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The Indian Society of Weed Science (since 1969) publishes the original research and scholarship in the form of peer-reviewed Weed Science research articles in Indian Journal of Weed Science. Topics for Weed Science include the biology and ecology of weeds in agricultural, aquatic, forestry, recreational, rights-of-ways, and other ecosystems; genomics of weeds and herbicide resistance; biochemistry, chemistry, physiology and molecular action of herbicides and plant growth regulators used to manage undesirable vegetation and herbicide resistance; ecology of cropping and non-cropping ecosystems as it relates to weed management; biological and ecological aspects of weed management methods including biocontrol agents, herbicide resistant crops and related aspects; effects of weed management on soil, air, and water resources. Unpublished papers presented at symposia, perspective articles, opinion papers and reviews are accepted. Consult the Chief Editor for additional information.

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PERSPECTIVE ARTICLE

Weed management role in meeting the global food and nutrition security challenge

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ABSTRACT

The global agricultural production must increase by around 70% to meet the food and nutrition demands of 9.9 billion people, by 2050. It was predicted that 670 million people will still be undernourished in 2030. Hence, feasible and cost-effective strategies in the global agri-food system need to be implemented for meeting nutrition security. Weed management played a key role in achieving global food and nutrition security, till to date. In this paper the role of weed management in meeting food and nutrition security is revisited in view of the changed scenario of prevailing unintended ecological imbalance, climate change, water overuse and waste, soil degradation, loss of natural resource quality, and declines in biodiversity, increased herbicide use, and chemical runoff that are decreasing crop growth yields and raising reasonable concerns about the sustainability of the current agricultural methods in meeting the future food and nutrition security. The future role of weed management is discussed in terms of: reducing the continued losses caused by weeds and improving crops productivity and production by reducing yield gap; improving resources (land, water, light, nutrients); improving farmers income; advancement of farmers livelihood; combating climate change and balancing biodiversity. The possible role of climate resilient integrated weed management in playing the intended roles in agri-food system is discussed. In order to play much more sustainable role, the weed management, as an integral part of agricultural production, needs to move away from its mono-disciplinary perspective at targeting weeds to multidisciplinary and multifaceted technological solution to serve as a component of overall technological solutions to improve agricultural production for achieving ever increasing food and nutritional security challenges.

Keywords: Climate resilience, Crop yield gap, Food security, Integrated weed management, Nutrition security, Resource use efficiency, Weeds competition

INTRODUCTION

Food and nutrition security challenge

The global food and nutrition security challenge is to meet the growing demand for food to an estimated as 9.9 billion people by 2050, an increase of more than 25% from 2020. The global agricultural production must increase by around 70% by 2050, to satisfy a growing demand for food. Food insecurity can disrupt agricultural efforts and economic growth and hence future efforts should aim at reducing poverty while providing access to nutritious foods as per growing population's food and nutrition demand.

The term nutritional security refers to the intake, in an adequate amount, of food enriched with essential nutrients. The calories that are available to a higher percentage of the world's population are greater today, than earlier. Yet, 828 million in 2021 are undernourished (food insecurity) (FAO, IFAD, UNICEF, WFP and WHO 2021) resulting in wasting and stunting with 2 billion lack essential nutrients (Haddad *et al.* 2014; Huang *et al.* 2020) causing a reduced potential to attain full physical and cognitive development, while 2 billion suffer from over-nutrition resulting in excess weight or obesity (Haddad *et al.* 2014; Huang *et al.* 2020). In the United States, 42.2 million citizens are suffering from inadequate access to nutritious food–suffering from either hunger or obesity (https://www.aplu.org). The food insecurity varied in different regions of the world (**Figure 1**). It was predicted that 670 million people will still be undernourished in 2030. The global threat to food and nutritional security, due to the growing population, addresses the need to implement feasible and cost-effective strategies in the global agri-food system.

Climate change, including weather extremes and variability of temperatures and rainfall patterns, is already affecting agri-food systems and natural resources and is expected to threaten farm productivity, decreasing harvests and accelerate

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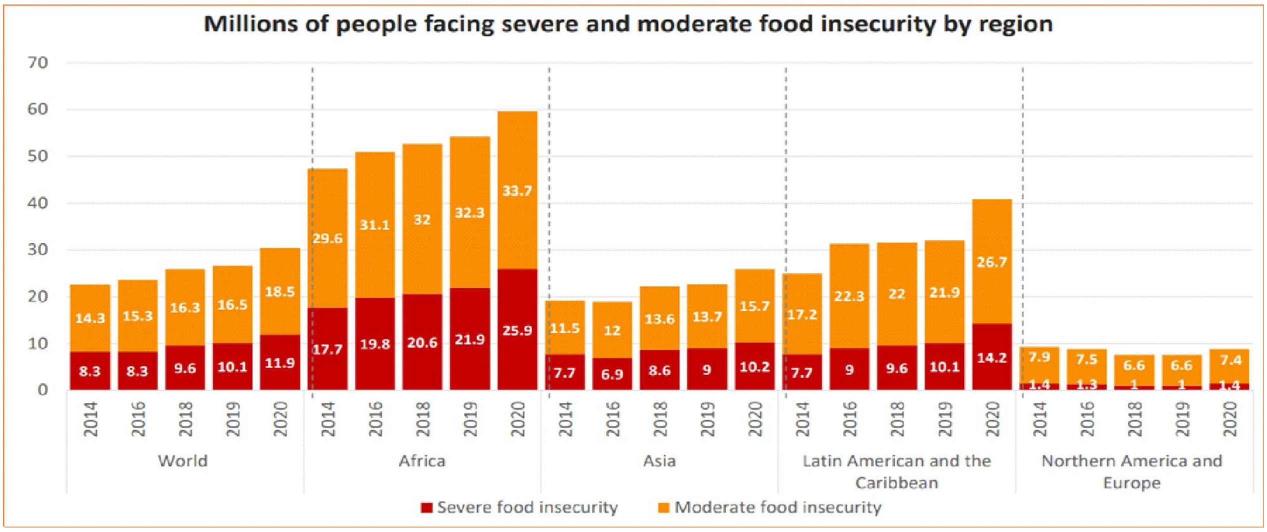

Figure 1. Food security differences in the world and its different regions (Source: FAO, IFAD, UNICEF, WFP and WHO. 2021)

hunger and poverty (FAO 2022). The direct effect of climate change on food systems is on the crop production. A study on the climate change impact on the yields of the top ten global crops–barley, cassava, maize, oil palm, rapeseed, rice, sorghum, soybean, sugarcane and wheat indicated that the percentage change in recent yield over all harvested croplands ranged from -13.4% (oil palm) to +3.5% (soybean) (Ray *et al.* 2019). Among the top three global cereals, recent yields have decreased for rice (-0.3% or ~-1.6 million tons (MT) annually) and wheat (-0.9% or ~-5.0 MT annually) and increased negligibly for maize (0% or ~0.2 MT annually) which means an annual 0.4%, 0.5% and 0.7% decrease in consumable food calories available globally from rice, wheat and maize, respectively. The range of impacts of mean climate change on crop yields and production in different regions was observed indicating the underlying variations and interactions of the agro-meteorological conditions and crop management, whose understanding is vital to achieve food and nutrition security in a sustainable manner. Climate change also reduces levels of nutrients in plant-based foods (particularly cereals and legumes) as a result of increased levels of carbon dioxide in the atmosphere (Myers *et al.* 2014).

The possible way to achieve food and nutrition security, in the era of climate change, is to identify the biological and physical constraints and sustainably alleviate them by developing and implementing location specific technologies that improve total factor productivity of agri-food systems.

Weeds and agri-food systems

One of the main causes of the chronic food insecurity witnessed in the world is poor crop yields, largely caused by pests including weeds which are causing the loss of more than 40% of the world's food supply (Carvajal-Yepes *et al.* 2019) with the highest losses in food-deficit regions with fast-growing populations (Savary *et al.* 2019). Amongst the pests, weeds cause the highest potential crop yield loss (34%), while the insect pests and pathogens cause 18 and 16% losses, respectively (Oerke 2006).

Weeds have the ability to survive under adverse condition, as they extract more water, nutrients and other resources thereby reduce crop yield by 10 to 80% (Rao and Chauhan 2015; Singh *et al.* 2018). The crop yield losses due to weeds depend on several factors such as associated weed flora, weed emergence time, weed density, type of weeds, crops, cropping systems and management practices used (Rao *et al.* 2007; Rao *et al.* 2014). In monetary terms, the reported annual losses due to weeds varied across different countries [*eg.* AU$ 3.3 billion in Australia (Llewellyn *et al.* 2016); US $ 11 billion for ten crops in India (Gharde *et al.* 2018); the potential spring wheat production loss due to weeds was estimated as 4.8, 1.6, and 6.6 billion kg with a potential loss in value of US$1.14, US$0.37, and US$1.39 billion for the United States, Canada, and combined, respectively (Flessner *et al.* 2021); potential loss in value for corn is $27 billion and for soybean is $16 billion in USA based on data from 2007 to 2013 (https://wssa.net/wssa/weed/croploss-2/)]. Certain weeds like red rice (Morat *et al.* 2018) and *Parthenium* (Sushilkumar 2014, Corin *et al.* 2017) alone cause tremendous crop yield losses and can have significant impacts on global food security. An empirical case study on the economic, environmental, and food security impact of red rice infestation in the U.S. indicated that losses under a moderate infestation scenario from 2002 to 2014 amount to 5.7 million tons or 6%, which is enough to feed 12 million additional people a year, with an environmental cost of $457 million (Morat *et al.* 2018).

In addition to causing enormous crop yield losses, weeds reduce resources (land, water, nutrients, light, energy, labor) use efficiency and crop quality, serve as alternate hosts to several pests and diseases, cause health (skin and respiratory) problems to human beings, waste human energy and increase cultivation cost to manage them. Weeds infestations can result in livelihood impacts beyond crop yield losses, with school age children spending time weeding instead of attending education classes and limiting future prospects. Many of the weed impacts may be difficult to quantify economically, but are significant if the true costs of weeds are considered. To ensure food security on sustainable basis, reducing weeds interference and boosting resources use efficiency are critical.

The negative impacts of weeds may be prevented, or contained, by implementing weed management measures including cultural (cultivar choice, crop rotation, tillage, mechanical weeding, *etc.*), preventive, biological (parasitoids, predators, *etc.*) and chemical measures (biopesticides and herbicides) (Mishra and Singh 2012; Ramesh *et al.* 2017, Rao *et al.* 2021). The progress made so far on developed weed management methods will not be discussed in this paper, in detail, as the research progress in weed management in different countries and weed management approaches, developed and used so far, were reviewed earlier (Rao *et al.* 2014; 2015, 2020; Rao and Yaduraju 2015; Mishra *et al.* 2016; Rao and Matsumoto 2017; Westwood *et al.* 2018; Dilipkumar *et al.* 2020; Zhu *et al.* 2020). Recently, the climate resilient integrated weed management approach (CRIWM) has been suggested (Rao 2022).

The need for revisiting the role of weed management

Global food production increased enormously during the second half of the twentieth century, keeping pace with population growth. Taking 1961 as a base year, average yields of staple cereals have increased throughout the world, but to different degrees. The strongest increases have been witnessed in Latin America where average yields are more than four-fold larger. In Europe and in (irrigated) agriculture in Asia, yields have doubled or tripled but more modest increases of around 70% have been observed in Africa (Giller *et al.* 2021). Different regions of the world have expanded food production along contrasting pathways. The green revolution has relied greatly on intensification and agrochemicals to increase yields (Tilman *et al.* 2002) and caused unintended ecological consequences leading to a slowdown in yield growth, water overuse and waste, soil degradation, natural resource quality loss, and biodiversity decline, pesticide use increase, and chemical runoff are decreasing crop growth yields and raising justified concerns about the sustainability of the current agricultural methods (Tilman *et al.* 2002; Robertson and Swinton 2005). Such environmental degradation will trigger substantial losses in food supply capacity by 2050.

The climate change, together with other global changes in water availability, and land cover, and altered nitrogen availability and cycling (all strongly influenced by human activities), has increased concerns about achieving global food security (Rosegrant *et al.* 2014). The global agri-food systems have become vulnerable to ongoing climate change which has reduced global agricultural total factor productivity (TFP) by about 21% since 1961 with substantially more severe (a reduction of ~26–34% in warmer regions (Ortiz-Bobea *et al.* 2021). The stagnation of crop yield (Grassini *et al.* 2013) and the overall decline in total factor productivity (Ortiz-Bobea *et al.* 2021) necessitates the revisit the agricultural technologies. The unsustainable agri-food systems reduce the access to affordable, healthy diets, increasing their risk of poor health and diet-related diseases (Fanzo and Downs 2021). Thus, the agricultural research should focus on developing agri-food systems and technologies that meet both production and environmental targets together while enabling farmers adapt to other emerging challenges, such as water deficit/abundance, pesticide/herbicide resistance, yield plateaus, and the changing climate (Hunter *et al.* 2017).

Weeds are the universal constituents of global agri-food systems causing varying negative impacts and one of the most vital challenges in agriculture due to their capacity to quickly adapt to weed management practices and the changing climate. Hence, weed management plays a key role in attaining the intended food-nutrition security. Herbicides are commonly used for managing weeds in developed world and herbicide use is increasing in developing world. Herbicides constitute half of the consumed 4 million tons of pesticides worth 84.5 billion USD in 2019 and is expected to be 130.7 billion USD by 2023, globally. The discovery of new herbicides has declined significantly over the past few decades and herbicide-tolerant or herbicide-resistant crop technologies have allowed the use of available nonselective herbicides to manage weeds in crops

(Kraehmer *et al.* 2014). The overreliance on herbicides for weed control by farmers of the world, for a long period of time, has resulted in selection of weeds with resistance to herbicides in many countries (Heap 2022). More herbicide-resistant weeds are expected in future, especially in developing countries as their economies grow and where herbicide resistance is currently under-reported (Hulme 2022). Any effort involving improvement in food grain production to meet current and future food demands and double the farmers' income must involve weed management (Rao *et al.* 2017). The growing demand for agri-food products requires to explore innovative ways of managing weeds for attaining current and future food and nutrient security, under a changing climate and loss of biodiversity. The innovative ways can be identified, experimented, fine-tuned and adopted only when we revisit existing technologies and identify each component technology role in managing weeds under changing scenario of agri-food system.

In this paper, the weeds impact in aggravating the existing food and nutrition challenge is explained, the role of weed management in attaining food and nutrition security is revisited and the components of climate resilient integrated weed management (CRIWM) to combat specific challenges are specified for further strengthening to play key role in technological inputs of agri-food systems for meeting global current and future food and nutrition goals.

THE ROLE OF WEED MANAGEMENT

Weed management proved to be an important component of agricultural technology that enabled agriculture to produce food as per the needs of increasing population, so far. The current situation of global food and nutrition demands and currently prevailing adverse conditions in agri-food systems necessitates Weed Scientist to revisit the role of weed management to ascertain how the available knowledge be utilized and on which areas research should be focused to evolve technologies needed to successfully meet the challenge of food and nutrition security, in years to come. Different roles of weed management in improving agri-food systems productivity, sustainability and profitability are discussed briefly.

Reducing the losses caused by weeds and improving crops production by reducing crops productivity gap

Large yield gaps (the gap between actual production and the best crop yield achievable with available crop varieties, technologies and management) exist in irrigated and in rainfed agriculture (Giller *et al.* 2021) in both Africa and Asia indicating that there is still an enormous potential for improving crops productivity. The crop protection could help farmers increase crop productivity and production by the management of diseases, insects and weeds, which could result in 20-30% global increases of maize, rice and wheat yields (Rosegrant *et al.* 2014). Amongst pests, weeds cause more yield losses than others and the yield gaps due to the crop losses caused by weeds must be highest as unmanaged weeds cause loss up to 100%. Weed control accounted for 30% of crop yield losses, while pests and diseases together accounted for 50% of the difference in sugar beet yield between growers (Hanse *et al.* 2018) and the weed management represents one of the critical agronomic strategies to fill the yield gap, improve crop productivity and reduce yield gap (Eash *et al.* 2019, Peramaiyan *et al.* 2022).

IWM technology was proven to successfully bridge the crops yield gap, thus, enhancing crops productivity in different countries of the world (Rao and Nagamani 2010; Alagbo *et al.* 2022; Peramaiyan *et al.* 2022; Rao *et al.* 2017a; Rao 2022). The climate change has already affected global food production (Ray *et al.* 2019). The suitability of crops to a particular region and weeds associated with the crops will change as a result of climate change, and as a consequence crops area may shift. Potential crop weed competition and crop yields in particular climate-soil zones will change and hence yield gap may alter. The CRIWM strategies need to be identified and used to fill yield gaps under climate change scenario (Rao 2022).

Improving resources use efficiency

The sustainable management and utilization of natural resources, including land, water, air, climate and genetic resources for the benefit of present and future generations (FAO 2022). Increasing crop production is thus an important challenge in addressing economic growth, alleviating poverty and arresting environmental degradation across the world. Cereals [including rice, maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* (L.) Moench)], pulses and oil seeds are the most important food and cash crops for millions of rural farm families in the predominantly mixed crop-livestock farming systems. The efficient production of cereals and oil seeds, per unit of input, is therefore central to the food security challenge. Weed Science is not just about weed control and it should help show the way in shaping and improving our management of all natural resources (Chandrasena and Rao 2017).

