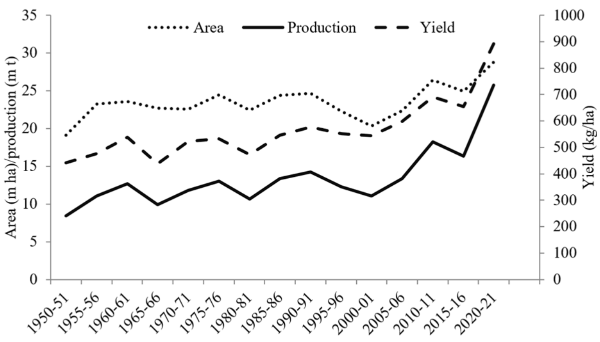

Figure 1. Area, production and yield trend of total pulses in India

Table 1. Per cent share of major states in area and production of pulses in India (2020-21)

State	Per cent share	
	Area	Production
Madhya Pradesh	16.95	20.60
Rajasthan	21.32	16.75
Maharashtra	15.49	16.71
Uttar Pradesh	8.24	9.97
Karnataka	10.82	8.25
Gujarat	4.80	6.86
Andhra Pradesh	4.31	4.22
Jharkhand	2.99	3.64
Others	15.07	12.98
All India	100.00	100.00

productivity of 0.892 t/ha. Maximum growth rate per annum of total pulses in India in area (2.97%), production (6.46%) and productivity (2.70%) was recorded during decade period of 2000-01 to 2010-11. After independence during 1951, pulses availability in the country was 60.7 g/person/day or 22.2 kg/person/yr, which reached to all time high of 69.0 g/person/day during 1961. Thereafter, as a result of stagnant pulse production and continuous increase in population, the per capita availability of pulses decreased considerably and reached all-time low of 30 g/person/day during 2001. The availability of pulses remained 40-43 g/person/day up to 2016. With the increase in pulses production in the country during 2017 onward, further increase in availability of pulses was observed and it reached to 54.8 g/person/day in the year of 2018. It is also expected that the availability of pulses will further increase with time.

WEEDS MENACE IN PULSES

One of the major problems encountered in the successful cultivation of pulses is the heavy infestation of weeds. Weeds are most adopted with prolific seed production abilities and efficient seed dispersal mechanisms (Das 2008). Weeds affect farm production by reducing yield and quality of crop produce (food, fibre, oil, fodder/forage) and animal products (wool, meat, milk) by sheltering crop pests and diseases and increasing the cost of cultivation and processing (Zimdahl 2013; Yaduraju *et al.* 2015). Weeds compete with pulses for moisture, space, light and nutrients that limit the pulses growth and drastically reduce their yield. The extent of loss depends upon nature and intensity of weeds and weed species, soil fertility, cultivars, density of the crop and duration for which weeds compete with the crop. Weed management is often the costliest agronomic input. Hence, economically viable crop production and sustainable farm income largely depend on weed management (Das *et al.* 2012; Nath *et al.* 2017, Rao *et al.* 2020). All weed control methods such as manual and mechanical, cultural, biological, chemical have inherent limitations. Single method could hardly provide desired level of weed control efficacy (Das 2008; Rao and Chauhan 2015; Yaduraju *et al.* 2015). Among these methods, herbicide is proven easier to apply, more efficient and cost-effective tool for weed management in diverse agro-ecosystems. Since its introduction, herbicide has been the major strategy for weed control in the developed countries, where it has revolutionized agriculture (Gianessi 2013).

Common weed flora in pulses

Intensity of weed infestation in pulses varies with the agro-ecological condition and cultural practices followed. The reduction in growth and yield depends on the kind of weed flora and their infestation in the field. Various types of weed flora including narrow-leaf (mono-cots, grasses), broad-leaf (dicots) and sedges are found in different pulse crops. *Celosia argentea, Cleome viscosa, Commelina benghalensis, Cucumis trigonus, Cynodon dactylon, Cyperus rotundus, Echinochloa colona, Echinochloa crusgalli, Eleusine indica, Lapidium sativum, Medicago denticulate, Phylanthus niruri, Physalis minima, Sorghum halepense, Trianthema monogyna, Triathema portulacastrum, Vicia sativa* were the problematic weeds reported in blackgram *(*Chandrashekharan 1998; Chand *et al.* 2004; Bhandari *et al.* 2004, Kumar and Tewari 2004). The weed flora in north-western region is different than the southern region. Kumar *et al.* (2015) reported *Cyperus rotundus*, *Anagallis arvensis*, *Chenopodium album*, *Polygonum plebejum*, *Phalaris minor* and *Cyperus rotundus* as the most dominant weeds in chickpea.

Seasonal variation in weed flora was observed. The summer sown greengram was dominated by *Cyperus* spp. *Triathema portulacastrum* and *Eragrostis tenella* (Kaur *et al.* (2010). In the rainy season, carpet weed (*Trianthema portulacastrum* L.) grows profusely in semi-arid regions. It is also a major weed in summer pulses in Indo-Gangetic Plains. Day flower (*Commelina benghalensis* L. and false amaranth [*Digera muricata* (L.) Mart.] are of secondary importance. *Echinochloa colona* (L.) Link, *makra* [*Dactyloctenium aegyptium* (L.) Willd.], *Digitaria sanguinalis* Scop. and guinea grass (*Panicum maximum* Jacq.) are the major grassy weeds which invade the crops heavily during the rainy season. Nut grass (*Cyperus rotundus* L.) is most common in the summer and rainy season, and offers the rhizospheric competition through its chain of underground tubers. Kans (*Saccharum spontaneum* L.) and Johnson grass [*Sorghum halepense* (L.) Pers.] are perennial grasses, which reproduce through underground rhizomes. Quail grass (*Celosia argentea* L.) occurs in the rainy season pulses in light textured soils of northern and Bundelkhand regions, and heavy soils of central and southern parts of the country. In winter season, lamb's quarters (*Chenopodium album* L.), scarlet pimpernel (*Anagallis arvensis* L.) and *Fumaria parviflora* Lam. are found in irrigated as well as in rainfed pulses. *Asphodelus tenuifolius* L. emerges in different flushes and poses problem in rainfed chickpea and lentil throughout northern and central India under light soils (Kumar 2013; Kumar *et al.* 2016a). Wild safflower (*Carthamus oxyacantha* M. Bieb.) and prickly poppy (*Argemone maxicana* L.) are troublesome weeds in field pea and other winter pulses, as harvesting and threshing becomes difficult due to their spiny nature. Similarly, deer's foot (*Convolvulus arvensis* L.) binds the plants of chickpea, pea and lentil in northern and central India and renders harvesting difficult (Kumar and Yadav 2013). Small canary grass (*Phalaris minor* Retz.) and *Avena fatua* L. are the major grassy weeds in winter pulses growing in irrigated condition. Common vetch (*Vicia sativa* L.) has emerged as a major weed in rainfed winter pulses in Bundelkhand region of Uttar Pradesh and Madhya Pradesh. Similarly, *Lepidium didymium* L.; syn. *Coronopus didymus* L. is becoming serious in winter pulses in many parts of India due to its resistance against almost all herbicides and fast spreading nature due to production of a large number of minute seeds.

Losses caused by weeds in pulses

Weeds cause significant yield loss in major crops by around 34% across the globe (Oerke 2006). In India, the annual economic loss in 10 major field crops in 18 States of India could be USD 11.0 billion (approx.) due to weeds (Gharde *et al.* 2018). The reported reduction in blackgram grain yield due to uncontrolled weeds varied with the location and it was 45.2% in Amritsar, Punjab (Bhandari *et al.* 2004), 40.1% in Kanpur, Uttar Pradesh (Kumar and Tewari 2004), 29.0% in Palampur, Himachal Pradesh) (Kumar and Angiras 2005), 43% in Bapatla, Andhra Pradesh) (Begum and Rao 2006). Singh *et al.* (1995) indicated from Jabalpur that weed caused 42% reduction of grain yield of greengram. Productivity of pigeonpea + sorghum intercropping was affected more due to narrow-leaf weeds and sedges than dicot weeds (IIPR 2009).

WEED MANAGEMENT WITH HERBICIDES IN PULSES

Weed management using herbicides is gaining popularity amongst farmers due to scarcity of labor for weeding on time and enhanced cost of limited labor which is making manual weeding expensive in addition to its less performance efficiency under adverse soil and weather condition. The availability of low-dose, high potency, non-residual, broad-spectrum herbicides have provided great opportunity to accomplish effective weed control at much lower cost than mechanical methods. Therefore, herbicides are being preferred as an alternative of manual or mechanical weeding. The efficiency of these herbicides depends largely on their nature and agro-climatic conditions in which they are used. Many herbicides have been tested and recommended for weed control in pulses as pre-emergence or pre-plant incorporation.