Weeds compete severely with crops that have similar resources requirements for optimal growth and thus management practices designed to improve crop yield may also help the weeds growth and development. One of the approaches to face the challenge is production of crops with increased input resource use efficiency by managing impediments such as weeds, which are adaptable to all adverse environments and compete with the crops for utilization of land, labor, light, nutrients and water resources and reduce crops productivity, leading to low efficiency of input use, suppressed crop output and reduced food security (Yaduraju and Rao 2013) .

a. Land use efficiency (LUE)

1,550 Mha of land is being cultivated (Deininger and Byerlee 2011). There is no or very little new land to bring under cultivation in the land-scarce countries and regions such as Eastern Europe and Central Asia, East and South Asia, Middle East, Near East and North Africa, Australia and other countries (Bruinsma 2009; Blomqvist *et al.* 2020). In sub-Saharan Africa and Latin America, with some in East Asia large tracts of land with varying degrees of agricultural potential without adequate infrastructure or to be protected for environmental reasons (Tilman *et al.* 2001), or lack access to appropriate agricultural technologies or the economic incentives to adopt them (Bruinsma 2009). The crop production increased dramatically, so far, without a corresponding expansion of cropland area due to improvement in agricultural practices (Blomqvist *et al.* 2020). Hence, in future too, for the increased crop production without disturbing ecological balance, the crop productivity increase will remain as the driving force behind the majority of crop production gains.

Weeds compete with the crop for the land too by covering crop land space available for crop growth. When weeds shade crop plants, less sunlight is available for crop production (Gianessi and Sankula 2003). The most obvious way to improve the LUE is adoption of components of CRIWM such as intercropping which was proved to suppress weeds and increase land equivalent ratio (LER) which is the ratio of the area under sole cropping to the area under intercropping needed to give the same yields. The intercropping strategies saved 16–29% of the land as compared to mono-cultures grown under the same management as the intercrop (Li *et al.* 2020). The choice of legume for intercropping with cereals determines the productivity of intercropping systems by ensuring compatibility in utilizing growth resources (Iqbal *et al.* 2019). The green gram (*Vigna radiata* L.) and black gram (*Vigna mungo* L.) may impart sustainability to cereal-legume intercropping system by enhancing LUE attained through higher utilization efficiency of farm applied inputs. Intercropping produces from about 16% to 30% greater yields on a given piece of land than do each crop species cultivated in monoculture and helps in suppression of weeds (Himmelstein *et al.* 2017; Martin-Guay *et al.* 2018).

Utilization of weed smothering ability of component crops coupled with adoption of best weed management in inter cropping systems was reported to increase LUE by 47% (Rao *et al.* 2017). The maize-green gram intercropping hold potential to impart sustainability to maize production by reducing weeds infestation (431% lower than sole maize) and could be a viable option for smallholder farmers in semi-arid environment (Abbas *et al.* 2021). The optimization of intercropping system may potentially reduce the degree of inter and intra species competition and boost the resources use benefits offered by cereal-legume intercropping systems (Amos *et al.* 2012). Other component of CRIWM *viz.* a crop rotation, and more crops per year, maximizes land productivity (Zohry and Ouda 2018).

b. Water use efficiency (WUE)

The water is becoming increasingly scarce and expensive across the world due to its excessive exploitation of water, climate change induced rise in temperatures and erratic rainfall patterns and resulting ground water depletion. Management of water resource and improving WUE are the most challenging since the agricultural sector consumes 70 % of this resource that cannot be replenished. The crop yield gap reduction is often limited by “economic water scarcity” due to several economic and ecological reasons in both developed and developing countries (Jägermeyr *et al.* 2016, Rosa *et al.* 2020). Weeds use water which could be used by the crop. Thus, efficient and improved irrigation technological components of CRIWM can be used for managing weeds and improve WUE.

The weed-crop competition for water depends on the relative growth of the crop vs. the weeds and plant stress status depends on the light intercepted and soil water reserves depletion rates (Berger 2007). Weeds competition for moisture under moisture stress conditions cause crop yield loss of more than 50% depending on weed density and the plant’s physical characteristics (Abouziena *et al.* 2015). Water transpired by weeds could aggravate crop drought stress in dry periods through increasing soil moisture deficits, resulting in a decrease in crop water use efficiency. The processes in crops/weeds WUE in crop-weed systems are intertwined in arable lands, owing to crop-weed competition and overlapping drivers (Singh *et al.* 2022). To increase the crops water use efficiency, an important measure adopted is the control of weeds as weeds utilize a considerable amount of soil water (Rao and Shetty 1983; Farooq *et al.* 2019). An increase in WUE of 30 to 70% was obtained with weed management in maize (Borza 2018).

In maize-wheat cropping system in India, higher grain yield, enhanced water productivity and profitability were obtained when irrigation was applied, using drip irrigation system, either at 80- or 120-mm cumulative pan evaporation (CPE) coupled with pre-emergence application (PE) of atrazine 750 g/ha or post-emergence application (PoE) of tembotrione 120 g/ha in maize and CRI + 75 or 100 mm CPE in with of clodinafop + carfentrazone 60 + 20 g/ha PoE or pinoxaden + metsulfuron 50+4 g/ha PoE in wheat (Rawal *et al.* 2022).

An eco-friendly weed-control and water-conservation technology for direct-seeded rice saved about 40% in irrigation and costs of cultivation without any yield penalty, when compared to the high cost of labor and inputs for transplanted rice (Yaduraju *et al.* 2021). Technological adoption of micro-irrigation systems in different crops was reported to cause minimized weed problems (Kumar *et al.* 2022; Mohanpuria *et al.* 2022), improves water productivity (Mohanpuria *et al.* 2022), saves more than 60% water and increases the yield by 30-40% over traditional methods (Magar and Nandgude 2005), enhanced inputs use efficiency and also reduced expenditure on weed management (Kumar *et al.* 2022). It is possible to increase in irrigated area by saving water through best weed management and utilize saved water for bringing more area under irrigation (Rao *et al.* 2017). Intercropping is a sustainable way to offers ecological mechanisms for weed suppression, efficient use of water and increase crop productivity (Rao and Shetty 1983a; Li *et al.* 2020).

Soil mulching component of IWM can cut evaporation by around 75%, cuts water loss from 0 to 30cm soil depth, raises soil water storage (up to 41%), increases grain water use efficiency by 14% (Abouziena *et al.* 2015). The weed management with organic or plastic film mulching, and different conservation tillage systems improved crop grain yield remarkably while conserving soil moisture (Liu *et al.* 2014). Maize, wheat, cotton and potato yields have increased by 33.7%, 33.2%, 26.1% and 36.7%, respectively, while their corresponding water use efficiency levels have increased by 38.9%, 30.2%, 30.2% and 37.8%, respectively with plastic mulching in China (Yan *et al.* 2010). Plastic mulching, a technique to cover the soil around the root zone of a plant with a plastic film, is a useful practice to restrict weed growth, conserve moisture and reduce the effect of soil-borne disease. In addition to preventing weed growth, plastic mulch also causes soil disinfestation due to solarization; soil cover for heat absorption; minimization of evaporation and escape of fertilizer; insects repelling or attracting; and soil temperature manipulation (Patle *et al.* 2020).

The opportunities exist to enhance crops WUE through adoption of CRIWM practices such as tillage, time of crop planting, crop establishment method, cover crops, drought tolerant weed competitive crop cultivars, and herbicide use (Rao 2022).

c. Light use efficiency (LUE)

The cultural weed management practices such as using smother crops and narrow row spacing exploit plant light responses to promote crop growth and suppress weed growth while improving LUE. The LUE can be improved by understanding weed/crop interactions the physiological and morphological responses of crops and weeds to light, particularly in these times of climate change. Light interception pattern and leaf area index (LAI) observations revealed that inclusion of smother crop viz, cowpea and mungbean resulted In quicker and earlier attenuation of maximum LAI and percentage of light by crops (Rao and Shetty 1981). Intercropping is a sustainable way for weed suppression, efficient use of light and crop productivity improvement (Li *et al.* 2020)

d. Nutrients use efficiency (NUE)

The nutrients are essential for crop growth along with water and, as demand for food grows, so does demand for fertilisers too. The macro- and micro-nutrient deficiency in soil has been assessed across many parts of the world, thus limiting the nutrient uptake in plants and ultimately in humans (Dhaliwal *et al.* 2022). Hence, globally many countries are facing silent epidemics of nutritional deficiencies in human beings and animals. The lack of diversity in diet, i.e., cereal-based crops deficient in mineral nutrients is an additional threat to nutritional quality (Dhaliwal *et al.* 2022). Thus, diversified crops with optimized by balanced nutrient availability and increased nutrient use efficiency of crops by managing crops and weeds is essential.

The NPK content of the weeds was reported to be higher as compared to the crop plants resulting in reduced nutrient use efficiency. Adoption in different crops the improved CRIWM practices such as mulching (Ram *et al.* 2017), use of competitive crops (Rao and Nagamani 2007), inter cropping (Choudhary and Choudhury 2016), appropriate crop establishment methods (Rao *et al.* 2017), tillage (Monsefi *et al.* 2014), cover crops (Ullah *et al.* 2020), water management, optimal fertilization schedule adoption (Rao and Ladha 2011), and use of appropriate nutrient source (Ghosh *et al.* 2020), etc. was reported to increase crop nutrient uptake and use efficiency. Across Sub-Saharan Africa, the traditional maize systems maintain productivity while reducing biotic constraints such as weeds by intercropping or rotating leguminous trees and shrubs, and annual legumes with maize (Snapp *et al.* 2010; Ajayi *et al.* 2011), or by incorporating legume weed residues into croplands (Mapfumo *et al.* 2005). The extrapolation of such technologies should be encouraged.

In rice, improved weed management adoption was reported to cause reduced input use, increased energy output and energy use efficiency. Achievement of a mean 54% higher grain energy yield with a 104% increase in economic returns, 35% lower total water input, and a 43% lower global warming potential index was observed (Ladha *et al.* 2015) in a study conducted at different countries in South Asia, when integrated weed management was a component of best management practices, conservation agriculture and crop diversification (Ladha *et al.* 2015). Thus, weed management plays a key role in improving resources use efficiency while improving crop productivity to help increase food production and attain food and nutrition security.

Improving farmers' economic returns

FAO estimated there are about 570 million farms in the world, of which about 475 million (about 84 %) are small (≤2 ha) (Lowder *et al.* 2014). About 92% of all farms are located in developing countries. Smallholder farms will continue to produce the major share of the food in rural areas and will be critical to the food security of a large proportion of the world's population (Giller *et al.* 2021). Majority of the research findings on integrated weed management proved that managing weeds, irrespective of method of establishment, by the use of herbicide or their combinations in integration with hand weeding results in increased economic returns of small holder farmers (Rao and Ladha 2013). For example: crop rotations are a component of CRIWM. The increases in crop productivity can also be achieved by improving cropping system yield by adopting crop rotations through modification of spatial and temporal arrangement of individual crops (Zohry and Ouda 2018). Inclusion of weed smothering pulse crops helps in improving nutrition security. In multiple cropping feasible environments, with a longer growing season, capture of resources, crop yield, the farmers income and livelihood are often improved (Gaba *et al.* 2014; Guilpart *et al.* 2017). An eco-friendly weed-control and water-conservation technology for direct-seeded rice uses less energy and fertilizer consumption in DSR with lower production costs than in transplanted rice and higher economic returns (Yaduraju *et al.* 2021). Enhancing smallholders' production capacities and their economic and social resilience may have a positive impact on food security and nutrition at different levels (Riesgo *et al.* 2016).

Advancement of the farmers' livelihood

Agri-food systems directly employ over 1 billion people and provide livelihoods to another 3.5 billion (FAO 2022a). Labour inputs into African and Asian smallholder agriculture are very high and a shortage of labour from land preparation through to harvest, but especially for adequate weeding, is a widespread and severe constraint to crop production (Ogwuike *et al.* 2014; Leonardo *et al.* 2015). The scarcity of agricultural workers in developing countries is due to migration of rural labours to multi-cities for industrial work in crop growing season. The migration of labor to cities can be avoided by improving their livelihoods in rural areas. Weeds use is one of the important components of CRIWM. Farmers may be encouraged to utilize the weeds, prior to flowering, to initiate simple processing units to make vermicompost or compost and market to earn additional income (Rajkhowa *et al.* 2005, Chandrasena and Rao 2019). Medicinal and pharmaceutical properties of weeds (Ekwealor *et al.* 2019) also can be a profitable venture for rural areas to improve their livelihoods.

The improved weed management technology is knowledge intensive and needs to be extended to farming community to improve the crops productivity and farmers income (Rao *et al.* 2014a). The livelihood of rural youth/labor can be improved along with farmers using the technology if they are trained on improved weed management technologies of CRIWM and encouraged financially to initiate custom hiring centers to give improved equipment such as drones for herbicide application and improved automated mechanical weeders/implements (Balas *et al.* 2022) used in precision weed management (Monteiroand Santos 2022). In future, many more knowledge intensive weed management technologies based on computing power, artificial intelligence, deepfield robotics, big data or digital farming, automated weed control and precise spot spraying of herbicides will emerge (Westwood *et al.*

2018, Korres *et al.* 2019. Amend *et al.* 2019) and weed management will play much greater role in improving the farmers income and livelihood.

Combating climate change impact

Agriculture accounts for about 14-24 per cent of greenhouse gas (GHG) emissions. Addressing the challenges of climate change, and improving food security will require increased food production with reduced emissions of GHG and make agri-food systems more resilient to shocks and climate change negative impacts. The climate change may be mitigated by adoption of CRIWM approach which involves weed management components like improved agronomic practices, direct-seeding, location specific climatic conditions adopted weed competitive crops and cultivars, location specific nutrients/fertilizer/irrigation/ herbicide application and the conservation agriculture components like zero tillage, crop rotation and crop residues mulching (Rao 2022).

The genetically modified herbicide tolerant crop cultivar technology component of integrated weed management decreased the carbon emissions and allowed more carbon to be retained in the soil due to utilization of practices such as reduced tillage with farm equipment, decreased burning of fossil fuel and use of relatively lesser quantity of herbicides with lesser EIQ values (Brookes and Barfoot 2020). However, over reliance on the use of glyphosate by farmers and the lack of crop and herbicide rotation by farmers, in some regions, has contributed to the development of weed resistance (Brookes 2022). The widespread adoption of transgenic crops carrying foreign genes have also concerns of potential toxicity and allergenicity to human beings, potential risks such as chances of gene flow, adverse effects on non-target organisms, evolution of resistance in weeds (Kumar *et al.* 2020). Hence, cautious approach, with strict adoption of stewardship guidelines adoption, is essential .while using the technology for combating climate change, improving crop production which is essential for food security.

Balancing biodiversity

The global warming, natural habitats destruction, deforestation and exposure to pesticides have contributed to the loss of biodiversity (FAO 2021, Renard and Tilman 2021) which impact food systems in a variety of ways including loss of crop diversity, traditional varieties, and lower in-field diversity, increases vulnerability to climate change and increases crop failure. The weed management component, intercropping, along with crop biodiversity, helps lead to greater and more stable yields, decrease land clearing, and lower the use of harmful agrochemicals (Renard and Tilman 2021).

Weeds are also a part of the primary producers within farming systems and are an important component of the agroecosystem as weeds play an important role within agroecosystems in supporting biodiversity (Marshall *et al.* 2003). Weed diversity is indicative of the wider sustainability of the whole cropping system (Storkey and Neve 2018) as weed species support a great diversity of wildlife, including insects, which use them as larval food plants (Capinera 2005). The presence of non-crop plants, such as weeds, can also have agronomic benefits, including nutrient cycling and improvement in soil physical properties (Blaix *et al.* 2018). The maintenance of biodiversity by CRIWM would allow weeds to provide resources that attract and maintain populations of parasitoids, predators and pollinators and can make crops less attractive to pests, thus acting as trap crops (Balfour and Ratnieksps 2022). Thus, an appropriate climate resilient weed control measure plays a key role of balancing the weeds requirements for biodiversity and more sustainable crop production methods. CRIWM helps in maintaining the needed biodiversity as it focuses to match crop production with conservation of biological resources and the development of more sustainable agri-food systems.

CONCLUSIONS

Improving global food and nutrition security and alleviating poverty is possible only through need based agricultural innovation. The key challenge for common global future will be to grow food sustainably—meeting the demands of a growing population without degrading our natural resource base and associated environment. The adoption of appropriate technologies would substantially increase food production, and improve food security, even under climate change conditions (Rosegrant *et al.* 2014). Sincere efforts need to be made to develop sustainable CRIWM to include them as a component of improved agricultural technologies intended to protect crops from biotic and abiotic stress, alleviate the global food crisis, and ensure food and nutrition security.

Weed management as an integral part of agricultural production needs to move away from its mono-disciplinary perspective at targeting weeds to multidisciplinary and multifaceted technological solution to serve as a component of overall technological solutions to improve agricultural production for achieving ever increasing food and nutritional security challenges. The future weed management technologies that are being invented and adopted will also have much greater impact on global agricultural production, food consumption, food security, and environmental quality. Hence, they should target at agricultural transformation aimed at an eco-efficient revolution with increases in the efficiency of scarce resources used to meet the food demands of increasing population while minimizing many negative environmental impacts associated with current agri-food systems (Rao *et al.* 2017, Rao 2022). Food and nutrition security can be achieved by developing and using knowledge of the best CRIWM practices based on interdisciplinary inputs. The component technologies of CRIWM, prior to their use by farming community, have to be well chosen and be fine-tuned for location specific needs of farming community.

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OPINION ARTICLE

Weed biology: An important science to develop effective weed management strategies

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ABSTRACT

The world's population is increasing at an alarming rate and to feed this population, food production needs to be increased significantly. There are several abiotic and biotic factors affecting the productivity of crops. Among biotic factors, weeds are the most important constraint to crop production throughout the world. They cause a huge yield loss in different crops and cost growers a significant amount of money. Herbicides are widely used to control weeds; however, there are concerns over the evolution of resistance in weeds, limited availability of herbicides with new modes of action, and environmental pollution. These issues suggest the need to reduce reliance on herbicides and develop sustainable weed management programs. However, to develop such programs, there is a need to gain a better understanding of weed biology. This article briefly describes the importance of weed biology in managing weeds.

Keywords: Genetic diversity; Phenology; Seed ecology; Weed biology; Weed emergence; Weed management

INTRODUCTION

The global population is expected to be increased by 1 billion in the next 10 years and to feed this ever-increasing population, food production needs to be increased significantly. Several abiotic (*e.g.*, drought, flood, heat, *etc*.) and biotic (*e.g.*, insects, diseases, weeds, *etc*.) factors adversely affect the productivity of a crop. Among biotic factors, weeds are one of the most important constraints to crop production. In fact, weeds cause the highest potential crop yield loss among different pests (Oerke 2006). In India, for example, they cost more than US$ 11 billion each year to the Indian agricultural sector (Gharde *et al.* 2018). In Australia, weeds cost more than US$ 2 billion each year to grain growers (Llewellyn *et al.* 2016). These monetary values suggest that weeds cost agricultural production in low-income as well as high-income countries.

Herbicides are widely used to control weeds. Because of quick results and ease to use, herbicide use is replacing hand weeding in countries, where it was a common practice in the past. Sole reliance on herbicides, however, has resulted in the evolution of resistance in several weed species throughout the world. Globally, more than 500 unique cases of herbicide-resistant weeds have been reported and out of these, about 20% are from Australia (Heap 2022). Only three herbicide-resistant weed species (*Phalaris minor*, *Rumex dentatus*, and *Cyperus difformis*) have been reported from India; however, these limited numbers could be due to unawareness of the reporting procedure and limited research done on this aspect in India. In addition to the risk of developing resistance in weeds, there are concerns over the limited availability of chemicals with a new mode of action and environmental pollution. Recent reports on health concerns over the use of glyphosate have resulted in the ban of this most effective herbicide in some regions. These issues have challenged weed scientists around the world to develop ecologically-based weed management programs that rely less on herbicides. However, to develop such programs, detailed knowledge of weed biology and ecology is a prerequisite.

Previous review and perspective articles from my lab described in detail the importance of weed biology in improving the management of weeds (Chauhan 2012; Chauhan 2020; Chauhan and Johnson 2010; Chauhan *et al.* 2017; Mahajan and Chauhan 2020); therefore, this article will only briefly highlight the importance of weed biology. Weed biology is a broad topic and it is not possible to cover all the aspects of weed biology in this article. Seed ecology (including, seed bank dynamics), weed

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emergence patterns, weed phenology, phenotypic plasticity, fitness penalty (in relation to herbicide resistance), and genetic diversity are some of the components of weed biology. We, researchers and extension specialists, must understand that weed biology studies do not create new management products (*e.g.*, herbicides). These studies provide a concept for weed management, which weed scientists need to use in making informed decisions in the selection of weed control tactics for the industry.

Seed ecology

Seed germination and seedling emergence are affected by several environmental factors, such as temperature, light, water stress, seed burial depth, crop residue retention, flooding depth, *etc*. Information on the germination response of a weed species to these factors can help develop effective weed management programs through either suppressing germination or encouraging germination at times when weeds can easily be controlled (Chauhan and Johnson 2010). For example, information on the maximum depth, from which a weed species could emerge, helps in selecting tillage systems to bury seeds deep in the soil or promote their germination. Knowledge of vertical seed placement in the soil also indicates relative seed bank persistence life. For example, seeds on the soil surface under no-till farming systems would deplete faster than seeds buried in the soil under conventional-tilled farming systems (Chauhan *et al.* 2006). In a recent study, germination of *Phalaris paradoxa* was found to be very low on the soil surface (Kibasa *et al.* 2022). The authors suggested that adopting no-till systems could inhibit the germination of this species. Therefore, knowledge generated from seed ecology studies strengthens integrated weed management programs.

Emergence pattern

Weed emergence is a key process in determining the number of weed plants and their timing of appearance. Information on weed emergence patterns (i.e., these two variables) justifies or does not justify the application of herbicides to the crop. Predicting weed emergence timings can strengthen integrated weed management programs (Grundy 2003) by implementing models into technological platforms, such as software or Apps. This will be very important in dryland farming systems. Differential emergence patterns of different populations of a weed species indicate the occurrence of different emergence ecotypes and such knowledge highlights the need to adopt more location-specific and diversified weed control strategies to manage weed seed banks (Kumar *et al.* 2018).

Phenology

Phenology is the study of the timing of plant growth stages in response to environmental factors. Because of less interest in weed biology, crop phenology is heard and known more than weed phenology. Weed phenology is an important factor in understanding weed-crop competition. There are several factors affecting weed phenology but temperature and photoperiod are the most important factors, especially in irrigated conditions. Knowledge of phenology is critical to understand weed growth, weed seed production, weed biomass, and the level of potential competition with various crops. Phenology can also provide information if a particular weed species could be targeted using harvest weed seed control practices.

A recent study on *Echinochloa colona* phenology reported that this weed could emerge throughout the year in the eastern cropping systems of Australia (Chauhan 2022). This weed produced a considerable number of seeds at all planting times (**Figure 1**). Although *E. colona* is a summer weed species, these results suggest that it has the potential to expand its seasonality. Seasonal expansion is not new in weed species but in-time information could help tackle such weeds in a better way.

Genetic diversity

Genetic diversity is the heritable genetic variation within and among populations of a weed species (Li *et al.* 2007). It is one of the most important reasons for the success of a weed species. Information on genetic diversity helps in understanding the ability of a weed to adapt to different environments and the impact of herbicide selection on weed populations.

A species showing a high genetic variation would require a variety of control measures and constant changes in management practices to counter adaptation in weed populations (Bommarco *et al.* 2010). A recent study, for example, reported that high genetic diversity was present in *E. colona* populations from the Queensland and New South Wales states of Australia (Chauhan *et al.* 2022). The authors concluded that this response was indicative of free gene flow or herbicide resistance had evolved multiple times in this species. The study also indicated that the frequent use of herbicides for *E. colona* control may be the most important factor in the current extent of herbicide resistance observed in this species.

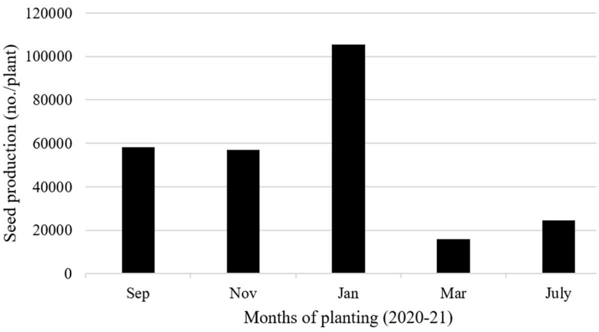

Figure 1. Seed production of *Echinochloa colona* when planted at Gatton, Queensland, Australia, in different months (Chauhan 2022).

Conclusions

Weeds will keep adapting to different management practices. Therefore, we need to be proactive and understand their biology before they become very problematic. Just relying on one tool (e.g., herbicides) for their management will not be enough. Based on weed biology knowledge, diversified weed management programs need to be developed. Such programs should not eliminate the use of herbicides but increase efficiency of herbicides.

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OPINION ARTICLE

Invasive alien weeds problem in South Asia: Challenges and prospects of their management

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ABSTRACT

South Asian region, like other regions of the world, is witnessing a rising problem of invasive alien weeds with wide ranging environmental and socio-economic impacts. Current policy and management responses, and national capacities of the South Asian countries are inadequate in slowing down the rate of invasion process, suggesting a need for new approaches to address the problem. Through narrative review of selected references and author's own experiences, several challenges of invasive weed management in South Asia have been identified, including inadequate policy responses, ineffective quarantine and biosecurity rules, low national capacity, knowledge gaps on key aspects, and a lack of common and agreed standards for species categorization. Future prospects identified for effective management of invasive weeds in South Asia include improving awareness of invasive weeds problem among policy makers and other stakeholders, regional networking for information exchange, regional collaboration for biological control program, and regional collaboration among researchers to generate policy relevant information. In a nutshell, formulation of the South Asian Regional Strategy for Invasive Alien Species and its proper implementation will prevent introduction of new invasive weed species and control of established invasive weed species for the benefit of imperiled biodiversity, ecosystems and billions of people inhabiting in this region.

Keywords: Biological invasions, Invasive weeds, Invasive plants, Management strategy, Regional collaboration

INTRODUCTION

Movement of organisms beyond their native distribution range crossing natural biogeographical barriers is a prominent ecological foot print of humanity in the era of Anthropocene (Kueffer 2017). Such organisms introduced by humans are often referred to as 'alien' or 'exotic' species in their new introduced range. Some of these alien species are the valuable sources of food, fiber and medicine while others are pests, pathogens and weeds. A subset of the alien species which spread rapidly in the introduced range with potentially negative impacts to native biodiversity, ecosystems, and human welfare are referred to as invasive alien species (IAS) (https://www.cbd.int/idb/2009/about/what/, accessed on 15 Nov 2022). Global agriculture production system has been also threatened by a large number of such IAS and many of them are invasive alien weeds (Paini *et al.* 2016). The invasive weeds and other IAS reduce agriculture production and increase crop protection cost, with ultimate negative impacts to global food security. To address this and other similar problems caused by the IAS, efforts have been made for their prevention and control by individual nations and global community (*e.g.* Aichi biodiversity target 9 of the Convention on Biological Diversity, https://www.cbd.int/sp/targets/rationale/target-9/). However, the past efforts remain inadequate as the number of IAS and the associated economic costs have increased continuously with their higher rate in more recent years (Seebens *et al.* 2017; Diagne *et al.* 2021). Additionally, the IAS interacts with other drivers of global environmental degradations such as the land use and climate changes, with their synergistic negative impacts to biodiversity, ecosystems and agricultural productions (Lopez *et al.* 2022; Ravi *et al.* 2022). Therefore, the management of IAS is becoming increasingly more challenging at all levels of management – national, regional and global.

South Asia constitutes eight countries (Afghanistan, Bangladesh, Bhutan, India, Myanmar, Nepal, Pakistan and Sri Lanka), which share similar climate, environment and socio-cultural features, and have high interconnectedness through trade and travel. There are three (of 35) global biodiversity hotspots (Himalaya, Indo-Burma, and Western Ghat-Sri Lanka) and one (of 17) mega-diverse country

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(India) in South Asia. The region is inhabited by nearly 1/4th of global human population and ranked first in population size among different sub-regions of Asia (https://www.worldometers.info/world-population/population-by-asia-subregion/, assessed on 15 Nov 2022). The agriculture is the mainstay of the national economy in most countries of this region, with half of the population directly dependent to agriculture for their livelihood. In recent decades, the agriculture sectors of this region have been threatened due to global environmental changes such as climate change and the biological invasions (Bang *et al.* 2022; Pathak 2023). Threats to agriculture due to the IAS is relatively high in this region with Nepal and Bangladesh ranked third and fourth most threatened countries globally (Paini *et al.* 2016). Additionally, Asia in general and the South Asia in particular are lagging behind the rest of the world in terms of IAS related researches, knowledge bases, and management activities (Shrestha *et al.* 2022). In this paradoxical context, major challenges of the invasive alien weed management in this region have been summarized and future prospects have been discussed based on a narrative review of selected references and author's own experiences. In absence of systematic regional assessment of the invasive species problem in South Asia, the regional patterns of their spread, impacts and appropriate management options at regional level remain elusive. However, the author hopes that this communication will encourage regional dialogue and networking among diverse stakeholders to understand and address the emerging problem of invasive weeds and other species at regional level in South Asia.

DIVERSITY

All countries of the region do not have a comprehensive list of invasive alien weeds and they have not followed the same standard for assigning the alien species to 'invasive' status. This situation has made comparing and collating the number of invasive weeds reported in each country challenging. Available literature clearly revealed a disparity on the number of invasive weeds reported in each country. For example, the number of invasive weeds reported in Bhutan is exceptionally high based on the normalized value of species number (#species/10^5 km^2) (**Table 1**). It is likely because of the differences in the definition used by the researchers of Bhutan (Dorjee *et al.* 2020) and other countries such as Nepal (Adhikari *et al.* 2022). It appears that in 'invasive' species of Bhutan, Dorjee *et al.* (2020) included all widely distributed naturalized species irrespective of their ecological and socio-economic impacts while in the 'invasive' species of Nepal, Adhikari *et al.* (2022) included those naturalized species which have reported negative impacts (ecological and/or socio-economic) in Nepal. For example, *Alternanthera pungens, Amaranthus viridis, Cannabis sativa* and *Crassocephalum crepidioides* are present both in Bhutan and Nepal but they have been considered as invasive by Dorjee *et al.* (2020) but not by Adhikari *et al.* (2022) because their negative impacts have not been reported though they are also widespread in Nepal. When information related to impact is unavailable, the number of invasive alien species reported is likely an underestimate of the real situation. For example, while the available literature reported >100 species to be invasive in India (Khuroo *et al.* 2021), Sandilyan *et al.* (2019) reported that 60 alien species are naturalized in terrestrial and inland freshwater ecosystems of India and met the criteria (with high weightage give to impacts on ecosystem, biodiversity and livelihood) adopted by the National Biodiversity Authority of India for invasive species.

Except Bhutan, the normalized species number is relatively high in island countries like Maldives and Sri Lanka (**Table 1**) which is quite expected because islands are highly vulnerable to plant invasions relative to the comparable areas in the mainland (Lonsdale

Table 1. Number of invasive alien weeds reported in eight countries of South Asia

Country	Area (Km^2)#	Number of invasive alien weeds (Reference)	Species/ 10^5 Km^2*	Number of globally worst invasive weeds**
Afghanistan	652,230	-	-	1
Bangladesh	147,570	46 (Mukul *et al*. 2020)	31	6
Bhutan	38,394	101 (Dorjee *et al*. 2020)	263	5
India	3,287,590	145 (Khuroo *et al*. 2021)	4	15
Maldives	300	9 (Sujanapal and Sankaran 2016)	3000	5
Nepal	147,181	28 (Adhikari *et al*. 2022, Shrestha *et al*. 2021)	19	7
Pakistan	881,912	73 (Qureshi *et al*. 2014)	8	6
Sri Lanka	65,610	39 (Bambaradeniya (2002)	59	13

#https://www.worldometers.info/geography/largest-countries-in-the-world/ (Accessed on 14 Nov 2022); *Species number normalized following Turbelin *et al*. (2017); **After Shrestha *et al*. (2022)

1999). The number of globally worst invasive alien weeds is the highest in India followed by Sri Lanka. Among them, *Lantana camara* has been reported from all countries in South Asia while other commonly reported species are *Leucaena leucocephala*, *Pontederia crassipes* and *Mikania micrantha* (Shrestha *et al.* 2022).

IMPACTS

A wide range of environmental and socio-economic impacts of invasive alien weeds have been reported in South Asia (**Table 2**). Commonly reported environmental impacts includes reduction in native species diversity, change in soil nutrient and chemical properties, negative effects on tree regeneration, and degradation of wildlife habitats. Similarly, the frequently reported socio-economic impacts include reduction in agriculture and livestock production, health hazards to human and livestock, and a decline in forest resources supply (*e.g.* forage, wild edible fruits). These environmental and socio-economic impacts of invasive weeds have been reported mostly from India, Nepal, Bhutan and Pakistan, suggesting that the study which assesses impacts of invasive weeds is virtually lacking in the remaining four countries (Afghanistan, Bangladesh, Maldives and Sri Lanka).