Pendimethalin is the most popular herbicide used in all pulse crops. However, it is not effective in controlling all kinds of weeds for long periods. For season long weed management, pre-emergence herbicide pendimethalin + manual weeding at 30-35 days after sowing is commonly recommended in chickpea, but its use is decreasing because of labour scarcity at critical time of weeding and increasing cost (Kumar 2010; Kumar *et al.* 2013). Post-emergence application (PoE) of imazethapyr, broad spectrum herbicide, has been recommended for use in rainy-season pulses like pigeonpea, blackgram and greengram. However, in winter-season pulses like chickpea, lentil and fieldpea, it has shown toxicity even at lower dose of 15 g/ha (Kumar *et al.* 2013). Clodinafop PoE and quizalofop-ethyl PoE can also be used in most pulse crops, if only the grassy weeds are predominant in the field. Research is underway to develop imazethapyr and metribuzin-tolerant chickpea (Gaur *et al.* 2013; Chaturvedi *et al.* 2014), and lentil and field pea (Parihar *et al.* 2016). Some of the commonly used herbicides in pulses and their time of application are listed in **Table 2**.

Present status of post-emergence herbicides in pulses

A few post-emergence herbicides such as clodinafop-propargyl + sodium-acifluorfen in soybean (*Glycine max* L. Merr.) (Jha *et al.* 2014) are recommended for effective weed control. Clodinafop-propargyl + sodium-acifluorfen is a ready-mix herbicide with acetyl-CoA carboxylase and protoporphyrinogen oxidase inhibitors. It causes inhibition of fatty acid and pigment biosynthesis (Das 2008). It is rapidly metabolized by the soybean to non-active substances and is effective for broad-spectrum weed control (Jha *et al.* 2014) and resulted in effective weed control and higher grain yield of soybean (Meena *et al.* 2022) and blackgram (*Vigna mungo* (L.) Hepper) (Thimmegowda *et al.* 2022). The clodinafop-propargyl + sodium-acifluorfen minimized total weed density and biomass more than pendimethalin - quizalofop.

Broad-spectrum control of weeds and reduced weed biomass with clodinafop-propargyl + sodium-acifluorfen resulted in higher plant dry weight and seed yield. The studies are limited on the selectivity and efficacy of clodinafop-propargyl + sodium-acifluorfen in greengram (Maji *et al.* 2020).

Quizalofop-ethyl, clodinafop-propagyl, imazethapyr, topramezone, imazethapyr + imazamox (ready-mix) and clodinafop-propagyl + Na-acifluorfen (ready-mix) are new generation post-emergence herbicides used in many crops. These

Table 2. Herbicides recommended for greengram, blackgram, pigeonpea, chickpea, lentil and fieldpea

Herbicide	Dose (g/ha)	Product (g or ml/ha)	Application time	Crops	Remarks
Alachlor	2000-2500	4000-5000	0-3 DAS	greengram, blackgram and pigeonpea	AG and some BLWs
Topramezone	20.6-26.7	60-75	14-21 DAS	Chickpea	BLWs
Metolachlor	1000-1500	2000-3000	0-3 DAS	Chickpea, lentil and fieldpea	AG and some BLWs
Metribuzin (in peas)	250	350	0-3 DAS or 15-20 DAS	fieldpea	AG, some BLWs and sedges
Oxadiazon	250	1000	0-3 DAS	greengram, blackgram and pigeonpea	BSW
Oxyfluorfen	100-125	400-500	0-3 DAS	greengram, blackgram and pigeonpea, peas	BSW
Pendimethalin	750-1000	2500-3000	0-3 DAS	greengram, blackgram and pigeonpea	AG and some BLWs
Quizalofop-ethyl	50 -100	1000-2000	15-20 DAS	100 g/ha: greengram, blackgram and pigeonpea; 50 -100 g/ha: chickpea, lentil and fieldpea	AG
Imazethapyr	50-100	500-1000	20-25 DAS	greengram, blackgram and pigeonpea	BSW
Pendimethalin (PI) *fb* Imazethapyr (PoE)	1250 *fb* 100	4170 *fb* 1000	0-3 (PI) *fb* 20-25 (PoE) DAS	green gram, blackgram and pigeonpea; chickpea, lentil and fieldpea	BSW

Source: Dixit and Varshney (2009); modified by authors with suitable options., AG = Annual grasses; BLWs = broad-leaved weeds; BSW= Broad spectrum weeds; DAS = days after seeding; PI = Preplant incorporation; PoE = Post emergence application; *fb* = followed by herbicides provide broad spectrum of weeds control, flexibility in application time, low usage rates and low mammalian toxicity. However, till date no systematic study was conducted to see the efficacy of these post-emergence herbicides in chickpea. Clodinafop-propargyl + sodium-acifluorfen could lead to increased weed control and grain yield of crops such as soybean, groundnut, and blackgram in India. The studies conducted in the diversified agro-ecologies that include the soil orders Vertisol, Alfisol, and Inceptisol (Hanumanthappa *et al.* 2021; Meena *et al.* 2022; Thimmegowda *et al.* 2022) indicated that clodinafop-propargyl + sodium-acifluorfen has the potential to enhance weed control efficacy and greengram yields across regions. A few herbicides with higher selection pressure on weeds reduce the species richness and increase the risk of resistance development in a production system (Rao 2018). In this line, over-reliance on imazethapyr in greengram could reduce bio-efficacy and fasten the resistance development (Gaur *et al.* 2013). Rotation of herbicides and herbicides mixture are effective strategies to delay the resistance development in weeds (Neve *et al.* 2014). Hence, clodinafop-propargyl + sodium-acifluorfen can be effectively utilized for future research for its adoption and selectivity across the agro-ecologies in greengram.

Chickpea is severely affected by weeds because of its slow initial growth (upto 45 DAS) and less ground cover (Khope *et al.* 2011, Bolat *et al.* 2019). The weed management in chickpea with post emergence application of quizalofop-ethyl, imazethapyr and chlorimuron ethyl was studied and quizalofop-ethyl was found effective for weed control in chickpea (Kumar *et al.* 2015). Quizalofop-p-ethyl 100 g/ha (Kumar *et al.* 2015) and fenoxaprop-p-ethyl 100 g/ha (Ansar *et al.* 2010) are recommended in chickpea to control grass weeds, but the dominant broad-leaved weeds such as *Medicago polymorpha* L., *Vicia sativa* L., *Convolvulus arvensis* L., *Chenopodium album* L., *Melilotus indicus* (L.) All. and *Rumex dentatus* L. cause severe yield loss in chickpea (Nath *et al.* 2018). Thus, there is an urgent need to investigate the selectivity of different POST herbicides for their broad-spectrum activities in chickpea to minimize the yield loss and higher weed control efficiency. In this line, topramezone could be effective in chickpea under the rice fallow region for higher WCE and crop yield (Nath *et al.* 2021). Topramezone is a new herbicide for post-emergence control of broad-leaved and grass weeds in maize (Gitsopoulos *et al.* 2010). Its recurrent and residual effects were tested in soybean, groundnut (*Arachis hypogaea* L.) and beans in Zambia. Phytotoxicity of topramezone on these legumes varied at different application rates (0, 1.0, 2.0 and 4.0 L/ha). The recommended herbicide rate of topramezone showed moderate toxic effect compared to the overdosed r ate of 4 L/ha (Siabusu *et al.* 2020). Neve and Powles (2005) demonstrated that by repeatedly using reduced herbicide rates, resistant weed populations increased more compared to when a full, recommended rate of the herbicide was used. Therefore, judicious use of herbicides is essential to ensure proper selectivity, weed control, crop growth, yield and environmental safety. A study conducted during 2015–2016 at ICAR-Directorate of Weed Research (DWR), Jabalpur (Annual Report (Bilingual), 2018-19) and subsequently during 2016-8 at ICAR-Indian Institute of Pulses Research, Kanpur (Nath et al, 2018, 2021) to see the efficacy of topramezone, a post-emergence herbicide, in chickpea. The study shoede topramezone 20.6 g/ha at 25 DAS resulted in higher phytotoxicity on weeds (toxicity scale of 7-10) without any phytotoxicity on chickpea. It significantly controlled the dominant broad-leaved weeds like *Chenopodium album*, *Lepidium didymum*, *Spergula arvensis*, *Medicago polymorpha* and *Fumaria parviflora* compared to the remaining herbicides. Topramezone reduced total weed density by 68-70% and 48–51% (Pd”0.05) at 45 and 95 DAS compared with UWC, respectively. Topramezone increased 15.3-19.6% chickpea seed yield than the recommended herbicide pendimethalin 1000 g/ha - quizalofop-p-ethyl 100 g/ha without affecting the nodulation and fluorescein diacetate activity. Similarly, in mungbean, clodinafop-propargyl + sodium-acifluorfen 122.5 g/ha applied at 15 days after sowing (DAS) reduced the broad-leaved weed dry weight at 35 DAS and harvest by 55.8% and by 58.6% ($p<0.05$) compared with the unweeded control, respectively (Nath *et al.* 2022).