Impacts of invasive weeds have been assessed in terms of monetary values too but such studies are available only for a few species in South Asia. For example, total cost associated with damage and control of *Parthenium hysterophorus* in agroecosystems of India between 1955 and 2009 was estimated to be ₹ 2.067 trillion (equivalent to UD $ 24.8 billion as per the exchange rate of 17 November 2022) (Sushilkumar and Varshney 2010). In Punjab province of Pakistan, Bajwa *et al.* (2019) estimated annual cost of *P. hysterophorus* invasion associated

Table 2. Selected examples of environmental and socio-economic impacts of invasive alien weeds in South Asia

Invasive weed	Impacts	Countries	References
Environmental impacts			
Ageratina adenophora	Native plant species reduced	India (Uttrakhand)	Kumar *et al.* (2020)
Chromolaena odorata	Native species richness reduced	Nepal	Thapa *et al.* (2016)
	Tree (*Shorea robusta*) regeneration negatively affected	Nepal	Thapa *et al*. (2016)
Lantana camara	Native species richness and diversity reduced	India (Himachal Pradesh, Uttrakhand), Nepal	Singh *et al.* (2014); Bhatt *et al.* (2020); Kumar *et al.* (2020)
	Fire regimes altered	India	Hiremath and Sundaram (2005)
Leucanthemum vulgare	Species diversity reduced	India (Kashmir)	Khuroo *et al*. (2010), Ahmad *et al.* (2019a)
	Soil nutrient and chemical properties altered	India (Kashmir)	Ahmad *et al*. (2019b)
Mesosphaerum suaveolens	Native species richness declined	India (Chandigarh)	Sharma *et al.* (2017)
	Soil organic carbon and electrical conductivity increased	India (Chandigarh)	Sharma *et al.* (2017)
Mikania micrantha	Habitat of one-horned rhino degraded	Nepal	Murphy *et al.* (2013)
	Soil nutrient cycling enhanced	India (Meghalaya)	Swamy and Ramakrishnan (1987)
Parthenium hysterophorus	Native species richness and abundance reduced	India	Kaur *et al*. (2019); Sushilkumar (2014)
	Plant species (above ground + soil seed bank) composition modified	Nepal	Timsina *et al.* (2010), Rokaya *et al.* (2020), Khatri-Chettri *et al.* (2022)
	Nutrient concentration in soil changed	India (Chandigarh), Nepal	Kaur *et al.* (2019), Timsina *et al*. (2010)
Pontederia crassipes	Diversity and abundance of threatened birds reduced	Nepal	Basaula *et al.* (2021)
Prosopis juliflora	Nesting habitat of breeding bird degraded	India	Chandrasekaran *et al*. (2014)
Xanthium strumamrium	Species richness and diversity reduced	Pakistan (Punjab)	Qureshi *et al.* (2019)
Socio-economic impacts			
Ageratum houstonianum	Livestock toxicity and increased weed problem in agriculture	Nepal	Shrestha *et al.* (2019a)
Alternanthera philoxeroides, *Azolla filiculoides*	Fishing and availability of wild edible fruits affected negatively	India (Kashmir)	Keller *et al.* (2018)
Mikania micrantha	Fodder availability reduced in forests	Nepal	Rai and Scarborough (2015); Sushilkumar (2014)
Parthenium hysterophorus	Human skin disease (dermatitis), allergy	India, Nepal, Bhutan	Sharma and Verma (2012), Shrestha *et al.* (2015); Chhogyel *et al* (2021)
	Crop and livestock production as well as quality of human life negatively affected	Pakistan (Punjab), Bhutan	Bajwa *et al*. (2019); Chhogyel *et al.* (2021)

with crop and livestock production, health, and social well-being to be US $ 913 per household. Similar estimates are not available for other species and in other countries of this region. Bang *et al.* (2022) estimated economic cost of invasive alien species to Indian economy (US$ 127.3 to 182.6 billion for the period of 1960-2020) but they have not specified the cost associated with invasive alien weeds.

MANAGEMENT

Current management practices

Management of invasive weeds is complex, challenging and highly contextual. Suitable management approaches vary according to the invasion stage of invasive weeds, invaded ecosystems, socio-economic status of the people involved in management, and government policy. In general, prevention, early detection and rapid response (EDRR), control (physical, chemical and biological control), ecosystem based management, and community participation are common approaches of invasive weeds management in Asia including South Asian region (Shrestha *et al.* 2022). *Prevention* is the most effective and economic method of invasive weeds management, yet it is also the most challenging in South Asian region because of open (*e.g.* Nepal-India border) and porous international borders (*e.g.* India-Bhutan and India-Bangladesh borders) with very poor implementation of border quarantine rules. When prevention fails, the next option available is the Early Detection and Rapid Response (EDRR) which involved an early detection of founding populations of invasive weeds and subsequent eradication or containment through rapid responses before they become widespread (Reaser *et al.* 2020).

Once the invasive weeds are widespread, control measures such as physical, chemical and biological methods are implemented. *Physical control* including the use of mechanical tools has been routinely used in farm lands while it has been also implemented frequently in natural ecosystems such as the managed forests, plantations, and wetlands (Shabbir *et al.* 2019, Shrestha 2019). Physical control measures are mostly implemented by farmers, local people and community based organizations, and therefore these activities seldom appear in scientific literature. In chemical method, herbicides are used to control invasive and other weeds in farmlands but their use in natural ecosystems is not recommended due to their negative impacts to non-target organisms. Biological control using carefully selected natural enemies (*e.g.* arthropods, fungi) found in the invasive weeds' native range is considered the most effective, environment friendly, economic and sustainable for their long-term control (Day and Witt 2019). However, the biological control program has been implemented only in a few countries such as India (Rabindra and Bhumannavar 2009; Sushilkumar 2015) and Pakistan (Weyl *et al.* 2021) in South Asia, possibly because of a relatively high initial cost and a longer time period required for screening and subsequent release of the suitable biological control agents. Yet, some of the biological control agents have crossed the international border naturally and established in countries where they have not been released officially. For example, a leaf feeding beetle *Zygogramma bicolorata* was released in India during early 1984 to control *Parthenium hysterophorus* (Jayanth and Visalakshy 1994). The beetle has spread naturally and reached to Nepal (Shrestha *et al.* 2019b; Sushilkumar 2015), Bhutan (Dorji and Steve 2020) and Pakistan (Javaid and Shabbir 2006; Sushilkumar 2015) crossing international border where it has already established with partial control of *P. hysterophorus*. At least 18 biological control agents targeting 11 invasive weeds have established in one or more of five South Asian countries (Bhutan, India, Nepal, Pakistan and Sri Lanka) after deliberate and/or fortuitous introductions (**Table 3**). *Lantana camara* has the highest number of biological control agents (4 spp.) followed by *Pontederia crassipes* (3 spp.). Most of the biological control agents reported in South Asia have established in India with low to high impacts on the target invasive weeds. Only a few agents have established in the remaining four countries. The author is not aware of the presence of biological control agents against invasive weeds in Afghanistan, Bangladesh and Maldives.

Ecosystem based approach of invasive weeds management seems promising (Byun *et al.* 2018), yet its potential has not been adequately explored and documented in South Asian countries. A few studies have revealed that abundance of invasive weeds and their negative impacts can be reduced by restoring degraded forests (Khaniya and Shrestha 2020), and promoting native and other useful species in ecosystems (Khan *et al.* 2014; Thapa *et al.* 2017). It is highly likely that some of the invasive weeds might have been controlled when the indigenous people and local communities (IPLC) managed forests and other ecosystems. However, such benefits of ecosystem management have not been well recognized and documented in this region. Similarly, community participation through direct involvement of the IPLCs and various community based organizations for

Table 3. Established biological control agents with their targeted invasive alien weeds in South Asian countries (modified and updated from Shrestha *et al*. 2022)

Targeted weed [Family]	Biocontrol agents [Family]	Countries with established population	General impacts	References
Ageratina adenophora [Asteraceae]	*Procecidochares utilis* [Tephritidae]	Nepal, India	Low	Day *et al*. (2018); Sushilkumar (2015); Shrestha (2019)
Chromolaena odorata [Asteraceae]	*Cecidochares connexa* [Tephritidae]	India	Low	Rabindra and Bhumannavar (2009); Sushilkumar (2015)
	Pareuchaetes pseudoinsulata [Arctiidae]	India	Low	Rabindra and Bhumannavar (2009) Sushilkumar (2015)
Mikania micrantha [Asteraceae]	*Puccinia spegazzinii* [Pucciniaceae]	India	Nil	Sreerama (2016)
Parthenium hysterophorus [Asteraceae]	*Puccinia abrupta* var. *partheniicola* [Pucciniaceae]	Bhutan, Nepal, Pakistan	Low	Dorji and Adkins (2020), Shrestha (2019), Iqbal *et al*. (2020)
	Zygogramma bicolorata [Chrysomelidae]	Bhutan, India, Nepal, Pakistan	Moderate	Dorji and Steve (2020); Shrestha *et al*. (2019b), Javaid and Shabbir (2006)
		India	High	Sushilkumar (2009, 2014, 2015
Xanthium strumarium [Asteraceae]	*Puccinia xanthii* [Pucciniaceae]	Sri Lanka	Moderate	Shen *et al*. (2018)
Opuntia stricta [Cactaceae]	*Dactylopius opuntiae* [Dactylopiidae]	India, Sri Lanka	High	Shen *et al*. (2018); Sushilkumar (2015)
Opuntia elatior [Cactaceae]	*Dactylopius opuntiae* [Dactylopiidae]	India	High	Rabindra and Bhumannavar (2009); Sushilkumar (2015)
Opuntia monacantha [Cactaceae]	*Dactylopius ceylonicus* [Dactylopiidae]	India, Sri Lanka	High	Rabindra and Bhumannavar (2009); Sushilkumar (2015)
Pontederia crassipes [Pontederiaceae]	*Neochetina bruchi* [Erirhinidae]	India	High	Sushilkumar (2015)
	Neochetina eichhorniae [Erirhinidae]	India	High	Sushilkumar (2015)
	Orthogalumna terebrantis [Galumnidae]	India	Moderate	Rabindra and Bhumannavar (2009); Sushilkumar (2015)
Salvinia molesta [Salviniaceae]	*Cyrtobagous salviniae* [Curculionidae]	India	High	Rabindra and Bhumannavar (2009); Sushilkumar (2015)
Lantana camara [Verbenaceae]	*Octotoma scabripennis* [Chrysomelidae]	India	Low	Rabindra and Bhumannavar (2009); Sushilkumar (2015)
	Teleonemia scrupulosa [Tingidae]	India, Sri Lanka	Moderate	Shen *et al*. (2018); Sushilkumar (2015)
	Uroplata girardi [Chrysomelidae]	India	Low	Rabindra and Bhumannavar (2009); Sushilkumar (2015)
	Epinotia lantana [Tortricidae]	India	Low	Rabindra and Bhumannavar (2009); Sushilkumar (2015)

invasive weeds management have been reported in South Asian countries (Shrestha *et al*. 2022). Various efforts have been made to create awareness among communities about the problems of invasive species and increase their participation through organizing awareness campaigns (*e.g*. Parthenium awareness week, Varshney and Sushilkumar 2009, 2014) and publication of community education materials in local language (e.g. Adhikari *et al*. 2022). However, the current efforts remain inadequate because many of the IPLCs are still unaware of the invasive species problems and available management options (Shrestha *et al*. 2019a).

Policy responses

National biodiversity strategy and action plans (NBSAP) of all eight South Asian countries have recognized invasive species as an important threat to ecosystems, biodiversity and agriculture productions (all documents available at https://www.cbd.int/countries/?country). Assessment of invasive species problems in these countries and their future plans are largely guided Aichi Biodiversity Target 9 of the Convention on Biological Diversity (CBD) (https://www.cbd.int /sp/targets/ rationale/target-9). According to the national reports submitted to the CBD secretariat (available at https://www.cbd.int/countries/?country), progress towards meeting Aichi Biodiversity Target 9 is improving but at an insufficient rate in Bangladesh, Bhutan, India, Maldives, Nepal and Sri Lanka but there was little or no progress in Afghanistan and Pakistan (both these countries submitted the last report in 2014). Besides NBSAP, countries like India (Sandilyan 2019) and Sri

Lanka (Biodiversity Secretariat 2016) also have separate national strategy for the management of invasive species including invasive alien weeds. The author is not aware of such a separate national strategy for invasive species in the remaining six South Asian countries. In addition to the national policies, researchers have also proposed frameworks for weed risk assessment in Bhutan (Dorjee *et al*. 2021) and prevention and control of invasive species in India (Banerjee *et al*. 2021). Such scholarly exercises are lacking in other countries of the region.

Management challenges

A brief review of literature, as discussed above, reveals that the current management practices are insufficient to address the increasing problems of invasive weeds. There are various management challenges which need to be overcome before effective management of invasive weeds is anticipated. Major challenges among them are summarized below:

Inadequate policy responses: Appropriate national policies and strategies are crucial for the effective management of invasive weeds. However, most South Asian countries do not have such dedicated national policy and strategy. All countries of this region have performed poorly on the national targets set in the national biodiversity strategy and action plan to prevent and control the invasive species.

Ineffective quarantine and biosecurity rules: International borders are either porous or open and interconnectedness in trade and travel is high among countries in South Asia. This has made the implementation of quarantine and biosecurity rules highly challenging. However, prevention of invasive species is far more effective and economic than their control after invasion. Therefore, there is no alternative to strengthening quarantine and biosecurity rules by each country in South Asia to combat increasing problem of invasive species.

Low national capacity: Countries in South Asia have relatively low national capacities (both proactive and reactive) for invasive species management in terms of expertise and available resources (Early *et al.* 2016). While national expertise has been improving gradually in some countries (e.g. Bhutan, Nepal), helps from international experts can be solicited to fill the shortfalls of national expertise. Countries have to increase their spending on invasive species control programs because any delay on the control of invasive species will significantly increase their impacts and management cost in future.

Key knowledge gaps: Available data and knowledge on some of the key aspects such as dispersal (introduction) pathways, economic valuation of impacts, and cost-benefit analyses of various management options are insufficient for informed policy and management decisions. Interdisciplinary and transdisciplinary approaches as well as regional/ international collaboration in research can generate additional data to improve knowledge gaps on these key issues.

Lack of common and agreed standards for species categorization: Absence of common and agreed standard for species categorization among South Asian countries has led to a large difference in the number of invasive species reported for the same country by different researchers (e.g. India: 60 spp. by Sandilyan 2019 but 145 spp. by Khuroo *et al.* 2021). Similarly, there is a large difference in the number of invasive weeds reported by geographically, climatologically and socio-economically similar countries such as Nepal (28 spp.) and Bhutan (101 spp.) (**Table 1**).

Future prospects

In spite of several challenges for invasive weed management in South Asia, there are also some opportunities for better management outcomes through improved stakeholder awareness, regional collaboration for research and knowledge/data sharing, and formulation and proper implementation of regional strategy for invasive species management. These future prospects have been discussed briefly in the following section.

Improving awareness among stakeholders: Over the past few years, researchers have generated a wealth of data and knowledge revealing the severity of invasive species problems across various geographical, jurisdictional and governance scales in South Asia and beyond. Minimum data and knowledge required to initiate stringent prevention and control measures are available for most of the South Asian countries. In some countries, however, policy makers and practitioners appear not to be fully aware of the seriousness of the invasive species problems, available management options, and future consequences of the lack of timely intervention. Improved communication among various stakeholders including researchers, policy makers and practitioners will increase policy uptake of the research findings and effectiveness of management activities.

Regional network for information exchange: The problem of invasive species originates outside political border of any country. In other word, what is happening in the neighboring countries determine, to some degree, what would happen (*i.e.* the extent of invasive species problem) in a country. Therefore, the invasive species is clearly a transboundary and regional/international problem requiring effective communication and cooperation among countries for their long term management. The COVID19 pandemic has also reminded us the value of information sharing by countries for tackling such global problem (Jit *et al*. 2021). Therefore, establishment of a platform for invasive species information sharing and exchange will i.) provides opportunities for the prevention of additional invasive species by countries, ii.) increases probability of early detection of and rapid response to founding populations of invasive species, and iii.) provides avenue for up-scaling and out-scaling of appropriate management options.

Regional collaboration for biological control program: One major hindrance of biological control program of invasive species is the requirement of screening phylogenetically related native and useful species in standard quarantine facilities. Partly, because of this, most of the South Asian countries have not institutionalized biological control program and thus unable to get benefit from this environmentally friendly and sustainable measure of invasive species control. The South Asian countries not only share several invasive species, they also share several native and useful species which are phylogenetically closely related to the invasive species in question. If host range expansion of a biological control agent to a set of species is ruled out in a quarantine screening facility of a country, it is not necessary to repeat quarantine screening of the same set of species in another neighboring country with similar climatic condition. In such situation, quarantine screening of phylogenetically related additional species may be adequate for final decision of whether or not to release the agent. A great amount of resources and time can be saved when countries follow same protocol for quarantine screening and officially share their findings to other countries in the region. This will create a conducing technical and financial environment to initiate biological control program by countries which have not done it yet.

Regional collaboration for research: South Asian researchers collaborate extensively with researchers of Europe, America and Australia but they do less so with fellow researchers of other south Asian countries (Rana *et al*. 2022). However, collaboration among South Asian researchers working on invasive weed species provide opportunities for mutual learning of common regional problems such as the invasive weed species spread, reveal regional pattern of biological invasions, may increase success rate of international funding applications, and complement each-other's research findings for a broader understanding of the regional problems. Additionally, such collaboration may also help to fill data gap of countries with very low research efforts (e.g. Afghanistan, Maldives). In a situation when political relations between countries is contested, research collaboration can improve the state of science diplomacy which ensure joint efforts to tackle regional problems (Shrestha and Bhadra 2019). In specific, collaboration among researchers of different South Asian countries provide an avenue for the development of regional strategy for invasive species management.

Regional strategy for invasive species management: As discussed above, invasive weed species is trans-boundary and global problem, and therefore a regional strategy is needed in South Asia to manage invasive weed species and protect native biodiversity, ecosystems and improve people's livelihood. Researchers, policy makers, practitioners and representatives of indigenous and local communities, among others, can work together for the preparation of South Asian Regional Strategy for prevention and control of invasive weed species. Such strategy will encourage information sharing and technology transfer (e.g. biological control program) among South Asian countries. Additionally, the regional strategy will also help to i.) harmonize data standards (e.g. definition and thus the number of invasive species) of individual countries, ii.) improve national funding for invasive weed species research and management, iii.) prevent introduction of new invasive weed species to South Asia, iv.) encourage regional collaboration for research and innovation, v.) create enabling environment for the development of national strategy by individual countries, and vi.) meet global targets of the Contention on Biodiversity Diversity and the United Nations.

CONCLUSION

Hundreds of invasive alien weeds have invaded diverse natural habitats and agriculture lands in South Asian countries with wide ranging environmental and socio-economics impacts. Number of invasive weeds and their impacts are likely to increase further in future due increased international trade and travel globally as well as in South Asia, and inadequate management and policy responses. There are several shortfalls in data availability (*e.g.* no national list of invasive weeds in some countries), empirical evidences of ecological and economic impacts, national capacity in terms of expertise and available resources, and policy and management responses of the South Asian countries. Invasive weeds being a regional problem, improving awareness of invasive weed problems among policy makers and other stakeholders, regional networking for information exchange, regional collaboration for biological control program, and regional collaboration among researchers to generate policy relevant information will create enabling environment for effective management of invasive weeds at national and regional level. Overall, formulation of the South Asian Regional Strategy for Invasive Alien Species and its proper implementation will prevent introduction of new invasive weed species and control established invasive weed species for the benefit of imperiled biodiversity, ecosystems and billions of people living in this region.

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ANALYSIS ARTICLE

Risk associated with the weed seeds in imported grain

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ABSTRACT

The risk of introducing weeds to new areas through grain (cereals, oilseeds and pulses) intended for processing or consumption is considered less than that from seed or plants for planting. However, within the range of end uses for grain, weed risk varies significantly and should not be ignored. There is a need to examine the association of weed seeds with grain commodities throughout the production process from field to final end use, and inspection of representative samples for grain crops commonly imported to India. In the field, weed seed contamination of grain crops is affected by factors such as country of origin, climate, biogeography, production and harvesting practices. As it moves toward export, grain is cleaned at a series of elevators and the effectiveness and degree of cleaning are influenced by grain size, shape and density as well as by grade requirements. In cases where different grain lots are blended, uncertainty may be introduced with respect to the species and numbers of weed seed contaminants. During transport and storage, accidental spills and cross-contamination among conveyances may occur. At the point of import to India, inspection data show that grain shipments contain a variety of weed seeds including seeds of regulated weeds. However, grain cleaning and processing methods tailored to end use at destination also affect the presence and viability of weed seeds. For example, grains that are milled or crushed for human use present a lower risk of introducing weed seeds than grains that undergo minimal or no processing. Risk analysis allows each of these stages to be evaluated in order to characterize the overall risk of introducing weeds with particular commodities, and guide regulatory decisions about trade and plant health.

Keywords: Dissemination, Grain shipments, Interception, Plant Quarantine, Risk analysis, Weed seeds

INTRODUCTION

Import of plant material in bulk like food grains is always of high plant quarantine risk. Increasing trade and globalization coupled with liberalized policies further increase the risk of introduction of exotic weeds through bulk imports. Grain is defined as "seeds intended for processing or consumption and not for planting" (IPPC 2015) and grain commodities consist of bulk shipments of cereal, oilseed or pulse crops destined for use as human food, livestock feed or industrial products. Many weed seeds associated with grain crops in the field are harvested along with the crop and can be difficult to remove due to similarities in shape and size of the seeds. Depending on the destination and intended end use of the grain some of these seeds may be introduced into new environments suitable for growth and establishment. Because large volumes of grain are traded internationally each year, this pathway may represent a considerable contribution to the spread of new weeds around the world. Several studies have reported large numbers of weed species found in sampled grain commodities and a number of globally important weeds of agriculture are thought to have been spread as contaminants in grain (Singh *et al.* 2005, 2014; Nagaraju *et al.* 2021; Dasari *et al.* 2022).

Regulating the spread of weeds via this pathway is the responsibility of individual countries under the guidelines of the International Plant Protection Convention (IPPC), and many countries have legislation and import requirements that mitigate the risk of introducing new weed species to some degree. However, according to the principles of the IPPC, regulations must be based on risk analysis and characterizing the risk associated with complex pathways such as this one remains a challenge. International standards for pest risk analysis are well developed for addressing individual species in terms of the likelihood they will enter, establish and spread in a new area, and the impacts they may have. In this

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paper we discuss the association of weed seeds with imported grain from point of origin to end use at destination, and provide a qualitative description of the pathway that can be used as a framework for weed risk analysis (Pheloung *et al.* 1999, Singh *et al.* 2014). We identify six points, or events, along the pathway that have relevance for weed risk, namely: crop-weed associations at the point of origin; farming practices; grain handling practices; transport and storage; import requirements; and end use of grain in the country of import.

CROP-WEED ASSOCIATIONS AT THE POINT OF ORIGIN

The weed seed dispersal in grain begins in the field where the crop is grown in the country of origin. Weed communities and species assemblages are determined by geography and vary according to the crop species and conditions (e.g. climate, soils) in the country or area of origin. Although the exact species and numbers of weeds present will vary from field to field and season to season in response to local conditions, farming practices and weather, it is possible to use this type of information to develop a preliminary understanding of the weeds likely to be associated with the crop at the point of origin. The risk of introducing new weed species to India depends not only on the number of weed seeds contaminating imported grain, but on the particular species assemblages present, and the likelihood of their dissemination to a suitable environment for establishment and spread (Nagaraju *et al.* 2021; Dasari *et al.* 2022). Many contaminants moving in the international grain trade may be common weeds that are already present in India, and thus do not present a risk of new species introductions. Information about the point of origin allows for generalizations about risk. For example, the risk of new species introductions is generally considered lower from countries with similar weed floras or different climates, and higher from countries with different weed floras and similar climates.

FARMING PRACTICES

Crop production

Prior to planting, factors such as previous land use, crop rotation, pre-planting tillage, herbicide application, seed bank composition and crop seed purity can play a role in characterizing a field's weed flora for a particular year. At planting time, farmer decisions about crop type, planting date and planting density will influence the crop's ability to compete with weeds. Throughout the growing season, climatic factors, fertilization and weed control methods can further affect the performance of both weeds and crops. In general, weeds with similar biology and requirements to those of crops tend to be favoured, with well-known examples including jointed goatgrass (*Aegilops cylindrica* Host) in wheat, Johnson grass (*Sorghum halepense* (L.) Pers.) in sorghum, and wild mustard (*Sinapis arvensis* L.) in canola. Some crops and crop cultivars are more competitive than others. Crop competitive ability varies from region to region, but a general ranking puts cereals first, followed by canola and then pulses (Blackshaw *et al.* 2002). Highly competitive crops are able to germinate, emerge and accumulate biomass more rapidly than weeds and have an advantageous height and canopy structure for intercepting light. Chemical weed control options also vary by crop. In general, broad-leaved weeds are easier to control in cereals and other monocot crops, while grass weeds are easier to control in broad-leaved crops. For some crops, such as flax and pulses, herbicide options tend to be more limited than those for others, such as cereal grains or corn. Herbicide tolerant cultivars of crops such as corn, soybean and canola allow more comprehensive weed control than many conventional varieties, reducing the number of weeds in the field (Shaw and Bray 2003) and changing the species composition of weed communities. On the other hand, the rise of herbicide resistant weeds may reduce the advantages of herbicide tolerant cultivars over time, as herbicide resistant weed seeds are disseminated as seed and grain contaminants around the globe (Shimono *et al.* 2010). In the case of organically grown crops, a variety of non-chemical weed control options, such as mechanical and thermal methods, mulching and intercropping, may be employed to keep weeds in check. As a result, the quantity and composition of weed seeds in organic grain can differ significantly from that which is conventionally grown.

Harvest

At harvest, critical factors contributing to weed contamination levels include timing, weather conditions, crop vs. weed height, weed maturity and combine settings. Grain crops are usually harvested by direct combining and weeds most likely to be harvested with the crop are those that are taller than cutting height at the time of harvest, with mature seed retained in the seed heads. Early maturing weed species shed most or all of their seeds prior to harvest. In taller crops, seeds from short species are generally eliminated during harvesting for example, sunflower is one of the cleanest grains taken into a mill when the combine is set high at harvest. On the other hand, pulse crops are low-growing and harvested close to the ground, making them more likely to be contaminated with weed seeds. The action of the conventional combine includes reaping, threshing and winnowing. Weed seeds that have a pappus are easily dislodged and dispersed at harvest time and are more readily eliminated during the cleaning process (Shimono and Konuma 2008). The amount of weed seeds in grain can be reduced at harvest with correct combine sieve and fan adjustment (Humburg *et al.* 2009).

Overall, knowledge of crop production and harvesting practices can be helpful for considering their effect on weed seed contamination at source. Although weed levels and species complexes vary from farm to farm, with different agronomic, harvesting and cleaning practices, generalizations can be made based on the information available and applied to the evaluation of risk. For example, crops that are typically more competitive, treated with herbicides, harvested at a greater height or have large seeds might be expected to harbour less weed seed contaminants than crops that are less competitive, grown organically, harvested close to the ground, or that have small seeds that are difficult to separate from weed seeds.

Grain handling

Cleaning

Cleaning removes dockage, which is material that can readily be removed from grain prior to grading, such as stones, straw, chaff, broken grains, contaminant seeds, dust and hulls. Conventional seed cleaning includes the use of aspirators, screens, gravity tables and other separators to remove debris and weed seeds from the crop based on size, shape or weight. As with harvesting, larger-seeded crops are relatively easier to clean than smaller-seeded crops, as they tends to be less overlap with weed seeds in terms of seed dimensions and weight (Salisbury and Frick 2010).

Grading

The percentage of foreign material allowed in a grade can be an indicator of the level of contamination with weed seeds. Using import data by grade, it is possible to estimate the maximum amount of foreign material that might be imported along with the crop.

Table 1. Plants currently regulated as quarantine weeds under plant quarantine (regulation of import into India - order 2003)

S. no.	Scientific name	Common name
1.	*Alectra vogelii*	Yellow witch weed
2.	*Allium vineale*	Crow garlic/ Wild garlic
3.	*Amaranthus blitoides*	Prostrate pigweed
4.	*Ambrosia maritime*	Sea ambrosia
5.	*Ambrosia psilostachya*	Perennial ragweed
6.	*Ambrosia trifida*	Giant ragweed
7.	*Anthemis cotula*	Dog fennel
8.	*Apera spica-venti*	Loose silky bent grass
9.	*Bromus secalinus*	Rye brome
10.	*Cenchrus incertus* (Syn. *Cenchrus tribuloides*)	Spiny burr grass
11.	*Centaurea diffusa*	Diffuse knapweed
12.	*Centaurea maculosa*	Spotted knapweed
13.	*Centaurea solstitialis*	Yellow starthistle
14.	*Centrosema pubescens*	Butterfly pea
15.	*Chrysanthemoides monilifera*	Bone seed
16.	*Cichorium pumilum*	Dwarf chicory
17.	*Cichorium spinosum*	Spiny chicory
18.	*Cirsium vulgare*	Spear thistle
19.	*Conyza sumatrensis*	Tall fleabane
20	*Cordia crassavica*	Black sage/Wild sage
21.	*Cuscuta australis*	Australian dodder
22.	*Cynoglossum officinale*	Hound’s tongue
23.	*Digitaria velutina*	Velvet finger grass
24.	*Echinochloa crus-pavonis*	Gulf cockspur grass
25.	*Fallopia japonica* (Syn. *Polygonum cuspidatum*)	Japanese Knotweed
26.	*Froelichia floridana*	Florida snake cotton
27.	*Fumaria officinalis*	Common fumitory
28.	*Galium aparine*	Cleavers
29.	*Helianthus californicus*	California sunflower
30.	*Helianthus ciliaris*	Texas blueweed
31.	*Heliotropium amplexicaule*	Blue heliotrope
32.	*Leersia japonica*	Cut grass
33.	*Lolium multiflorum*	Italian ryegrass
34.	*Lonicera japonica*	Japanese honeysuckle
35.	*Matricaria perforata*	False chamomile
36.	*Orobanche cumana*	Sunflower broomrape
37.	*Orobanche minor*	Common broomrape
38.	*Oryza longistaminata*	Perennial wild rice
39.	*Pennisetum macrourum*	African feather grass
40.	*Polygonum lapathifolium*	Pale persicaria
41.	*Proboscidea louisianica*	Devil’s claw
42.	*Pueraria Montana var. Montana*	Rhodesian Kudzu
43.	*Raphanus raphanistrum*	Wild radish
44.	*Richardia brasiliensis*	While eye – Australia
45.	*Salsola vermiculata*	Mediterranean saltwort
46.	*Senecio inaequidens*	African ragwort
47.	*Senecio jacobaea*	Common ragwort
48.	*Senecio madagascariensis*	Fireweed
49.	*Solanum carolinense*	Horse nettle
50.	*Striga aspera*	Witch weed
51.	*Striga hermonthica*	Witch weed
52.	*Thesium australe*	Austral toadflax
53.	*Thesium humiale*	Dwarf thesium
54.	*Thlaspi arvense*	Field pennycress
55.	*Urochloa plantaginea (*Syn. *Brachiaria plantaginea)*	Plantain signal grass
56.	*Veronica persica*	Creeping speedwell
57.	*Viola arvensis*	Field pansy

Blending

In commercial trading, the quality of grain in demand fluctuates with changing markets and intended uses. Producers, handlers and exporters must balance the costs of cleaning grain against the value it will have on the market. To achieve this, many grain elevators use the practice of blending to produce grain with the desired level of foreign material; that is, rather than cleaning all grain delivered, a portion of high- foreign material grain is cleaned to a level well below the desired limit and then blended with the rest to achieve the targeted level in the final product. It is unclear to what extent grain lots from different origins are blended prior to export, but this could create highly unpredictable weed assemblages in blended grain shipments. Overall, the variation in composition of foreign material and the practice of blending are significant sources of uncertainty with respect to the potential numbers and species of weed seeds found in grain. Blending of grain lots from different origins with distinct weed seeds has the potential to greatly increase the number of weed species in the resultant lot. Unfortunately, information on whether or not a particular grain lot has been blended and the origins of the original grain lots is very difficult to obtain.

Transport and storage

Transport and storage of grain at every stage along the pathway introduces the possibility of cross-contamination and spills. The pathway may be simple or complex in terms of the number of transfers and conveyances prior to arrival at destination. From the point of origin, grain may be moved by truck, rail car and/or ship as it moves towards export and final destination, and may be unloaded and reloaded at a series of intermediate elevators and storage facilities along the way. Each step contributes to uncertainty with respect to the potential for cross-contamination and the risk of spillage post-import.

Cross-contamination

Good sanitation requires the thorough cleaning of all grain harvesting, transporting, and handling equipment between loads. Practically, however, the cleaning of combines, transportation vehicles and storage facilities between different lots of grain is difficult and often incomplete, resulting in some carry over (Shimono and Konuma 2008). The different lots may represent different grades, origins or even crop types. Howell and Martens (2002), reported that after careful cleaning of a combine, three bushels of red corn (the original crop harvested) were found in the subsequently harvested yellow corn. In a similar way, weed seed contaminants can get trapped in machinery and end up in subsequent loads of grain.

Accidental spills

Accidental spills are also an unfortunate reality of the grain handling system, as evidenced by the weed and volunteer grain flora along railway tracks, roadsides, ports and around mills and other grain processing facilities.

As with grain cleaning and blending, the possibility of cross-contamination of conveyances and spills during the transport and storage of grain illustrates the complexity of the pathway and introduces a significant element of uncertainty with respect to the species of weed seeds that might be found in imported grain.

Import requirements

Import requirements are an important means by which countries can reduce the risk of introducing new pests and protect their agriculture and environments. Currently, all grain imported to India is expected to arrive free of soil and regulated pests, and a range of different requirements (e.g., import permits, phytosanitary certificates, treatment certificates) exist for particular crops and countries of origin (PQ Order 2003). Pests of concern in imported grain include a number of crop pathogens, nematodes and storage pests in addition to weeds (PQ Order 2003)). Regulated weeds include 57 taxa that have been identified as quarantine weeds under Schedule VIII of Plant Quarantine (Regulation of Import into India) Order (2003), based on weed risk analysis (**Table 1**).

End use of grain in the country of import

The end uses of grains, unprocessed or minimally processed screenings present the highest risk for containing viable weed seeds, and potentially large numbers of them. The weeds seeds in screenings can be unintentionally spilled in a variety of environments conducive to germination, including areas around mills, bins and farm fields.

Interception of weed seeds in imported grain consignments

Compliance with import requirements is monitored through inspection and sampling at the point of import (Nagaraju *et al.* 2021). During the period 2015– 2021 an import sampling and inspection program focussed on weed seeds in grain was initiated to monitor for regulated weed species in

Table 2. Imported grain, sample size, number of samples examined, range of contamination, other crop seeds and weed seeds reported in imported grain during 2015-2021

Imported grain	Samples		Range of weed species reported per sample	Total number of other crop seeds and weed species reported in all samples			
	Size (kg.)	Number(s)		No. of other crop seeds	Indigenous weeds	Exotic weeds	Total
Corn	1.0	198	0–11	29	14	7	50
Rice	1.0	11	2–12	5	18	4	27
Soybean	1.0	70	3–26	35	19	10	64
Wheat	1.0	223	5–35	55	28	24	107
Pulses	1.0	251	6–36	36	20	4	60
Canola	1.0	52	3–18	18	17	3	38
Sunflower	1.0	42	0–14	22	15	2	39
Flax	1.0	7	0–13	5	11	3	19
Millet	1.0	69	0–18	17	12	3	32
Sorghum	1.0	24	1–16	12	13	2	27
Total		947		234	167	62	463

Table 3. Exotic weed species intercepted in imported grain crops during 2015-2021

Name of weed species	Frequency	No. of crops	Name of weed species	Frequency	No. of crops
Agrostemma githago	130	6	*Neslia paniculata*	46	7
Amaranthus caudatus	30	8	*Papaver hybridum*	03	8
Ambrosia trifida	17	5	*Phalaris paradoxa*	28	4
Ambrosia psilostachya	05	9	*Polygonum convolvulus*	39	3
Apera spica-venti	60	3	*Polygonum cuspidatum*	04	2
Avena barbata	16	4	*Polygonum lapathifolium*	11	1
Avena sterilis L.	112	6	*Polygonum persicaria*	02	6
Bromus diandrus	85	7	*Raphanus raphanistrum*	24	5
Bromus catharticus	50	5	*Rapistrum rugosum*	130	4
Bromus secalinus	18	2	*Reseda lutea*	89	9
Bromus sterilis	50	5	*Rumex crispus*	78	8
Carrichtera annua	98	7	*Rumex maritimus*	101	6
Carthamus lanatus	33	3	*Salva verbenaca*	128	7
Cenchrus pauciflorus	84	8	*Sida rhombifolia*	130	5
Cenchrus tribuloides	91	9	*Sylibum marianum*	29	3
Centaurea diffusa	126	7	*Sisymbrium officinale*	28	2
Centaurea melitensis	32	7	*Vicia villosa*	11	7
Centaurea solstitialis	18	6	*Vulpia bromoides*	65	9
Cynoglossum officinale	79	3	*Thlaspi arvense*	07	6

imported grain. In total, 947 samples were taken from imported shipments of the 10 grain commodities most commonly imported to India, and analyzed for presence of weed seeds (**Table 2**).