INTEGRATED WEED MANAGEMENT (IWM)

Herbicide is a dominant weed control tool and more effective than other methods in modern agriculture. However, it cannot be a sole and complete solution/fool-proof strategy to the complex challenge that weeds present (Harker and O'Donovoan 2013). Herbicides hardly attain 100% weed control because the spectrum of weed control by many herbicides is narrow (Bajwa *et al.* 2015). Therefore, developing effective, economical, eco-friendly and durable weed management strategies in the form of integrated weed management (IWM) are important paradigms in future weed research across crops and locations to achieve higher and sustained pulses yield. The IWM is defined in a range of ways,

Table 3. Weed management recommendation in pulse crops

Crop	Weed management practice*	Reference
Kharif pulses		
Pigeonpea	Pendimethalin 0.75 kg/ha followed by (*fb*) hand weeding (HW) at 30 DAS	Ali 1991
	Pendimethalin 0.75 kg/ha *fb* paraquat 0.48 kg/ha 42 DAS	Padmaja *et al.* 2013
	Pendimethalin 1.0 kg/ha *fb* HW 45 DAS	Dhonde *et al.* 2009
	Trifluralin 1.0 kg/ha PPI *fb* 1 HW at 60 DAS	Malik and Yadav 2014
	Pendiemthalin 1.0 kg/ha *fb* imazethapyr 100 g/ha	Kumar *et al.* 2013, Kumar and Hazra 2012
Blackgram	Oxadiazon 0.75 kg/ha PE	Soni and Singh 1988
	Pendimethalin 0.75 kg/ha PE *fb* HW 25 DAS	Singh 2011
	Pendimethalin 1.0 kg/ha PE *fb* imazethapyr 100 g/ha PoE 20-25 DAS	Kumar *et al.* 2013, Kumar and Hazra 2012
	Imazethapyr 55 g/ha 15 DAS	Mandal *et al.* 2015
	Imazethapyr + imazamox 75 g/ha PE *fb* HW 35 DAS	Tiwari *et al.* 2018
Greengram	Pendimethalin 0.75 kg/ha PE *fb* HW30 DAS	Parasuraman 2000
	Trifluralin 0.75 kg/ha PPI, linuron 0.75 kg/ha and acetachlor 1.0 kg/ha PE *fb* HW 30 DAS	Malik *et al.* 2000
	Pendimethalin 1.0 kg/ha PE *fb* imazethapyr 100 g/ha PoE 20-25 DAS	Kumar *et al.* 2013
	Clodinafop-propargyl + sodium-acifluorfen 122.5 g /ha 15 DAS	Nath *et al.* 2022
Cowpea	Pendimethalin 0.75 kg/ha PE *fb* HW 30 DAS	Parasuraman 2000
	Pendimethalin at 0.75 kg/ha PE *fb* HW35 DAS	Patel *et al.* 2003
	Pendimethalin 0.75 kg/ha as PE *fb* one hoeing 20-25 DAS	Hanumanthappa 2012
	Imazethapyr 40 g/ha 20 DAS	Gupta *et al.* 2016
Horsegram	HW 20 DAS	Patra and Nayak 2000, Anitha *et al.* 2003
Rabi pulses		
Chickpea	Pendimethalin 1.0 kg/ha PE *fb* quizalofop-ethyl 100 g/ha 20-25 DAS	Kumar *et al.* 2015
Lentil	Pendimethalin 0.75 kg/ha *fb* HW, metribuzin 250 g/ha PoE (some varieties)	Yadav *et al.* 2013
Peas	Pendimethalin 1 kg/ha *fb* HW	Dixit and Varshney 2009
Rajmash	Pendimethalin 1.0 kg/ha *fb* HW	Ali 1988
Lathyrus	Trifluralin 0.75 kg/ha fb HW, Trifluralin 0.75 kg/ha fb sethoxydim 0.3 kg/ha or metribuzin 250 g/ha	Wall and Friesen 1991
Spring/summer pulses		
Greengram / blackgram	Imazethapyr 80 g/ha PoE 20-25 DAS (summer greengram)	Kumar *et al.* 2016

*DAS = days after seeding; PPI = Preplant incorporation; PE = Pre-emergence application PoE = post-emergence application

but, at its core, is the idea that many weed management tools be used, in an integrated way, to manage weeds (Rao and Nagamani 2010). Some of the recommendations of effective weed management in pulses are mentioned in **Table 3**.

Preventive methods

Restricting/stopping perpetuation of weeds from the existing stands of weeds in crop fields over the years is an approach toward prevention (Rao *et al.* 2017). Preventive measures could be: pure and clean crop seeds/seedlings; clean farm machineries and animals; well-decomposed farm yard manure (FYM)/ compost/sewage and sludge; weed control in nurseries; clean farm bunds, roadsides and other non-crop areas; clean irrigation channels and water and alternate irrigation systems; and enacting plant/weed quarantine law (Sonoskie *et al.* 2006, Rao *et al.* 2017). These should be followed for a long period to restrict introduction and spread of weeds. Agronomic practices as well as the weed control measure adopted for raising crops have inherent weed prevention approach. Impact assessment/ quantification of prevention approach should focus on the combined effects of all practices adopted together rather than that of a single practice.

Physical (manual and mechanical) methods

Mechanical weeding is machine-intensive and can be adopted using tractor-drawn equipment in large farms under conventional agriculture. Some tractor-operated weeders are standard/high residue rotary hoe, spike-tooth/ spring tine harrow, flex-tine weeder, finger weeder, rotating wire weeder, pneumatic weeder (Bond *et al.* 2003). Except hand pulling and residue cover/ mulching, physical methods can hardly be recommended for conservation agriculture systems because soil disturbance is not permitted and residue is retained on the soil surface (Brainard *et al.* 2013). This, however, is a boon in itself that continuous no tillage with residue can reduce annual weeds over times, but amidst weed dynamics (Das *et al.* 2020a; Susha *et al.* 2018). Brown manuring provides smothering effect and can control perennial weeds like *C. rotundus*, *Cynodon dactylon* (Behera *et al.* 2018, Das *et al.* 2020b). Digging-out underground perennating structures from deep soil layers can reduce perennial weeds considerably, but is labour-intensive and less economical (Brainard *et al.* 2013). During hot summer months, soil solarization or deep ploughing for 3-5 years may lead to better control of perennial weeds (Das and Yaduraju 2012; Kumar *et al.* 2012, Bajwa *et al.* 2015). Flooding un-cropped field with 20-25cm standing water for 5-10 weeks can reduce perennial weeds like *Cyperus* sp., *C. dactylon*, and *Convolvulus arvensis*, but is more resource-exhaustive. Similarly, there is scope for thermal weed control in conservation agriculture (Bauer *et al.* 2020), but selectivity achieved through a certain heat tolerance of the crop is difficult to actuate in fields having difference in crops and their growth stage/ age, tillers height/age, which may pose risk of crop damage as well as fire from dry plant residues. Although most conventional physical methods are less economical and labour-intensive, they offer enough potential for location-based integration as a component of the IWM.

Cultural methods

It is well-known that a good/healthy crop is the best weed killer (Fletcher 1983). Being inherent recommended agro-practices for a crop, the cultural practices usually do not incur extra-cost for weed management. These practices include: competitive crops/crops cultivars, tillage, geometry, time, method, rate and depth of sowing (Susha *et al.* 2018). It also includes the kind, time, method and rate of fertilizers application time, method, and frequency of irrigation, intercropping, stale seedbed (Gopinath *et al.* 2009), brown manuring (Behera *et al.* 2018), crop rotation (Singh *et al.* 2016). Crop rotation can help to control some permanent weeds under mono-cropping. *Phalaris minor* and *A. ludoviciana* existing in wheat crop (Das and Yaduraju 2002) and *E. colona* existing in rice crop under rice-wheat cropping system were largely controlled when wheat was replaced with berseem (*Trifolium alexandrinum* L.), mustard (*Brassica juncea* L.) or winter maize for 3-4 years. Cowpea (*Vigna unguiculata* L.), greengram (*Vigna radiate* (L.) Wilczek), blackgram (*Vigna mungo* L.), soybean when was intercropped with maize, sorghum, and pearlmillet (*Pennisetum glaucum* L.) (Kumar *et al.* 2016) could manage weeds to a large extent.