The number of weed species per sample ranged between 0 and 16 (**Table 3**). Overall, 58 different weed seeds were reported in the samples analysed, 20 weeds are already present in India, and 38 weed species are not reported from India. All intercepted weed species were identified up to species level on the basis of their morphological characters. There was a significant and positive correlation between the number of samples taken for each crop and the total number of contaminant species reported, indicating that in general, more sampling is likely to result in more weed species reported.

CONCLUSIONS

In summary, imported grains represent a very complex pathway for the possible introduction of new weed species to India. Weed-crop associations at the point of origin, along with crop production and harvesting practices, can be researched to develop predictions of what weed species might be associated with which imports; however, subsequent steps along the pathway such as grain cleaning, blending, and the potential for cross-contamination in transport and storage mean the weeds found in import sampling programs are not always the ones that might be expected. Import interception data presented here shows that all imported grain commodities sampled were a source of associated weed contaminants, however information about end use indicates that grain destined for human food or industrial purposes in India likely presents a negligible risk of introducing new weeds into the agriculture, due to extensive cleaning and processing at destination. Further research on the effects of specific processes on weed seed viability would be useful to confirm this. However, the greater risk lies with imported grain that is direct-fed or minimally processed for livestock feed, and the fate of dockage or screenings that are removed from grain during the cleaning process.

The risk analysis approach provides a useful framework for characterizing the nature of a pathway, identifying events that affect weed risk, and highlighting possibilities for risk reduction or mitigation (Dasari *et al.* 2022). In this case, a qualitative description of the pathway from point of origin to end use at destination provides a better understanding of the multiple interacting factors that may affect weed seed contamination in grain imports, and this may help to focus plant protection efforts in future. For example, future risk analyses on specific grain commodities may call for less focus on the analysis of crop-weed associations at the point of origin and production and harvesting practices and more focus on end use. Likewise, risk mitigation efforts might be most usefully focused on grain used for livestock feed and management of screenings, as compared to grain for human consumption or industrial purposes which present little risk of introducing new weeds to the environment.

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REVIEW ARTICLE

Biology and management of wild oat in Australia

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ABSTRACT

Wild oat (*Avena* spp.) is one of the most serious weeds in Australian winter season crops such as wheat, barley, chickpea, *etc. Avena fatua* and *A. ludoviciana* are the dominant species of wild oat in cropping regions of Australia. Propagation of wild oat can occur through seeds. Dissemination of wild oat occurs by agricultural machinery, use of the contaminated seeds and crop residues, *etc*. Seed recruitment of wild oat in the soil occurs through high seed production and the shattering ability of plants. Wild oat has evolved resistance to many herbicides and continuous use of same herbicide could increase the resistance build-up in many populations on a large scale in Australia. The use of herbicides with different modes of action can provide cost-effective and sustainable control of wild oat. Non-chemical weed management practices, such as sanitation, residue burning, tillage operation, crop rotations, and improved crop competition approaches could reduce the infestation of this weed. For sustainable control of wild oat, integrated strategies involving chemical and non-chemical tactics may prove useful. Knowledge regarding the understanding of wild oat ecology could aid in strengthening the integrated management of this weed.

Keywords: *Avena fatua*, *Avena ludoviciana*, Herbicide resistance, Integrated weed management, Weed biology, Wild oat

INTRODUCTION

Wild oat (*Avena* spp.) is one of the most important weeds in the winter growing crops. The wild oat is included in the list of the world's top 10 worst weeds, causing yield reductions in cereals by up to 70% (Beckie *et al.* 2012; Holm *et al.* 1991). The extent of its problematic and cosmopolitan nature can be assessed from the fact that it causes an enormous yield reduction in more than 20 crops across 55 countries (Sharma and Born 1983; Holm *et al.* 1977). The genetic diversity in the populations of wild oat is considered to cause its wide adaptation and distribution.

Avena spp. has been claimed to be the weeds of agricultural systems for at least 4000 years (Malzew 1930), dating back to the Roman and Greek empires (Van Der Puy 1986). Malzew (1930) reported that wild oat originated in South West Asia. Nugent *et al.* (1999) and Kirby (2000) claim the origin of wild oat in Asia or the Mediterranean region. There is no clear and accurate information about the introduction of *Avena* spp. in Australia. However, it has been suggested that it was introduced into Australia as a contaminant of grains (Nugent *et al.* 1999; Kirby 2000). From the United Kingdom, *Avena* spp. entered Tasmania as a contaminant of cereals (Paterson 1976). It was introduced to Western Australia through settlement in Australia by 1830 and became a terrible weed in the fields of New South Wales in 1895 (Maiden 1985).

WILD OAT SPECIES

Along with cereal crops like wheat (*Triticum aestivum*), barley (*Hordeum vulgare*) and oats (*Avena sativa*), wild oat species belong to the family Poaceae. In Australia, there are three main species of wild oat, namely *Avena fatua* L. (wild oat), *Avena sterilis* ssp. *ludoviciana* (Durieu) Gillet and Magne, generally referred to as *A. ludoviciana* (sterile oat) and *Avena barbata* Pott ex Link (slender oat), which combinely cause the reduction in crop productivity and increase the cost of weed management, resulting

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in an annual monetary loss of AU$ 28 million to the Australia grain growers (Llewellyn *et al*. 2016). An increase in cropping intensity in most parts of Australia encouraged *A. fatua* and *A. ludoviciana* to be the dominant weed species and about 80% of wild oat populations in Australia contain both of these species (Storrie 2019; Fernandez Quinantilla *et al.* 1990). Southern Australia faces the dominance of *A. fatua*, while in southern Queensland and northern New South Wales, *A. ludoviciana* is the most dominant species (Nugent *et al.* 1999). *Avena barbata* is mainly a weed of non-agricultural land and mostly found along roadsides (Nugent *et al.* 1999; Cousens 2003). In the eastern region of Australia (New South Wales and Queensland), *Avena* spp., when assessed in terms of the infested areas, secured the highest ranking in the regional ranking of the top residual winter weeds in different crops (Llewellyn *et al*. 2016). As *A. fatua* and *A. ludoviciana* are the dominant weed species in Australia, these two species are mainly focused in this article.

WEED BIOLOGY

Botanical description

Although the two major species (*A. fatua* and *A. ludoviciana*) are quite similar morphologically, there are some variations, especially, during the reproductive growth stages which may be helpful to distinguish them from each other (Mennan and Uygur 1996; Holm *et al.* 1977; Thurston 1951). The growth habit and life cycle of *A. fatua* resemble with winter cereals; however, environmental conditions cause great flexibility in its life cycle (Medd 1996; Edgar 1980). Although *Avena* spp. are very similar to wheat and barley, these can be identified by their collar region before flowering. The leaf twist of wheat and barley is clockwise, while wild oat leaves twist anticlockwise (Paterson 1976). Florets of *A. fatua*, which are having hairy, bent, and twisted awns, resemble similarly with *A. ludoviciana* (Edgar 1980). The plants of *A. fatua* have loose and drooping panicles and open branches bearing spikelets whereas the panicles of *A. ludoviciana* plants are spreading and loose (Edgar 1980). The panicles of *A. fatua* are heavier than *A. ludoviciana* because its spikelets bear more and large florets (Edgar 1980). Keeping in view the similarities and differences in the botanical features of wild oat species, suitable management strategies may be devised effectively.

Propagation and dispersal of seed

Propagation of both species of *Avena* occurred exclusively through seeds (Holm *et al.* 1977). *Avena fatua* and *A. ludoviciana* are prolific seed producers (Storrie 2019; Storrie 2007). However, several studies suggested the variation in the seed production potential of both species. Environmental conditions also affect seed production in different wild oat species. *Avena fatua* can produce a large number of seeds *i.e.* up to 1000 seeds/plant (Rauber 1977). In a pot study, *A. fatua* was found to produce 480 seeds/ plant under well-watered conditions (Sahil *et al.* 2020). However, in the case of *A. ludoviciana*, a single plant was reported to produce up to 400 seeds/ plant (Sahil *et al*. 2020). Another Australian field study showed that under the conditions of low competition, *A. ludoviciana* can produce about 2,500 seeds/plant when emerged at the start of the winter season (Mahajan and Chauhan 2021a). Information regarding the seed retention or shattering behaviour of both the species in a crop is of great importance as seeds of *A. fatua* shatter individually while the spikelets of *A. ludoviciana* are too hard to break easily, thus, its seeds shatter in pairs at plant maturity (Sahil *et al*. 2020; Moss 2015; Mahajan and Chauhan 2021b). The reinfestation of these weed species in the fields is mainly caused by their shattering behaviour and thus, affects the severity of competition to the crop in the next season. Flowering in *A. fatua* occurs later than *A. ludoviciana* (Stace 1997; Holm *et al.* 1977), while the seed shattering of *A. ludoviciana* occurs 15-20 days before the harvesting of wheat (Balyan and Malik 1989). Seeds of *A. fatua* are elongated, large, and with hairs on them. Therefore, no report claims natural seed dispersal of *A. fatua* by water or wind. Dispersal is mainly through contaminants of winter crop seeds. In a study on weed dispersal, Wheeler *et al.* (2001) showed normal progress of patches of *A. fatua* by 1–3 m per year; however, the potential progress may reach up to 30 m in agricultural lands. Dispersal of wild oat species by anthropogenic activities also has great importance. In mixed farming systems, agricultural machinery (Thurston and Phillipson 1976), use of contaminated seed (Elliott and Attwood 1970), straw (Wilson 1970) or transportation of fodder (Thomas *et al*. 1984) are the major sources of dispersal of wild oat. Thus, prolific seed-producing nature, high seed viability, formation of a persistent seed bank, and effective dispersal nature enable *Avena* spp. to adapt successfully to a wide range of agroecosystems.

Dormancy

Dormancy in the seeds of both wild oat species maintains seed viability in the soil for several years. Due to the various interactions of *A. fatua* with the environment and high genetic variability, its dormancy behaviour is difficult to generalize (Holm *et al*. 1977). Seed recruitment of wild oat in the soil through shattered seeds by plants and their persistence in the soil through dormancy are the major factors that maintain the weed seed banks in the soil (Mahajan *et al*. 2021b; Jensen 2004). However, several studies claimed that persistence in the seed bank does not correlate with seed dormancy (Thompson *et al*. 2003; Honda 2008). It was suggested that the dynamics of the seed bank can be understood by determining the effects of environmental conditions on seed decay and seed longevity of *Avena* spp. (Vázquez-Yanes and OrozcoSegovia 1996). As reported by Fennimore *et al*. (1998), low temperatures increase the extent of dormancy in wild oat seeds, and dormancy is released when temperatures start increasing. Under unfavourable conditions for the seedling, the persistence of *A. fatua* becomes longer in the soil seed bank with the help of dormancy (Wu and Koetz 2014). Furthermore, under field conditions, seed dormancy and viability are dependent on the seed burial depth as the seed loss is increased with burial depth (Miller and Nalewaja 1990; Mahajan and Chauhan 2021c). In a study conducted by Miller and Nalewaja (1990), the seed viability of *A. fatua* was shown to be decreased by 80% soon after burial. However, 7% of seeds remained viable after 9 years of burial and a small portion of seeds were found viable even after 14 years of burial (Miller and Nalewaja 1990). A recent study conducted in eastern Australia reported that seeds of *A. fatua* and *A. ludoviciana* decayed in the soil within 3 years irrespective of burial depth (Mahajan and Chauhan 2021c). Thus, seed persistence and viability are correlated to environmental factors and soil conditions (Demo 1999).

Germination

The germination process shows complex patterns of variation both within and between populations of *Avena* spp. (Marshall and Jain 1970). Rains boost the germination of *A. fatua* seed bank. Approximately 40% of the seed bank germinates with the opening rain and a further 30% of seed bank germinates later in the season (Nugent *et al.* 1999). Germination remains continued from autumn to spring, consequently, the seed bank is replenished by enough seed production from the smaller and later cohorts. In reference to the suitable temperature for germination, *Avena* spp. shows a large range of temperature *i.e*. 10-26.5°C for germination. However, low temperatures favour the germination of *A. ludoviciana* more than that of *A. fatua* (Fernandez-Quintanilla *et al*. 1990); while germination of *A. fatua* is favored by relatively higher temperatures. There was a similar rate of germination for both species up to 10–18°C. However, at a temperature of more than 20°C, *A. fatua* germinated at a higher rate as compared to *A. ludoviciana*, the opposite trend occurred below 10°C (Fernandez-Quintanilla *et al.* 1990). Uremis and Uyagur (1999) reported 30, 2, and 10 °C as the maximum, minimum, and optimum temperatures, respectively, for germination of *A. ludoviciana*. Different wild oat species show spatial and temporal variation in the time of emergence (Aibar *et al.* 1991). Germination of *A. fatua* occurs from autumn to spring season while winter to early spring is the best time for germination of *A. ludoviciana* (Medd 1996). The knowledge regarding longevity of weed seeds within the soil and the timing of weed emergence under local conditions make a better understanding of a timely and efficient weed management strategy. Mahajan and Chauhan (2021c) found that a shallow depth of 2-5 cm favours the emergence of *A. ludoviciana and A. fatua* compared with the surface and 10 cm soil depth. Poor gas exchange and the absence of a light trigger around the buried seeds at 10 cm depth might be the reason for the lower emergence (Benvenuti and Macchia 1998; Benvenuti 2003). Fatal germination also might be a reason for the lower emergence of deeply buried seeds, as the seeds which germinate at a depth of 10 cm are likely to be died prior to reaching the soil surface (Davis and Renner 2007).

CLIMATE CHANGE AND WILD OAT

Generally, the distribution and prevalence of weed species within the crop and weed communities are affected by changes in climatic factors, such as atmospheric CO_2, rainfall, temperature, *etc*. (Chauhan *et al*. 2014). As wild oat populations have great genetic diversity, there are possibilities that with climate change, these will achieve more competitive advantage over the crop plants with which they have competition (O'Donnell and Adkins 2001). It was argued that wild oat species acquired a range of mechanisms for their survival in the cropping environment, such as a persistent seed bank and variable seed dormancy (Ali *et al.* 2021). In the present climate change scenario, with frequent changes in dry and hot spells during the late winter or early spring period (Cleugh *et al.* 2011), wild oat plants mature early and shed a major part of their seeds prior to harvesting of cereal crops (Ali *et al.* 2021).

For the germination of *A. ludoviciana*, 10 °C is considered the optimum temperature (Quail and Carter 1968). In an experiment on different Australian populations of wild oat, it was observed that major variables of climate change, *i.e.*, atmospheric CO_2, temperature, and soil moisture availability, had an important influence on the growth and development of wild oat species (O'Donnell and Adkins 2001). High plant biomass and an increase in the seed number of wild oat plants have resulted from increased CO_2, however, some degree of compensation was also observed in plant biomass for moisture-stressed plants grown at 480 parts per million by volume (ppmv) CO_2 (O'Donnell and Adkins 2001). Soil moisture stress and increased CO_2 were shown to reduce the dormancy level in after-ripened caryopses, and this may cause a change in seedling emergence patterns. Management strategies of wild oat may change under changing environmental conditions and new ecotypes.

HERBICIDE RESISTANCE IN WILD OAT

Among the major challenges to the sustainability of Australia's prevalent agricultural system, herbicide resistance is the important one. Due to the over-reliance on chemical weed control strategies in Australian farming systems, herbicide resistance has evolved in 49 weed species across 12 herbicide modes of action (MOA) groups (Storrie 2019). The first herbicide resistance case in wild oat was found in Western Australia in 1985 against the Group 1 herbicides (Heap 2008). Thereafter, in 1991, another incidence of resistance against the same group of herbicides was found in South Australia and New South Wales (Heap 2008). Since then, herbicide resistance cases have increased steadily and dramatically. A survey report of the year 2003 claimed the resistance to Group 1 herbicides in 10% of all wild oat populations in northern New South Wales and southern Queensland (Widderick and Walker 2007). An investigation on herbicide resistance in wild oat species in Australia showed that those wild oat populations have a high risk for evolving resistance that has been treated with acetolactate synthase (ALS) inhibitor herbicides repeatedly over the last 15 years (Storrie 2019; Storrie 2007). The wild oat populations were reported to be resistant to Group 1, Group 2, Group 9, and Group 31 herbicides in Australia with some populations resistant to sub-groups or multiple groups (Storrie 2019). Multiple herbicide resistance (resistance to both Group 1 and 31 herbicides) has been estimated in one of three wild oat populations. A recent study conducted in Australia reported the world's first case of glyphosate-resistant (GR) *A. fatua* and *A. ludoviciana* (Chauhan 2022).

As herbicide resistance in *Avena* spp. against a large number of herbicides including glyphosate, has been reported in Australia, sole reliance on herbicides may not be an effective strategy for the management of wild oat (Chauhan 2022; Heap 2022; Storrie 2019). Therefore, integrated weed management (IWM) strategies involving cultural weed management options, such as harvest weed seed control, improved crop competitiveness, and rotational use of herbicide, may provide better weed management options. For implementing IWM strategies against herbicide-resistant wild oat populations, two scenarios could be taken into consideration: those where resistance has still to evolve and those where resistance has already evolved (Nietschke *et al.* 1996). In those cases, where herbicide resistance in wild oat has already occurred, those strategies should be adopted which annihilate the resistant populations, such as crop removal for hay, silage, or green manure, so as to avoid the dispersal of resistant seeds. In the cases where resistance is yet to be experienced, adoption of those IWM strategies should be emphasized which minimizes or avoid the selection for herbicide resistance. If a variety of pre-and post-emergence herbicides and herbicides with different modes of action are used in a rotational way, it may help in delaying the onset of herbicide resistance (Anderson 2003). Besides, the survivor of herbicide-treated weeds needs to be tested with different groups of herbicides for susceptibility and an alternative method to be evolved for preventing seed set. A range of IWM techniques has been developed for the effective management of herbicide-resistant wild oat populations; however, an effective management strategy is needed to manage the weed seed bank in the soil. The development of an IWM program must be supported by a thorough understanding of the population dynamics operating within weed seed banks (Swanton *et al*. 2008). Therefore, it is suggested to know the biology of herbicide-resistant weed species which may help in the development of sustainable management practices.

MANAGEMENT MEASURES

As the wild oat species are listed among the most noxious, widespread, and terrible weeds in modern-day agriculture in Australia (Chauhan 2022; Nietschke 1997), there is a need to gain an understanding of the management of this problematic weed in crop production systems. A range of weed control or prevention methods have been identified for the management of wild oat species. These methods must be planned in such a way that they should focus on a whole farm basis rather than crop by crop or field by field. Initially, cultural methods were found more reliable on controlling wild oat, but since the 1960's, chemical control has become the most preferred method (Combellack 1992). However, after the development of herbicide resistance in wild oat species, the focus has shifted to IWM strategies for the sustainable control of wild oat.

Preventive methods and sanitation

One of the most important strategies in managing weeds is the prevention of weed introduction and spread regardless of crop, establishment method, and ecosystem. Preventive methods involve all possible means that restrict the entry and establishment of weeds in an area (Mahajan *et al.* 2016). Many sources may cause the spread of weeds from one area or field to another. As the seeds of wild oat do not disperse naturally, poor hygienic conditions on the farm can facilitate the introduction, spread, and persistence of wild oat. In such a situation, sanitation is considered an essential component of cultural control. In mixed farming systems, the spread of wild oat can be attributed to the use of contaminated grain (Elliott and Attwood 1970), transportation in fodder (Thomas *et al.* 1984), straw (Wilson 1970), or dispersal by agricultural machinery. Dispersal of wild oat seeds may be minimized by using clean and pure seeds, cleaning the tillage and harvest machinery between fields, and covering grain trucks used to transport grain (Thill *et al.* 1994).

Crop residue burning

One of the few cultural weed control methods that can be used for the control of wild oat in Australian farming systems is the crop residue burning from cereal crops. Nietschke (1997), from a series of experiments, demonstrated that crop residue burning helps to destroy the wild oat seeds on the soil surface. Seed killing is maximum if burning occurred directly after harvesting (Wilson and Cussans 1975). The position of seeds at the time of burning and the temperature and timing of burning are the major factors that affect the extent of control by the stubble burning method (Cussans *et al.*1987). However, it can, generally, be stated that wild oat seed destruction increases with the amount of residue burnt (Nietschke 1997). Additionally, residue burning can encourage the emergence of those wild oat seeds that were not killed by the burning process, therefore there is further depletion of seed banks when these emerged weeds are killed. However, potentially overriding these factors is that burning is generally not encouraged in Australia due to the established advantages of crop residue retention. However, if crop residue burning is used judiciously and may provide benefits to the agricultural system as a whole, it may prove a viable option for the IWM strategy in the management of wild oat and prevention of herbicide resistance in wild oat in Australia.

Tillage operation

There are complex and varied influences of tillage operations on the population dynamics of *Avena* spp. (Navarrete and Fernandez-Quintanilla 1996). Germination of wild oat is encouraged with tillage operations (Chancellor 1976). Tillage is considered a key factor in affecting the persistence of wild oat (Simpson 1992). A major proportion of wild oat seeds remained on the soil surface in minimum and no-till systems where they decay at a faster rate because of continuous variations in weather conditions and also can be killed by predators (Mahajan and Chauhan 2021c). Thus, wild oat seed banks decline more rapidly in minimum and no-till systems than in conventional cultivation (McGillion and Storrie 2006; Nugent *et al.*1999). In the conventional tillage system, seeds are buried in soil which promotes seed longevity and extends the life of the seed bank by inducing dormancy, however, the seeds released from dormancy and germinate when brought to the surface in subsequent tillage operations (Widderick and Walker 2007; Nietschke 1996). Thus, pre-sowing tillage operations are supposed to increase the wild oat infestation compared with practices which involve no or minimal soil disturbance during seedbed preparation, such as direct seeding (Medd 1990). Mahajan and Chauhan (2021c) suggested the depletion of seed bank of wild oat species with no-till systems. Further, the type of tillage implements also affects the seed bank. Some authors reported the more rapid decline of wild oat seed banks by using tyned implements as compared with deep ploughing (Wilson and Phipps 1985; Wilson 1978). The adoption of conservation tillage practices, thus seems the most appropriate for the management of wild oat in Australia.

Seeding rate

Cultural weed control strategies mainly focus on reducing yield loss due to interference of weeds by exploring crop competition against weeds (Gibson *et al.* 2002). It was established in the studies that increasing the crop density might be useful to improve the competitive ability of different crops against wild oat. High seeding rates were observed to suppress wild oat in common wheat (Carlson and Hill

1985), tame oat (May *et al.* 2009), barley (O'Donovan *et al.* 1999), and canola (*Brassica napus* L.) (O'Donovan *et al.* 2004). A recent study in Australia reported that a high seeding rate in early-planted wheat suppressed the growth of wild oat in terms of weed biomass and decreased weed seed production which resulted in increased wheat yield (Mahajan and Chauhan 2022). Banisaeidi *et al.* (2014) reported that an increase in the seeding rate of spring wheat from 152 kg seeds/ha to 266 kg seeds/ha reduced the shoot biomass of wild oat resulted in increased grain yield and the number of spike/m^2. Scursoni and Satorre (2005) reported the increased competitiveness in barley by increasing seeding rates which may be used as an effective crop management strategy to reduce the effect of wild oat on crop yield losses, particularly when herbicide use is reduced and when weed populations are low. However, it needs to be remembered while choosing a high seeding rate as a weed management tool that a high seed rate of crops can increase crop competitiveness against weeds only up to a certain level. Beyond that level, an increase in seed rate may not always result in a higher economic return, especially when seed costs are high.

Time of sowing

The time of sowing plays a vital role in crop-weed competition by affecting the initial growth of crops and weeds. By delaying the sowing date of spring cereals, wild oat, that germinate prior to sowing, can be controlled by cultivation. In general, delay in sowing of wheat is recommended in the paddocks which are highly infested with weeds. This delayed sowing maximizes weed control and helps to attain a high yield (Singh *et al.* 1995; Cussans and Wilson 1976). Recent studies in Australia have shown that early cohorts of wild oat (which emerge in May) are very competitive in nature and prolific seed producers (Mahajan and Chauhan 2021c). In such cases, delayed sowing of wheat can be used as an effective tool for weed management as early cohorts can be killed by pre-sowing tillage operation or by spraying non-selective herbicides (Cussans and Wilson 1976). Mahajan and Chauhan (2022) also reported the vigorous growth and high seed production of wild oat in the early sown wheat crop in Australia. However, it was further reported that weed seed production was reduced by 40% when timely sowing of wheat was sown at a high seed rate compared with a low seed rate (Mahajan and Chauhan 2022). A delay in the sowing of wheat, due to slower early growth, often causes a yield reduction (Shah *et al.* 2020). Some authors reported that delayed sowing of crops is a less effective method of controlling the first cohort of wild oat prior to crop sowing because of the staggered germination pattern of wild oat (Nugent *et al.* 1999; Nietschke 1996). These studies suggest that delayed sowing may not be the effective option for the control of wild oat, rather, early sowing along with the use of a higher seed rate may be a better option for smothering the weed flora and high profitability. However, in fields having a history of high infestation of wild oat, delayed sowing of winter crops may help in reducing seed bank in subsequent years.

Crop rotation

The continuous cropping of the same crops in Australia has resulted in detrimental effects on productivity in recent years. These negative effects have been associated with the increased selection pressure for the establishment of certain annual weeds, particularly problematic annual grasses (Bell *et al.* 2006; Seymour *et al.* 2012). As the weed management costs to Australian grain producers exceed AU$3 billion annually, advancements in easily adoptable and economic weed management techniques are needed (Gurusinghe *et al.* 2022). Crop rotations can be used as an objective to minimize the cost and to increase weed control efficiency by interspersing crops in which control can be attained. The long-term weed population dynamics are influenced by the choice and sequencing of crops. Every crop allows a particular weed to establish its association. These particular weeds are found in different rotations, and are controlled by rotating the crops which have different cultural habits and life cycles (Kumar *et al.* 2017). Diversified and specifically timed crop rotations give a specific benefit to farmers with respect to the control of annual weeds. Including broad-leaved crops such as canola, pasture legumes or lupins in crop rotation may enhance the suppression of grass weeds by improving crop competitiveness against weeds while also making available a broad range of selective herbicides for in-crop use (Weisberger *et al.* 2019).

Martin and Felton (1993) claimed that crop rotation is the most effective way to reduce wild oat seed banks in comparison to tillage and herbicide strategies. They found that the cultivation of wheat crops for four successive years with annual applications of either flamprop-methyl or triallate did not prevent the build-up of the wild oat seed bank. However, Johnson *et al.* (2006) found that continuous cropping systems did not decrease the seed banks of wild oat to an acceptable level and thus, benefited the wild oat. In the earlier studies in northern Australia, Martin and Felton (1993), Wilson *et al.* (1977) and Philpotts (1975) reported the effective reduction in seed reserves of wild oat through clean winter fallowing in association with a rotation from wheat to sorghum. Similarly, growing crops either for green or brown manuring, or for use as hay or silage, give an opportunity to growers for effective wild oat control while providing additional income from fattening stock or selling hay or silage (Storrie 2019). However, this technique will give effective control of wild oat only on the condition that removal of wild oat plants should be done prior to seed set.

Harvest weed seed control

Modern grain harvesters, while working in harvest condition specifications, collect and clean the crop grain efficiently, separate the grain from residues (*e.g.*, crop and weed plant material), and then, spread the straw residues and chaff (including collected weed seeds) from the rear of the harvester. This process disperses the collected weed seeds uniformly in the whole field. Thus, this process becomes inadvertently and ironically an efficient process for maintaining ongoing weed infestations. To disrupt this cycle, weed seeds can be harvested from the crop fields and their return to the field may be minimised. This is known as harvest weed seed control (HWSC) (Walsh *et al.* 2018). This is an effective weed control method that involves the collection and destruction of weed seeds that are present at the time of harvesting. As with several significant innovations in agriculture, HWSC system is one of the important innovations which targets weed seeds during crop harvest, was developed with the efforts of Australian grain growers. There are currently six HWSC methods being adopted in Australian agriculture systems: chaff carts; narrow windrow burning; chaff tramlining or chaff decks; chaff lining; seed impact mills and bale direct systems.

In Australia, HWSC technique has been proven an efficient weed management technique, particularly for *Lolium rigidum* (annual ryegrass), and is widely adopted in western Australia and increasingly in southern New South Wales, southern Australia, and Victoria (Walsh and Powles 2014). Some reports showed HWSC, a less effective tool for the management of wild oat, due to its early seed-shattering character before crop harvest (Nietschke *et al.* 1996). However, Walsh and Powles (2014), while studying the potential of HWSC in Western Australian wheat crops, showed high seed retention (HWSC potential) (84%) for wild oat species. This study confirmed that high proportions of the total seed production of wild oat could potentially be targeted with HWSC systems in Australian wheat crops. In another study, it was also found that *A. ludoviciana* has limited opportunity for HWSC (Mahajan and Chauhan 2021b). HWSC is considered more effective on wild oat when it germinates later in the crop as their maturity is closer to that of the crop. Any delay in harvest may result in a decline in the collection of weed seeds in the HWSC system (GRDC 2019).

Chemical weed control

Chemical weed control is generally considered the most important and cost-effective tool for the control of *Avena* spp. (Beckie *et al.* 2002). Due to the staggered emergence of wild oat, effective control has relied upon the most on the use of pre-and post-emergence herbicides, especially where early cohorts are responsible for major yield losses (Jones and Medd 1997). In the Australian cropping system, the first herbicides (*i.e.,* diallate and barban) for control of wild oat were introduced in the late 1950s (Hutson and Roberts 1987; Medd 1992). However, the selective spray topping method was introduced in the 1990s to prevent seed sets from the later germinating species (Cook *et al.* 1999). The ACCase-inhibiting (Group 1) herbicides, aryoxyphenoxypriopionates (fops) and cyclohexandiones (dims) (Group 2) have been widely used for in-crop wild oat control in Australia since the release of the first of these herbicides in 1978 (Broster *et al.* 2011). Efficient management of wild oat species is dependent on early post-application of aceto-lactate synthase (ALS) and acetyl-CoA carboxylase (ACCase) inhibitor herbicides (Owen and Powles 2009). Cyclohexanedione (CHD) and aryloxyphenoxy-propionate (AOPP) herbicides have also been broadly used for the management of wild oat (Burton *et al.* 1989). A number of herbicides including, barban, glyphosate, difenzoquat, linuron, chlorfenprop, monolinuron, metoxuron and metribuzin, have proved effective for the management of *A. fatua* and *A. ludoviciana* (Terry 1984).

Due to the over-dependence on herbicides, wild oat species have evolved resistance to ALS inhibitor herbicides, which are the most widely used herbicides for the control of wild oat in Australia (Storrie 2007). Therefore, pre-emergence herbicides may be an alternative for the control of wild oat in wheat in Australia. New pre-emergence herbicide options can give better flexibility for the control of wild oat in wheat, especially when integrated with other weed management tools. Today, a range of herbicides have been introduced worldwide which effectively control *Avena* spp. (**Table 1**). Mahajan and Chauhan (2022) reported that the application of pyroxasulfone and tri-allate as pre-emergence herbicides provided maximum control of wild oat in the Australian wheat system. Among the post-emergence herbicides, pinoxaden, clethodim, haloxyfop, and propaquizafop provide the best alternative herbicide options for the control of wild oat species (Chauhan 2022). Irrespective of the growth stage, these herbicides provide complete control of both *Avena* species. Some herbicides (e.g. butroxydim) provided the best results when applied at earlier stages (at the 3–4 leaf stage), however, delaying their spray till the 6–7 leaf stage resulted in the survival of *Avena* species (Chauhan 2022). Although, several herbicides have provided effective control of *A. ludoviciana* and *A. fatua* over the years, the evolution of resistance in herbicide has reduced the scope of chemical weed control. Owen and Powles (2009), in a survey conducted in the Western Australian grain belt, revealed the widespread resistance in wild oat to the ACCase-inhibiting herbicide diclofop-methyl across the studied area. However, alternative ACCase-inhibiting herbicides such as clodinafop, clethodim, and pinoxaden were shown to be effective on 97% of the wild oat populations which proved relatively low resistance in wild oat populations to AOPP and CHD ACCase herbicides. Similarly, herbicides of other modes of action, such as ALS inhibiting herbicides, triallate, glyphosate, and flamprop, also showed effectiveness in controlling those wild oat populations which showed resistance to ACCase herbicide. Thus, it may be concluded that still there is the scope for chemical weed control of wild oat by selecting a diverse range of herbicides available that permits flexibility in choosing herbicides with different modes of action, acting at different stages of crop growth (pre-seeding, seeding, post-seeding, and late stem elongation). This strategy may slow the onset of resistance to any single group and therefore, is widely recommended as a means of prolonging herbicide efficacy in Australian agriculture.