Allelopathy for ecological weed management

Allelopathy is the process in which one plant affects the other plant through the release of chemicals in the environment. Allelochemicals are present in all types of plants and tissues and are released into the soil rhizosphere by a variety of mechanisms, including decomposition of residues, volatilization, leaf leachate and root exudation. Some of the allochemicals important for pulses are listed in **Table 4**.

Weeds' allelopathy to crop or crop's allelopathy to weeds is a direct negative effect of one on another. Even though theoretically a crop is said allelopathic to weeds, it may not be equally inhibitive or at all inhibitive to all composite weed species in a field. Rather a weed, few weeds or all the weeds present in a crop if is/are allelopathic to a crop, the negative effect on crop may be significantly greater since only one species (crop plant) is under their influences or targeted (Das 2008). Thus, allelopathy may also exert influence on the severity of crop-weed competition. Effective utilization of their mulches would be of great benefit for the control of weeds. Using same crop residue mulch having allelopathic effect can act

Table 4. Allelochemicals of some important crops and weed species suppressed by them

Crops*	Scientific name	Allelochemicals	Weed species suppressed
Rice	*Oryza sativa* L.	Phenolic acids	*Echinochloa crus-galli, Cyperus difformis, Monochoria vaginalis, Leptochloa chinensis*
Wheat	*Triticum aestivum* L.	Hydroxamic acids	*Lolium perenne, Elusineindica, Amaranthus palmeri*
Cucumber	*Cucumis longa* L.	Benzoic and Cinnamic acid	-
Black mustard	*Brassica nigra* L.	Allylisothiocyanate	*Amaranthus palmeri, Chenopodium album*
Buck wheat	*Fagopyrium esculentum* L.	Fatty acids	*Avenafatua*
Clovers and Sweet clover	*Trifolium spp.*	Isoflavonoids, Coumarin, and Phenolics	*Phalaris minor, Orobanche spp.*
Oat	*Avena sativa* L	L Phenolic acids & Scopoletin	*Datura stramunium, Digitaria sanguinalis, Elusine indica*
Cereals		- Hydroxamic acids	-
Sudangrass		Phenolic acids and Dhurrin	*Cyperus rotundus, Sorgum halepense*
Sorghum	*Sorghum bicolour* L.	Sorgoleone	*Cyperus rotundus, Convilvulus arvensis, Portulaca oleracea*

*Some of the cultivars of these crops are having allelopathic effect on weeds; Adopted from Jabran *et al.* (2015)

as self-supporting weed management (*e.g.* rice) for the concurrent as well as rotational crops. This approach may forecast the most promising future in weed management practice globally. It provides scope to breed new crop variety having allelopathic potential to control weeds and, therefore, its success largely depends on the breeders. Development of novel bio-pesticides/herbicides from plant allelochemicals is another important aspect.

Biological methods

Biological control fosters a prey-predator relationship between the weed and employed bio-agent (insects, pathogens) and follows the natural law of homeostasis, the science of check and balance (Das 2008). It conveys not to eradicate weeds completely but bring weeds population below the economic threshold level (Bajwa *et al.* 2015). Biological control is relatively cheap; least toxic to humans/animals and environment; and effective and adaptable for controlling perennial, parasitic and invasive weeds. Bio-herbicides research gained attention in 1980s, when some potent pathogens were successfully utilized to make effective formulations for weed control. Despite its early gains, this field is still struggling regarding inventions or launching products, but consistent theoretical development is still evident (Hallett 2005). The most bio-agents kill single weed, therefore, weed problem in a crop infested with a large number of weeds remains hardly resolved. Furthermore, this is a slow process of killing or suppression of weeds; early weed competition may cause sufficient damage to crops before the bio-agents started to feed/act upon target weeds; environment and ecology greatly affect their stability across the world.

Site-specific/sensor-driven precision weed management

Site-specific weed management (SSWM), advocating control measures only where weeds are located at higher densities than those cause economic losses, offers economic and environmental benefits (Kneievic *et al.* 2003). Under usual patchy and scattered weed distribution in crop fields, site-specific, weed patch-specific or spot application of herbicide is more economical and less degrading to environment than blanket application. This reduces amount of herbicides as well as their intake into the environment. Band application with standard herbicide treatment at a half-recommended rate combined with mechanical weed control brought a satisfactory total weed reduction by 83–87% (Kneievic *et al.* 2003). Recently, artificial intelligence (AI) and robotics researches have geared up for weed management, which is one of the least mechanized aspects of agriculture (Young *et al.* 2014). Robotic machines can be used to control weeds mechanically, chemically or through flame. Merfield (2016) opined those current machines are not truly robotic weeders, rather they are essentially self-guiding vehicles carrying weeding tools. Completely autonomous robotic machine that replaces all human intervention should fulfill important requirements for fully autonomous mechanical weed management. Selectivity in mechanical weed control is obtained using dynamically actuated harrows. The AI enabled automated robotic weed management is a four-step process, involving guidance, identification, precision robotic removal, and mapping of weed species (Young *et al.* 2014). This may reduce herbicides use and their environmental impact, and hence, can improve sustainability, particularly in vegetable crops and organic agriculture (Korres *et al.* 2019). The feasibility of a robotic weed control system depends upon machine vision analyses, robotic efficiency/ suitability, variable rate application technology, decision support system, and strength of weed-sensing tools. Possibilities for absolute mechanical weed control through robotics are being explored to potentially eliminate herbicides use in fields. Some agricultural robots for weed control are: Weed Master®, Weed Seeker® (for pot spraying), Tertill, RIPPA, Hortibot, Swag Bot, ASTERIX, AgBot II, Blue River Lettuce Bot 2, Naïo Technologies. Several barriers prevent their large scale adoption, most important being the lack of a truly automated weed detection and identification method in crop fields, owing to mutual shading among plants and limitations in the capacity of highly accurate spraying and weeding apparatus (Thorp and Tian 2004). Integration of site-specific information on the distribution, species composition and density of weeds and their effect on crop yield is decisive for successful SSWM.

Herbicide mixture

Herbicide mixture might reduce/prevent the risk of herbicide resistance and/or delay the resistance development because of reduced selection pressure of herbicides (Farooq *et al.* 2013). The development of resistant biotypes within the weed species happens slowly with herbicide mixtures of those having different mode of action. The frequency of occurrence of resistance usually becomes lowered in mixture compared to the frequency of occurrence of resistance by a single herbicide (Susha *et al.* 2018).

Intercropping

Intercropping involves growing more than one crop in the same field at the same time. The crops may be seeded at the same time (mixed intercropping) or they may be seeded at different times (relay intercropping). Strip intercropping is a production system where different crops are grown in wide strips (usually the width of a seeder) in the same field. Intercropping can provide a number of benefits to a cropping system including stability, over yielding, and reduced chemical use (both fertilizers and pesticides). Research and experience from around the world have shown that intercropping and cover cropping systems tend to suppress weeds better than sole cropping systems. This is especially true with smother crops such as forage legumes inter seeded with a main crop such as a cereal. Intercropping grain crops can also be useful for suppressing weeds, especially when the desired crop is a poor competitor. The results of the experiment revealed that among the intercropping systems, maize + blackgram (1:1) intercropping recorded lesser total weed density and weed dry weight. Maize + blackgram intercropping along with pendimethalin 0.75 kg/ha as PE 3 DAS *fb* one HW 25 DAS recorded higher weed control efficiency. Inclusion of pulses as intercrop in jute smothered dicot and sedge weeds upto 54%. Weed control efficiency of intercropping jute with greengram followed by application of butachlor +1HW was 82% over 64% in conventional manual weeding twice.

Mulching

Mulches control weeds through light exclusion, physical barrier to seeding emergence and allelopathy (Das 2008). Mulch includes clean straw, hay or manure, tar paper, saw dust, crop stubbles and black plastic etc. Residue mulching suppresses weeds, reducing recruitment and early growth of weeds, by (1) imposing a physical barrier to emerging weeds and (2) releasing allelochemicals in the soil. Wheat residue mulch of 5 t/ha reduced the emergence of grass, broad-leaved weeds, and sedge species in the range of 73 to 76%, 65 to 67%, and 22 to 70%, respectively, compared with no residue control in zero till direct seeded rice (Kumar *et al.* 2013; Kumar *et al.* 2022). Despite the significant positive effects of mulches on weed suppression, the limited availability of residue for mulch during the rice season is a constraint (Kumar *et al.* 2014). Therefore, growing short-duration catch crops such as greengram during the fallow period between wheat harvest and rice planting and retaining the entire greengram residue as mulch in rice is an effective weed management practice in rice-wheat system. Materials such as black polyethylene have been used for weed control in a range of crops in organic production systems which raise soil temperature through one-way transmission of infrared radiation. Black polythene recorded significantly lower density and dry biomass of weeds over water hyacinth, paddy straw and wheat straw mulch, respectively.

Biotechnological/biochemical methods

Since the adoption in 1996 in an area of 1.7 million ha, transgenic/biotech crops have spread over an area of 189.8 million ha in 2017, a record increase in area by 112-fold (ISAAA 2017). Herbicide tolerant crops (HTCs) occupy 88.7 million ha (~46.7%) of the total area planted to biotech crops. HTCs of cotton, maize, canola, rice, sugar beet, alfalfa (*Medicago sativa* L.), *Brassica* and soybean have revolutionized weed control in USA, Canada, Australia (Duke and Powles 2009) and many other countries. They show tolerance to respective herbicides like glyphosate, glufosinate-AM, bromoxynil, dicamba, imidazolinones, cyclohexane-diones. They offer more effective weed control and greater economic benefits than conventional crops and herbicide programmes, therefore, getting adopted largely by the farmers (Gianessi 2013). HTCs can expedite the adoption of reduced or no-tillage in agriculture, which may reduce soil erosion and improve soil health, and can be an option for crop diversification in conservation agriculture. Adopting glyphosate-resistant soybeans, the 53% of USA soybean farmers could reduce the number of tillage in their fields by 1.8 tillages per acre since 1995. This enabled farmers to save $385 million per year from tillage (Gianessi 2005). Possible risks anticipated from using HTCs can be bypassed or managed by using some traditional methods such as rotating herbicides, mixing herbicides, and rotating crops. Gianessi (2005) reported that, by adopting glyphosate-tolerant crops, the US farmers saved $1.2 billion, which were required for conventional herbicide, tillage, and hand weeding. The glyphosate-resistant crops have reduced herbicide use by 37.5 million lbs in US agriculture. Carpenter and Gianessi (2002) also reported that there had been a significant reduction in the price of all major herbicides for soybeans due to introduction of glyphosate-resistant crops. These price reductions could save soybean growers by $216–307 million per year for weed control. It can be included in the IWM programme to manage weeds more economically and effectively for many years. A biochemical option of recent origin could be exploitation of the allelopathic potential of plants and microorganisms towards developing “botanical herbicides” (Farooq *et al.* 2013).

Biotechnological approaches towards developing herbicide-tolerant crops and bio-herbicides (Reddy and Nandula 2012), harnessing allelopathic potential of plants/micro-organisms

(Kalsa *et al.* 2004) and precision weed management using remote sensing and geographic information system (GIS), artificial intelligence/robotics are worth-mentioning for modern weed management and have possible integration under IWM. However, before framing an IWM, certain principles/guidelines *(i.e.*, weed ontogeny and characteristics, critical weed competition period, climate/weather and soil conditions, whole-farm community approach, system approach, history of chemical weed control, follow-up weed prevention measures and farmers' socio-economic conditions) should be considered for diagnosis of a situation and to select suitable weed control options to be integrated for effective and durable management of composite weeds or particular problematic weeds in an area.

LIMITATION OF WEED MANAGEMENT IN PULSES

Narrow-spectrum of weed control

Narrow-spectrum selective herbicides are either targeted towards grassy or broad-leaved species and cannot control diverse weed flora (Nath *et al.* 2018). Therefore, herbicide mixtures (tank-mix and/or pre-mix) are necessary to achieve broad-spectrum weed control that might increase cost of input and often difficult for farmers (Chauhan *et al.* 2012). Quizalofop-p-ethyl, propaquizafop-p-ethyl and clodinafop-propargyl can effectively control of grassy weeds but not broad-leaved weeds (Nath *et al.* 2021). These necessitate the use of herbicide mixtures in pulse crops/systems.

Limited availability of post-emergence herbicides

Pulse crops require an efficient weed management at the initial growth stage because of its short duration (55-60 days). Presently, pendimethalin is recommended as pre-emergence (PE) in greengram (Kumar *et al.* 2016). Pendimethalin as PE is not possible due to early rainfall immediately after sowing of rainy season pulses (Singh *et al.* 2014) and in rice-pulse relay system because of overlapping of crop growth. Hence, PoE herbicide is needed for controlling broad-leaved and diverse weed flora (Kumar *et al.* 2015b). Fenoxaprop-p-ethyl, cyhalofop-p-butyl, and quizalofop-p-ethyl provided lower weed control because these herbicides control only narrow-leaved weeds (Ghosh *et al.* 2016; Kumar *et al.* 2016). However, broad-leaved weeds were a hindrance to pulses. Kumar *et al.* (2016) and Singh *et al.* (2014) reported the poor weed control by narrow-spectrum herbicides in pulses. Two times application of herbicides (PE and PoE) are not feasible for pulse crops (Nath *et al.* 2017).

Shift in weed flora

Continuous use of a narrow-spectrum herbicide for years together might result in shift in weed flora. A crop field dominated by grass weeds for many years might gradually turn into broad-leaved weed domination after continuous use of grass-killer herbicide. Reverse may be true if there is continuous use of broad-leaved killer herbicides. The repeated usage of a single herbicide causes shifting of weed flora and threat of future weed control programmes. Therefore, herbicide rotation or herbicide mixtures should be employed for avoiding such situations.

Toxicity to sensitive crop in rotation

Herbicides having higher persistence in soil can lead to residual toxicity in succeeding crops. Sensitivity of succeeding crops to fomesafen and imazamox residues was reported in maize, soybean, and chickpea (Cobucci *et al.* 1998). Similarly, Bresnahan *et al.* (2000) reported that imazamox and imazethapyr applied fields should not be cropped with mustard and greengram in following season due to carry-over problems. Herbicides unlike insecticides and fungicides are dose and/or time specific for selective crops. Inappropriate application could either result in heavy crop damage/failure or poor efficacy. Higher than recommended dose of herbicides leads to negative impacts on crops and ecosystem along with higher cost of weed control (Oyeogbe *et al.* 2017).

Herbicide resistant weeds

Continuous use of same herbicides over many years leads to selection pressure towards tolerant individuals ultimately leading to resistance development (Malik and Singh 1993, 1995; Chhokar and Sharma 2008). Herbicide resistance occurs when a weed is no longer controlled by an herbicide at rates that previously were effective. Imazethapyr 75-100 g/ha was found effective in managing weeds in greengram (Kumar *et al.* 2016, Singh *et al.* 2014) and the efficacy of imazethapyr varied with its dose, greengram genotypes, and soil moisture (Ram and Singh 2011). Further, imazethapyr controls broad-leaved weeds leaving the dominant narrow-leaved weeds uncontrolled during the rainy season. Imazethapyr inhibits the acetolactate synthase (ALS) enzyme that blocks the synthesis of branched-chain amino acids (Ashton and Crafts 1973). The evolution of weed resistance to ALS-inhibiting herbicides occurs relatively quickly (Rao 2018). During the last 3-4 years, farmers have reported poor control of *Echinochloa colona* and *Trianthema portulacastrum* with imazethapyr. Hence, among the various weeds, few weed plant acquire mechanism which make it possible to survive against herbicide application and there was considerable chance for the development of herbicide resistance (Bhullar *et al.* 2017). This resistance development can lead to an increase in the cost of weed management both in the short-term and medium-term (Gaur *et al.* 2013). Therefore, ready-mix herbicides are effective for broad-spectrum weed control and delay resistance development (Nath *et al.* 2018; Susha *et al.* 2018). Hence, there is an urgent need to compare the efficacies of different herbicides in pulses to identify effective/selective post-emergence herbicides (Kumar *et al.* 2016).

WAY FORWARD

To meet the future demand of burgeoning population, concerted research efforts will be needed to increase its productivity and meet the self-sufficiency of pulses in India. The good management technologies that are expected to have significant impact on pulses production need to be given priority. Among good management technologies effective weed management strategies must be on top priority. In future, following issues may be important for improving weed management in pulse crops:

- Develop cultivars with early growth vigour to suppress weed growth.
- Inclusion of pulses in cereal-cereal systems needs to be promoted for restoring soil-fertility and to break the dynamics of weeds.
- Mechanical devices which are preferably machine driven are required for interculturing and weed control in pulse crops.
- Controlling broad-leaved weeds in pulses is a major issue but effective herbicides are not available for rabi pulses like chickpea and lentil. Identification of suitable herbicides and standardization of their doses and time of application is important.
- The main issue of conservation agriculture (CA) is efficient weed management. Therefore, technology for growing pulses in CA systems is required to be developed under different soil and climatic conditions.
- Development of herbicide tolerant cultivars of pulses will change the scenario of weed management in the coming years.
- Modern technologies such as AI, remote sensing, site-specific application, nano-technology, and drones must be included while formulating strategies for weed management in pulses.
- Under changing climate, it is expected to reduce the efficiency of herbicides. Thus, new herbicides and their dose and time of application need to be identified.
- Biological/ecological approaches must be included for long-term management of weeds.

REFERENCES

Ali M. 1988. Efficacy of herbicides for weed control in winter French bean (*Phaseolus vulgaris*). *Indian Journal of Agricultural Sciences* **58**(2): 440–443.

Ali M. 1991. Weed management in pigeonpea under rainfed conditions in India. *Tropical Pest Management* **37**(4): 345–348.

Anitha S, Sreenivasan E and Purushothaman SM. 2003. Integrated weed management in horsegram (*Macrotyloma uniflorum*) in the Oxisols of Kerala. *Indian Journal of Weed Science* **35**(1&2): 143–144.

Ansar M, Anwar A, Arif M, Nadeem M and Zahid A. 2010. Screening of Pre– and– Post emergence herbicides against chickpea (*Cicer arietinum* L.) weeds under semi rainfed conditions of pothohar, Pakistan. *Pakistan Journal of Weed Science Research* **16**(4): 421–430.

Ashton FM and Crafts AS. 1973. *Mode of Action of Herbicides. Mode of Action of Herbicides.* 504 p.

Annual Report (Bilingual). 2018-19. *ICAR-Directorate of Weed Research*, Jabalpur, 178 p.

Bajwa AA, Mahajan G and Chauhan BS. 2015. Non-conventional weed management strategies for modern agriculture. *Weed Science* **63**(4): 723–747.

Bauer MV, Marx C, Bauer FV, Flury DM, Ripken T and Streit B. 2020. Thermal weed control technologies for conservation agriculture–a review. *Weed Research* https://doi.org/10.1111/wre.12418.

Begum G and Rao AS. 2006. Efficacy of herbicides on weeds and relay crop of blackgram. *Indian Journal of Weed Science* **38**(1&2): 145–7.

Behera B, Das TK, Ghosh S, Kaur R and Singh R. 2018. Brown manuring in maize (*Zea mays*): Effects on weed interference and crop productivity. *Indian Journal of Agronomy* **63**(4): 524–527.

Bhandari V, Singh J, Randhawa JS and Randhawa RS. 2004. Studies on weed control in summer blackgram (*Phaseolus mungo*). *Indian Journal of Weed Science* **36**(1 & 2): 129–30.

Bhullar M, Kaur N, Kaur P and Gill G. 2017. Herbicide resistance in weeds and its management. *Agricultural Research Journal* **54**(4): 436–444.

Bolat A, Bayat A, Tetik Ö and Türkeri M. 2019. Determining of effectiveness of different nozzle types in weed control in chickpea cultivation areas according to application period. *Yuzuncu Yýl University Journal of Agricultural Sciences* **29**(3): 397–405.

Bond W, Turner RJ and Grundy AC. 2003. *A Review of Nonchemical Weed Management*. Henry Doubleday Research Association and Horticulture Research International, Coventry, United Kingdom, 81 p.

Brainard DC, Haramoto E, Williams MM and Mirsky S. 2013. Towards a no–till no–spray future? Introduction to a symposium on nonchemical weed management for reduced–tillage cropping systems. *Weed Technol.* **27**(1), 190–192.

Bresnahan GA, Koskinen WC, Dexter AG, Lueschen WE. 2000. Influence of soil pH" sorption interactions on imazethapyr carry–over. *Journal of Agricultural and Food Chemistry* **48**(5): 1929–1934.

Carpenter JE and Gianessi LP. 2002. Trends in pesticide use since the introduction of genetically engineered crops. In: *Economic and Environmental Impacts of Agbiotechnology: a Global Perspective,* Kluwer–Plenum Publishers, NY.

Chand R, Singh NP and Singh VK. 2004. Effect of weed control treatments on weeds and grain yield of late sown blackgram (*Vigna mungo* L.) during kharif season. *Indian Journal of Weed Science* **36**(1&2): 127–28.

Chandrashekharan S. 1998. Increasing pulse production in India. In: *Constraints and Opportunities*, Report, All India Co–ordinated Pulse Improvement Project, Kanpur.

Chaturvedi SK, Muraleedhar A, Gaur PM, Mishra N, Singh K and Nadarajan N. 2014.Genetic variations for herbicide tolerance (Imazethapyr) in chickpea (*Cicer arietinum*). *Indian Journal of Agricultural Sciences* **84**(8): 968–970.

Chauhan BS, Singh RG and Mahajan G. 2012. Ecology and management of weeds under conservation agriculture: a review. *Crop Protection* **38**: 57–65.

Cheema ZA, Farooq M and Khaliq A. 2013. Application of allelopathy in crop production: success story from Pakistan. *Allelopathy* 113–143.

Chhokar R and Sharma R. 2008. Multiple herbicide resistance in little seed canary grass (*Phalaris minor*): a threat to wheat production in India. *Weed Biology and Management* **8**(2): 112–123.

Cobucci T, Prates HT, Falcaom CLM, Rezende MMV. 1998. Effect of imazamox, fomesafen and acifluorfen soil residues on rotational crops. *Weed Science* **46**: 258–263.

DAC. 2021. Department of Agriculture & Farmers Welfare. https://agricoop.nic.in/en.

Das TK. 2008. *Weed Science: Basics and Applications*. Jain Brothers Publications, New Delhi. p 901. 50.

Das TK, Ghosh S and Nath CP. 2020b. Brown manuring optimization in maize: impacts on weeds, crop productivity and profitability. *The Journal of Agricultural Science (Cambridge)* **157**(7–8): 599–610.

Das TK, Nath CP, Das S, Biswas S, Bhattacharyya R, Sudhishri S, Raj R, Singh B, Kakralia SK, Rathi N, Sharma AR, Dwivedi BS, Biswas AK and Chaudhari SK. 2020a. Conservation Agriculture in rice–mustard cropping system for five years: Impacts on crop productivity, profitability, water–use efficiency, and soil properties. *Field Crops Research* **250**: 107781.

Das TK, Tuti MD, Sharma R, Paul T, Mirjha PR. 2012. Weed management research in India: an overview. *Indian Journal of Agronomy* **57**: 148–156.

Das TK and Yaduraju NT. 2002. Optimization of metribuzin use for controlling isoproturon–resistant *Phalaris minor* Retz. in wheat. *Pesticide Research Journal* **14**(1): 47–56.

Das TK and Yaduraju NT. 2012. The effects of combining modified sowing methods with herbicide mixtures on weed interference in wheat. *International Journal of Pest Management* **58**(4): 311–320.

Dhonde MB, Kate SR, Pandure BS and Tambe AD. 2009. Integrated weed management in pigeonpea. *Indian Journal of Weed Science* **41**(1&2): 102–105.

Dixit A and Varshney JG. 2009. *Handbook on Herbicide Recommendations*. Directorate of Weed Science Research, Jabalpur.

Duke SO and Powles SB. 2009. Glyphosate–resistant crops and weeds: now and in the future. *AgBioForum* **12**(3&4): 346–357.

FAOSTAT. 2020. “Online Interactive Database on Agriculture”, FAOSTAT. *www.fao.org*.

Farooq M, Bajwa AA, Cheema SA and Cheema ZA. 2013. Application of allelopathy in crop production. *International Journal of Agriculture and Biology* **15**(6), 1367–1378.

Fletcher WW. 1983. *Recent Advances in Weed Research*. Commonwealth Agricultural Bureaux (CAB), London.

Gaur PM, Jukanti AK, Samineni S, Chaturvedi SK, Singh S, Tripathi S, Simgh I, Singh G, Das TK, Aski M, Mishra N, Nadarajan N and Gowda CL. 2013. Large genetic variability in chickpea for tolerance to herbicides imazethapyr and metribuzin. *Agronomy* **3**(3): 524–536.

Gharde Y, Singh PK, Dubey RP and Gupta PK. 2018. Assessment of yield and economic losses in agriculture due to weeds in India. *Crop Protection* **107**: 12–18.

Ghosh PK, Hazra KK, Nath CP, Das A and Acharya CL. 2016. Scope, constraints and challenges of intensifying rice (*Oryza sativa*) fallows through pulses. *Indian Journal of Agronomy* **61**: 122–128.

Gianessi LP. 2005. Economic and herbicide use impacts of glyphosate resistant crops. *Pest Management Science* **61**(3): 241–245.

Gianessi, L.P. 2013. The increasing importance of herbicides in worldwide crop production. *Pest Management Science* **69**(10): 1099–1105.

Gitsopoulos TK, Melidis V and Evgenidis G. 2010. Response of maize (*Zea mays* L.) to post–emergence applications of topramezone. *Crop Protection* **29**: 1091–1093.

Gopinath KA, Kumar N, Mina BL, Srivastva AK and Gupta HS. 2009. Evaluation of mulching, stale seedbed, hand weeding and hoeing for weed control in organic garden pea (*Pisum sativum* Sub Sp. Hortens L.). *Archives of Agronomy and Soil Science* **55**(1): 115–123.

Gupta KC, Gupta AK and Rani S. 2016. Weed management in cowpea [Vigna unguiculata (L.) Wasp.] under rainfed conditions. *International Journal of Agricultural Sciences* **12**(2): 238–240.

Gupta KC, Gupta AK and Saxena R. 2016. Weed management in cowpea [*Vigna unguiculata* (L.) Wasp.] under rainfed conditions. *International Journal of Agricultural Sciences* **12**(2): 238–240.

Hallett SG. 2005. Where are the bioherbicides? *Weed Science* **53**(3): 404–415.

Hanumanthappa DC, Mudalagiriyappa R, Kumar GNV and Padmanabha K. 2012. Effect of weed management practices on growth and yield of cowpea (*Vigna unguiculata* L.) under rainfed conditions. *Crop Research (Hisar)* **44**(1/2): 55–58.

Harker KN and O’Donovan JT. 2013. Recent weed control, weed management, and integrated weed management. *Weed Technology***27**(1): 1–11.

IIPR. 2009. *25 Years of Pulses Research at IIPR*. Indian Institute of Pulses Research, Kanpur.

IIPR. 2010. All India Coordinate Research Project on Greengram, Blackgram, Lentil, Lathylus, Rajmash and pea, ICAR (online). (http://www.aicrpmullarp.res.in/crop_profile.html.).

ISAAA. 2017. Global status of commercialized biotech/GM crops in 2017; Biotech crop adoption surges as economic benefits accumulate in 22 years. International Service for the Acquisition of Agri–biotech Applications. Brief No. 53, Ithaca, NY.

Jabran K, Mahajan G, Sardana V and Chauhan BS. 2015. Allelopathy for weed control in agricultural systems. *Crop Protection* **72**: 57–65.

Jha BK, Chandra R and Singh R. 2014. Influence of post emergence herbicides on weeds, nodulation and yields of soybean and soil properties. *Legume Research* **37**: 47–54.

Kalsa KK, Das TK, Assefa Y and Sakhuja PK. 2004. Effect of sorghum foliar extracts on the germination and seedling growth of brome grass (*Bromus pectinatus* Thunb.). *Alemaya Univ. Newsletter* **2**(5): 18–21.

Kaur G, Brar HS and Singh G. 2010. Effect of weed management on weeds, nutrient uptake, nodulation, growth and yield of summer mumngbean (*Vigna radiata*). *Indian Journal of Weed Science* **42**(1&2): 114–9.

Khope D, Kumar S and Pannu RK. 2011. Evaluation of post–emergence herbicides in chickpea (*Cicer arietinum*). *Indian Journal of Weed Science* **43**: 92**–**93.

Kneievic M, Durkic M, Kneievic I and Lonearic Z. 2003. Effects of pre– and post–emergence weed control on weed population and maize yield in different tillage systems. *Plant, Soil and Environment* **49**: 223–229.

Korres NE, Burgos NR, Travlos I, Vurro M, Gitsopoulos TK, Varanasi VK, Duke SO, Kudsk P, Brabham C, Rouse CE, Salas–Perez R. 2019. New directions for integrated weed management: Modern technologies, tools and knowledge discovery. *Advances in Agronomy* **155**: 243–319.

Kumar N, Yadav A, Hazra KK, Yadav SL and Singh SS. 2015b. Prospects and potential of post–emergence herbicides for weed management in pulses. Pp. 199–207. In– *Pulses: Challenges and Opportunities under Changing Climatic Scenario*. (Eds. GP Dixit, J Singh and NP Singh), Indian Society of Pulses Research and Development, ICAR–Indian Institute of Pulses Research, Kanpur, India.

Kumar N, Nath CP, Hazra KK, Praharaj CS, Singh SS and Singh NP. 2022. Long–term impact of zero–till residue management in post–rainy seasons after puddled rice and cropping intensification on weed seedbank, above–ground weed flora and crop productivity. *Ecological Engineering* **176**(2022): 106540.

Kumar N, Hazra KK and Nadarajan N. 2016. Efficacy of post–emergence herbicide Imazethapyr in summer greengram (*Vigna radiate* L.). *Legume Research* **39**(1): 96–100.

Kumar N, Hazra KK and Yadav SK. 2014. Issues related to weed management in RCT. Pp. 567–575. In *Resource Conservation Technology in Pulses*. (Eds. Ghosh PK, Narendra Kumar, Venkatesh MS, Hazra KK and Nadarajan N), Scientific Publisher, Jodhpur.

Kumar N, Hazra KK, Singh MK, Venkatesh MS, Lalit Kumar, Jagadish Singh and Nadarajan N. 2013. Weed management Techniques in Pulse Crops. *Technical Bulletin 10/2013*. Indian Institute of Pulses Research, Kanpur (Uttar Pradesh), India. 47 pages.

Kumar N, Hazra KK, Yadav SL and Singh SS. 2015. Weed dynamics and productivity of chickpea (*Cicer arietinum*) under pre– and post–emergence application of herbicides. *Indian Journal of Agronomy* **60**(4): 570–575.

Kumar N, Hazra KK and Nadarajan N. 2017. Efficacy of pre– and post– emergence herbicides in rainy season greengram (*Vigna radiate* L.). *Indian Journal of Agricultural Sciences* **87**(9): 1219–24.

Kumar N, Nath CP, Hazra KK and Sharma AR. 2016a. Efficient weed management in pulses for higher productivity and profitability. *Indian Journal of Agronomy* **61**(4th IAC Special Issue): S93–105.

Kumar A and Tewari AN. 2004. Efficacy of pre and post–emergence herbicides in summer blackgram (*Vigna mungo* L.). *Indian Journal of Weed Science* **36**(1&2): 73–75.

Kumar M, Das TK and Yaduraju NT. 2012a. An integrated approach for management of *Cyperus rotundus* (purple nutsedge) in soybean – wheat cropping system. *Crop Protection* **33**: 74–81.

Kumar N. 2010. Imazethapyr: A potential post–emergence herbicide for kharif pulses. *Pulses Newsletter (July–Sept., 2010)* **21**(3): 5.

Kumar N. 2013. *A. tenuifolius:* An emerging weed of *rabi* pulses in Bundelkhand. *Pulses Newsletter (January–March, 2013)* **24**(1): 6.

Kumar N and Hazra KK. 2012. Post–emergence Herbicide for *Kharif* and Summer Pulses. *Pulses Newsletter (Oct. Dec., 2012)* **23**(4): 5.

Kumar N and Yadav SL. 2013. Infestation of *Convolvulus arvensis* in rice under RCT trial. *Newsletter (July–September, 2013)* **24**(3): 5.

Kumar N, Hazra KK, Yadav SL and Singh SS. 2015a. Weed management using post–emergence herbicides in chickpea + mustard intercropping system. *Indian Journal of Agricultural Sciences* **85**(8): 1074–1079.

Kumar S and Angiras NN. 2005. Efficiency of pendimethalin under different planting methods of blackgram. *Indian Journal of Weed Science* **37**(3 & 4): 216–219.

Maji S, Reja MH, Nath R, Bandopadhyay P and Dutta P. 2020. Herbicidal management in monsoon greengram (*Vigna radiata* (L.) Wilczek) and its effect on the following rapeseed (Brassica campestris L. var. Yellow Sarson) in the Indo–Gangetic plains of Eastern India. *Journal of the Saudi Society of Agricultural Sciences* **19**(8): 499–509.

Malik R and Singh S. 1993. Evolving strategies for herbicide use in wheat: resistance and integrated weed management. Pp. 225–238. In Proc. *Indian Society of Weed Science International Symposium*. Hisar, India.

Malik RS and Yadav A. 2014. Effect of sowing time and weed management on performance of pigeonpea. *Indian Journal of Weed Science* **46**(2): 132–134.

Malik RK and Singh S. 1995. Littleseedcanarygrass (*Phalaris minor*) resistance to isoproturon in India. *Weed Technology* **9**(3): 419–425.

Malik RS, Yadav A and Malik RK. 2000.Efficacy of trifluralin, linuron and acetachlor against weeds in greengram (*Vigna radiata*). *Indian Journal of Weed Science* **32**(3/4): 181–185.

Mandal T, Singh VK, Bhushan C and Kumar A. 2015. Weed dynamics, nutrient removal and yield of blackgram (*Vigna mungo* L. Hepper) as influenced by weed management practices under tarai conditions of Uttarakhand. *Annals of Plant and Soil Research* **17**(Special Issue): 245–249.

Meena BL, Meena DS, Ram B, Nagar G, Dhayal S and Meena H. 2022. Effect of pre–and post–emergence herbicides on weeds and yield of soybean. *Indian Journal of Weed Science* **54**: 201–202.

Merfield CN. 2016. Robotic weeding's false dawn? Ten requirements for fully autonomous mechanical weed management. *Weed Research* **56**: 340–344.

Mishra JS, Rao AN, Singh VP and Rakesh Kumar. 2016. Weed management in major field crops. Pp. 1-20 In: *Advances in weed management* (Eds. Yaduraju NT. *et al.*). Indian Society of Weed Science, Jabalpur, M.P., India

Nath CP, Kumar N, Hazra KK and Praharaj CS. 2022. Bio–efficacy of different post–emergence herbicides in greengram. *Weed Research*. Pp. 1–9.

Nath CP, Das TK, Rana KS, Bhattacharyya R, Pathak H, Paul S, Meena MC and Singh SB. 2017a. Weeds and nitrogen management effects on weeds infestation and crop productivity of wheat–greengram sequence in conventional and conservation tillage practices. *Agricultural Research* **6**: 33–46.

Nath CP, Dubey RP, Sharma AR, Hazra KK, Kumar N and Singh SS. 2018. Evaluation of new generation post–emergence herbicides in chickpea (*Cicer arietinum* L.). *National Academy Science Letters* **41**(1): 1–5.

Nath CP Kumar N, Hazra KK, Praharaj CS, Singh SS, Dubey RP, Sharma AR. 2021. Topramezone: A selective post–emergence herbicide in chickpea for higher weed control efficiency and crop productivity. *Crop Protection* **150**: 105814.

Neve P and Powles SB. 2005. Recurrent selection with reduced herbicide rates results in the rapid evolution of herbicide resistance in *Lolium rigidum*. *TAG* **110**: 1154–1166.

Neve P, Busi R, Renton M and Vila–Aiub MM. 2014. Expanding the eco evolutionary context of herbicide resistance research. *Pest Management Science* **70**(9):1385–1393.

Oerke EC. 2006. Crop losses to pests. *The Journal of Agricultural Science* **144**: 31–43.

Oyeogbe AI, Das TK, Bhatia A and Singh SB. 2017. Adaptive nitrogen and integrated weed management in conservation agriculture: impacts on agronomic productivity, greenhouse gas emissions and herbicide residues. *Environmental Monitoring and Assessment* **189**(4): 198.

Padmaja B, Reddy MM and Reddy D. 2013. Weed control efficiency of pre–and post–emergence herbicides in pigeonpea. *Journal of Food Legumes* **26**(1&2): 44–45.

Parasuraman P. 2000. Weed management in rainfed cowpea (*Vigna unguiculata*) and greengram (*Phaseolus radiatus*) under North–Western Agroclimatic Zone of Tamil Nadu. *Indian Journal of Agronomy* **45**(4): 732–736.

Parihar AK, Dixit GP, Kumar N, Mishra VD and Chaturvedi SK. 2016. Genetic variability for herbicide tolerance in fieldpea. *Pulses Newsletter (January–March, 2016)* **27**(1): 6.

Patel MM, Patel AI, Patel IC and Tikka SBS. 2003.Weed control in cowpea under rainfed conditions. Pp. 203–206. In: *Advances in arid legumes research*. (Eds. Henry A, Kumar D and Singh NB), Scientific Publishers Jodhpur (India).

Patra AK and Nayak BC. 2000. Response of horsegram (*Macrotyloma uniflorum*) to agronomic management practices. *Indian Journal of Agronomy* **45**(2): 357–360.

Ram H and Singh G. 2011. Studies on the bio–efficacy of herbicides for weed control in soybean under different sowing methods. *Indian Journal of Ecology* **38**: 11–13.

Rao VS. 2018. Herbicide resistant biotech crops and their import to Indian agriculture. *Indian Journal of Weed Science* **50**(3): 223–238.

Rao AN and Chauhan BS. 2015. Weeds and Weed Management in India - A Review. Pp. 87-118. In: *Weed Science in the Asian-Pacific Region*. Indian Society of Weed Science, Hyderabad.

Rao AN and Nagamani A. 2010. Integrated Weed Management in India–Revisited. *Indian Journal of Weed Science* **42**(3): 1-10

Rao AN, Singh RG, Mahajan G and Wani SP. 2020. Weed research issues, challenges, and opportunities in India. *Crop Protection* **134**: 104451

Rao AN, Brainard DC, Kumar V, Ladha J K and Johnson DE. 2017. Preventive weed management in direct-seeded rice: Targeting the weed seedbank. *Advances in Agronomy* **144**: 45-142

Reddy KN and Nandula V. 2012. Herbicide resistant crops: History, development and current technologies. *Indian Journal of Agronomy* **57**(1): 1–7.

Siabusu L, Kambikambi T, Lungu D and Chanda R. 2020. Phytotoxicity effects of topramezone and dicamba herbicide on selected legumes. *Journal of Research in Weed Science* **4**: 83–91.

Singh G. 2011. Weed Management in Summer and *Kharif* Season Blackgram [*Vigna mungo* (L.) Hepper]. *Indian Journal of Weed Science* **43**(1&2): 77–80.

Singh G, Aggarwal N and Ram H. 2014. Efficacy of post–emergence herbicide imazethapyr for weed management in different greengram (*Vigna radiata*) cultivars. *Indian Journal of Agricultural Sciences* **84**: 540–543.

Singh M, Kumar R, Kumar S and Kumar V. 2016. Critical period for weed control in field pea. *Legume Research* **39**(1): 86–90.

Singh S, Singh AN and Bhan VM. 1995. Studies on the chemical control of weed in summer greengram (*Vigna radiata* L.). *Indian Journal of Weed Science* **27**(4): 158–159.

Soni KC and Singh H. 1988. Weed Management in Urd Bean. *Indian Journal of Weed Science* **20**(3): 33– 37.

Sosnoskie LM, Herms CP and Cardina J. 2006. Weed seed bank community composition in a 35–year–old tillage and rotation experiment. *Weed Science* **54**: 263–273.

Susha VS, Das TK, Nath CP, Pandey R, Paul S and Ghosh S. 2018. Impacts of tillage and herbicide mixture on weed interference, agronomic productivity and profitability of a maize–Wheat system in the North–western Indo–Gangetic Plains. *Field Crops Research* **219**: 180–191.

Thimmegowda MN, Hanumanthappa DC, Ningoji SN and Sannappanavar S. 2022. Evaluation of weed management efficacy of PoE herbicides in blackgram under semi–arid Alfisols. *Indian Journal of Weed Science* **54**: 174–181.

Thorp KR and Tian LF. 2004. A review on remote sensing of weeds in agriculture. *Precision agriculture* **5**(5): 477–508.

Tiwari VK, Yadav RS, Mahajan R, Namdev B and Kumar S. 2018. Effect of weed management practices on yield attribution of blackgram under late sown. *Journal of Pharmacognosy and Phytochemistry* **7**(1): 742–746.

Wall DA and Friesen GH. 1991. Effectiveness of selective herbicides for the control of annual weed species in lathyrus (*Lathyrus sativus* L.). *Crop protection* **10** (6): 496–500.

Yadav RB, Vivek Singh RV and Yadav KG. 2013. Weed management in lentil. *Indian Journal of Weed Science* **45**(2): 113–115.

Yaduraju NT and Sharma AR and Rao AN. 2015. Weeds in Indian Agriculture: Problems and prospects to become self-sufficient. *Indian Farming*. **65**(07): 02-06

Young SL, Meyer GE and Woldt WE. 2014. Future directions for automated weed management in precision agriculture. Pp. 249–259. In: *Automation: The Future of Weed Control in Cropping Systems*. (Eds. Young SL and Pierce FJ), Dordrecht, The Netherlands: Springer.

Zimdahl RL. 2013. *Fundamentals of Weed Science*, 4th edn. Academic Press, San Diego, California, USA. 664 p.