Allelopathy

Allelopathy is a naturally occurring phenomenon in agricultural ecosystems which has been emphasized in recent years as a potential alternative to chemical weed management. Many studies around the globe have confirmed allelopathy as an effective weed management tool, especially in organic farming systems (Cheema *et al.* 2004; Jamil *et al.* 2009; Iqbal *et al.* 2007). Allelochemicals retard the growth of plants by suppressing their physiological functions when applied at high concentrations. The growth suppression of weeds is caused by the phytotoxic activity of allelochemicals (Farooq *et al.* 2013). Bajwa *et al.* (2013) reported the suppression of germination and growth of wild oat with the application of water extracts from some weeds and tree plants, applied either singly or in combination. Jabran *et al.* (2010), investigated the allelopathic effect of barnyard grass, winter cherry, mulberry, and sorghum on wild oat and found that the mulberry was the most inhibitory plant species with respect to germination, root, and shoot length, the number of roots and leaves, and seedling fresh and dry weight of

Table 1. Herbicides used to control wild oat

Herbicide	Dose (g/ha)	Time of application	Crop	References
Pyroxasulfone	100	PRE	Wheat	Mahajan and Chauhan (2022)
Tri-allate	800	PRE	Wheat	Mahajan and Chauhan (2022)
Butroxydim	45	POST	Resistance Screening study	Chauhan (2022)
Clethodim	60-120	POST	Resistance Screening study	Chauhan (2022); Broster *et al.* (2011)
Haloxyfop	78	POST	Resistance Screening study	Chauhan (2022)
Pinoxaden	20	POST	Resistance Screening study	Chauhan (2022)
Propaquizafop	30	POST	Resistance Screening study	Chauhan (2022)
Fenoxaprop-ethyl	60	POST	Wheat	Medd *et al.* (1992)
Flamprop-methyl	225-450	POST	Wheat	Medd *et al.* (1992)
Fenoxaprop	81	POST	Barley	O'Donovan *et al.* (2013)
Mesosulfuron	10	POST	Resistance Screening study	Broster *et al.* (2011)
Triallate	800	PRE	Resistance Screening study	Broster *et al.* (2011)
Pinoxaden	100	EPOST	Wheat	Travlos *et al.* (2011)
Mesosulfuron + iodosulfuron	7.5 + 7.5	EPOST	Wheat	Travlos *et al.* (2011)
Metribuzin	247	POST	Wheat	Mueen-ud-Din *et al.* (2011)
Clodinafop-propargyl	36	EPOST	Wheat, Barley	Scursoni *et al.* (2011)
Fenoxaprop-p-ethyl	55	EPOST	Wheat, Barley	Scursoni *et al.* (2011)
Pinoxaden	40	EPOST	Wheat, Barley	Scursoni *et al.* (2011)
Iodosulfuron + metsulfuron-methyl	3 + 3.75	EPOST	Wheat, Barley	Scursoni *et al.* (2011)

PRE: pre-emergence, POST: post-emergence, EPOST: early post-emergence wild oat. The allelopathic potential for different plants against wild oat was in the order: mulberry > winter cherry > barnyard grass > sorghum. Turk and Tawaha (2003) found that the water-soluble allelochemical substances in black mustard (*Brassica nigra* L.) inhibited the germination and seedling growth of *A. fatua*. This study also confirmed that the inhibitory effect on germination increased with increasing concentration of extract solution of the fresh plant parts. Similarly, Cheema *et al.* (2013) also found the potential effect of sunflower, sorghum, and mulberry as allelopathic crops. There is a lack of information regarding the allelopathic potential of different plant species to control wild oat in Australian conditions. So, research is needed to quantify the potential effect of allelopathy as an integrated part of weed management strategies in Australia.

INTEGRATED WEED MANAGEMENT APPROACH

Many weed management strategies have been developed for the effective management of wild oat. However, the adoption of any single technique cannot provide effective, sustainable, and season-long control of this weed as different species of wild oats vary in dormancy and growth habits. Sustainable and effective weed management strategies involve the combined use of preventive, mechanical, cultural, chemical, and biological weed control methods in an effective and economical pattern which is called IWM. This is the most suitable and effective strategy for weed management in progressive farming. No doubt, chemical weed management remains the central part of any IWM package, the inclusion of above-discussed methods may provide the best weed control results. Non-chemical weed management methods which may improve the performance of the IWM strategy for controlling wild oat species include tillage, crop rotation, crop competition, seed rate or seeding density, manipulation in sowing time, harvest weed seed control and allelopathic suppression (Mahajan and Chauhan 2022; Mahajan and Chauhan 2021b; Nalewaja 1999; Boerboom 1999; Thill *et al.* 1994). Instead of using only chemical methods, *A. fatua* can be controlled successfully with an integrated approach, and its seed production and competitive ability may be reduced by the adoption of different approaches in an integrated manner (O'Donovan *et al.* 2000). Different wild oat species have been reported to be effectively controlled by adopting appropriate combinations of different management tools (**Table 2**). By using the IWM approaches, weed biomass of *A. fatua* and *A. ludoviciana* has been reported to be reduced by up to 90% (Harker *et al.* 2009; Blackshaw *et al.* 2008; Anderson 2003). Mahajan and Chauhan (2021a) suggested that IWM could be the best strategy for the successful control of *A. ludoviciana*, and prevention of seed production is the most important action toward reducing the replenishment of seed banks.

As the wild oat species have evolved resistance to most of the selective herbicides available for their control including glyphosate in Australia and, therefore, have had the biggest impact on farm profitability. A range of IWM methods has been proven very effective for managing and reducing the herbicide-resistant populations of wild oat (Beckie 2006). Mahajan and Chauhan (2021c) emphasized the knowledge of the timing of the emergence and the emergence dynamics of *A. fatua* and *A. ludoviciana* from different depths, allows to make decisions making tools such as strategic tillage systems, making the best use of all principles of IWM and maintaining weed infestation at economically acceptable levels. Improving the competitiveness of

Table 2. Integrated weed management options for wild oat species

Integrated weed management strategy	Outcome of IWM strategy	Associated crop	References
Early sowing + effective pre-emergence herbicides, (pyroxasulfone and triallate)	Effective control of wild oat and limited production of weed seed resulting in high crop yield	Wheat	Mahajan and Chauhan (2022)
Crop competitiveness + reduction in herbicide dose	Reduction in biomass and minimal potential replenishment of the seed bank of *A. ludoviciana*	Barley	Walker *et al.* (2001)
High crop density (150 plants m^{-2}) + Reduction in herbicide dose	Reduction in biomass and seed production of *A. ludoviciana*	Wheat	Walker *et al.* (2002)
Tall cultivar + high crop density (400 plants m^{-2}) + diverse crop rotation (barley–canola–barley–pea–barley) + A 50% reduction in herbicide dose	Reduction in biomass of *A. fatua* and a 40-fold reduction in its seed production	Barley	O'Donovan *et al.* (2013)
Diverse crop rotations involving cereals and legumes + high seed rates + cover crops	Reduction in biomass and seed production of herbicide-resistant *A. fatua* resulting in high crop yields and economic returns	Canola, barley, wheat, pea, rye	Harker *et al*. (2016)

the crop by adopting multiple weed management approaches in an integrated manner has shown success in managing wild oat species in major field crops (Bajwa *et al*. 2016). So, the adoption of an appropriate IWM method could prove as a key to the successful management of wild oat species in the Australian crop production system.

CONCLUSION

Wild oat species, especially *A. fatua* and *A. ludoviciana* are the major challenge to the crop production system in Australia. The morphological features, propagation, dispersal, dormancy, and germination mechanism of these weed species enable them to survive in a wide range of environmental conditions. A range of herbicides with different modes of action and their use in rotations could provide long-term weed control by reducing selection pressure on weeds. Non-chemical methods such as sanitation, crop residue burning, optimizing seeding rate, increasing crop competition, allelopathy, harvest weed seed control, etc can be used for the management of wild oat. However, the adoption of any single technique cannot provide effective, sustainable, and season-long control of this weed as different species of wild oats vary in dormancy and growth habits. Sustainable and effective weed management strategies involve the combined use of preventive, mechanical, cultural, and chemical weed control methods in an effective and economical pattern.

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REVIEW ARTICLE

Bioavailability of allelochemicals in soil environment under climate change: Challenges and perspectives

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ABSTRACT

Weed management is an important component in sustainable agriculture. The current agriculture is changing with climate change. Allelopathy has been recognized as a component of integrated weed management over the years. The allelopathic ideas have been used in various facets of allelopathic implications. Some of these include use of cover crops, plant residues, plant extracts, crop cultivars and others. And it is being challenged under climate change factors such as increased atmospheric CO_2, temperature rise, erratic rainfall patterns and others. The relevance of allelopathy has been highly discussed due to the lack of phytotoxic concentrations of allelochemicals under field conditions. Crop residues from existing crop or rotational crops can provide selective weed suppression through their physical presence on the soil surface and/or through the release of allelochemicals. *Brassica nigra*, *Avena fatua*, *Fagopyrum esculentum*, *Secale cereale*, *Sorghum bicolor*, *Triticum aestivum* and other cover crops have been used in weed management on a limited basis. Some of the allelochemicals such as DIBOA, DIBOA-glycoside, dhurrin, isoflavonoids, isothiocyanate, juglone, momilactone, scopoletin, and sorgoleone have been reported to play a role in weed management under field conditions. The living and dynamic soil system influences the fate and functions of allelochemical activity. The bioavailability of allelochemicals in the soil is dependent on soil processes such as adsorption, leaching and degradation by abiotic and biotic factors. These processes and other related soil conditions are greatly influenced by several underlined climatic variables. Future allelopathic research should be focused on persistence and availability of allelochemicals in soil environment. The bioavailability of allelochemicals under field conditions with climate change associated rising atmospheric CO_2, rising temperature and intensity and erratic rainfall must be established for its effective practical role in weed management. Currently, we face challenges and opportunities in using allelopathy as a part of weed management strategies in today's agriculture.

Keywords: Allelopathy, Adsorption, Climate change, Cover crops, Crop residue, Microbial activity

INTRODUCTION

Allelopathy has been recognized, over the years, as a component of integrated weed management (IWM). The role of allelopathy has been reported in the usage of components of IWM such as the use of cover crops, plant residues, plant extracts, crop cultivars and others. Scavo and Mauromicale (2021) reviewed the role of crop allelopathy for sustainable weed management. It is a challenge to utilize allelopathy in future IWM strategies as a component under the times of climate change with increased atmospheric CO_2 and temperature, erratic rainfall patterns of rainfall and others.

The process of allelopathy is difficult to prove in nature in the agricultural fields as it is influenced by many interactive factors. Once a allelochemical is released to soil, all the chemicals can be adsorbed by soil components or transformed by soil microorganisms into less or even more harmful molecules for plants (Kobayashi *et al.* 2004, Tharayil *et al.* 2006).

Crop residues using cover crops or rotational crops for weed management in the field is challenging especially during climatic change. Sainju and Alasinrin (2020) reported that long-term cropping system and nitrogen fertilization contributed changes in soil chemical properties and crop yields. The cover crops usage under various cropping systems has limitations such as delayed planting, delayed crop emergence, phytotoxic effects to major crops, and increased pest pressure.

Weed suppression by rye (*Secale cereale* L.) residue on the soil surface in no-tillage system has been documented from 1980's. Weed suppression can be attributed to both the chemical and physical

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influences of rye residue (Fay and Duke 1977, Bhowmik and Doll 1982, Mennan *et al.* 2020).

Earlier reports have shown that weed suppression or control could be achieved by growing cover crops of rye, barley, wheat or sorghum to a height of 40 to 50 cm, and then desiccating the crop by either contact herbicides or winter freezing and then allowing the residue on the surface (Barker and Bhowmik 2001, Mennan *et al.* 2020).

Vicia villosa has been used as a cover crop and has been demonstrated potential use in weed management (Teasdale and Daughtry 1993). Perennial weed control is a challenging part of weed management. Cover crops are not much effective in managing perennial weed species. It is also believed that regrowth of certain perennial weeds may be favored due to far-red light environment under cover crops. Total weed density and biomass were lower in live *Vicia villosa* treatment compared to desiccated *Vicia villosa* plots. Red (660 nm) and far-red (730 nm) light ratio of transmitted light was reduced by 70% in live *Vicia villosa* and by 17% under *Vicia villosa* desiccated by paraquat. They concluded that factors such as light, soil moisture and temperature are responsible for the weed suppression by *Vicia villosa*. The question remains whether residues from crops or cover crops can provide successful weed management (100%) in the field.

The cropping system could be used to improve soil physical properties and suppression of weeds (Naeem *et al.* 2022). The barley-based cropping systems and weed control strategies influence weed infestation, soil properties and barley productivity (Naeem *et al.* (2022). The greengram-barley system with weed free control improved soil characteristics and barley yield over other cropping systems. The use of allelopathic water extracts significantly suppressed weeds and was equally effective as the chemical control.

The allelopathic effects of waste-land weeds on germination and growth of winter crops was reported (Hayyat *et al.* 2020). Lantana species such as *Lantana camara* L. has been studied well in relation to allelopathic activity to crop species and weed species. In a biometric analysis of allelopathic potential, Maity (2020) reported activity of *Lantana* spp. on mimosa seeds. Gindri *et al.* (2020) demonstrated the effect of allelochemicals from *L. camara* on the seed germination of *Avena sativa* L.. Qureshi *et al.* (2021) isolated natural herbicidal compound from *Lantana camara* L.. Mustafa *et al.* (2019) evaluated dominant allelopathic four weeds on germination and seedling growth of six crops. The effects of rhizome extracts from invasive knot weed *Fallpia japonica* and *F. xbohemica* on radish seed germination and root growth (Soln *et al.* 2021). In nature, plant products represent a vast diversity of compounds with a variety of biological activity (Duke *et al.* 2002, Bhowmik and Inderjit 2003, Weston and Duke 2003, Duke 2015). The natural products represent a diverse class of chemical compounds. These allelochemicals will have impact on different species of plants.

This presentation will highlight allelopathy as a component of integrated weed management, importance of soil factors in allelopathic activity, microbial activity, and potential challenges in allelopathy under climate change.

ALLELOCHEMICALS

Allelochemicals - crop cultivars

Crop cultivars have been screened for their differential allelopathic activity for the last several decades (Dilday *et al.* 1998, Gealy *et al.* 2000, Wu *et al.* 2002, Kato- Noguchi *et al.* 2010, Masum *et al.* 2018). This topic could be a separate review article and therefore I will briefly highlight some of the research work. *Avena* spp., *Oryza* spp., *Sorghum* spp. have been studied in detail over the years (Fay and Duke 1977, Rice 1984, Dilday *et al.* 1998, Gealy *et al.* 2000, Duke *et a*l. 2002, Olofsdotter 2001, Czarnota *et al.* 2003, Kato-Noguchi *et al.* 2010, Masum *et al.* 2016, Masum *et al.* 2018) and was reviewed in detail (Bhowmik 2018).

Fifty rice cultivars from Bangladesh have been screened against *Echinochloa crus-galli* (barnyardgrass) and *Echinochloa colona* (jungle rice) by using Equal Compartment Agar Method (Masum *et al.* 2016) and 7 to 37% suppression of *Lactuca sativa*, *Lepidium sativum*, and *Raphanus sativus* was reported. The allelopathy role in integrated weed management in rice was reviewed well (Patni *et al.* 2018).

Allelochemicals - plant extracts

Use of allelochemicals from plant extracts has been researched for weed management in agriculture. In Pakistan, for example, an aqueous extract deriving from sorghum shoots with a 10% concentration is left to ferment for several weeks and is subsequently sprayed post-emergence for weed control. This fermented water extract, known as "*Sorgaab*", reduced weed density and biomass up to 50%, in field trials, depending on the weed species (Cheema *et al.* 2002). The use of allelopathic water extracts significantly suppressed weeds and was equally effective as the chemical control (Naeem *et al.* 2022).

The research on usage of plant extracts for weed management was reviewed (Bhowmik 2018).

Allelochemicals - isolation

Thousands of allelopathic substances have been isolated from plants and their chemical structure has been determined. However, the mode-of-action (MOA) has only been elucidated for a limited number of allelochemicals (Cheng and Cheng 2015). Some of the allelochemicals such as allyl isothiocyanate (*Brassica* sp., black mustard), fatty acids (*Polygonum* spp.), isoflavonoids and phenolics (Trifolium spp., *Melilotus* spp.), phenolic acids and scopoletin (*Avena sativa*), hydroxamic acids (*Triticum* sp.), phenolic acids, dhurrin, and sorgoleone (*Sorghum bicolor*) have been reported for weed control (Duke *et al.* 2002). Duke and his group have shown artimisinin, a sesquiterpenoid lactone, to inhibit the growth of *Amarantus retroflexus*, *Ipomoea lacunosa*, *Artemisia annua* and *Portulaca oleracea*. Mushtaq and Siddiqui (2010) reported that plants belonging to Asteraceae family are the most studied species for allelopathic potential to control weeds in India. Some of the species including *Parthenium hysterophorus*, *Ageratum conyzoides* and others received more attention.

The allelopathic effects of sorghum on weed species was demonstrated (Czarnota *et al.* 2003, Weston *et al.* 2013). Root exudates of 100 cultivars of *Sorghum bicolor* were evaluated for their potency to affect the seed germination and growth of *Amaranthus retroflexus* (Alsaadawi *et al.* 1986). Some cultivars were more toxic than others.

The inhibition of shoot and root growth of *Echinochloa crus-galli* when co- cultured with rice (*Oryza sativa)* seedlings, in a bioassay, was reported (Kato-Noguchi *et al.* 2010). The momolactone A and B were identified in the bioassay medium of all rice cultivars. The concentrations of mamolactone A and B varied from 0.21-1.5 and 0.66-3.8 umol/L, respectively demonstrating the evidence of secretion of these two compounds from all rice cultivars into the medium.

In *Oryza* species, four biologically active compounds, syringaldehyde (4-hydroxy-3,5-dimethoxybenzaldehyde), (-) loliolide, 3*â*-hydroxy-5*á*,6*á*-epoxy-7-megastigmen- 9-one and 3-hydroxy-*â* –ionone, were isolated (Masum *et al.* 2018). The biological activity of these compounds showed that concentration > 10 ìM significantly inhibited the root and shoot growth of *E. crus-galli* seedlings, and the *I*50 (50% growth inhibition) values ranged from 16.03 to 27.23 ìM and 23.94 to 75.49 ìM for root and shoot growth, respectively.

In recent years, allelopathic research has been increased on trees, invasive species in forest areas. Bitchagno *et al.* (2022) found alkaloids as the main component of the extracts from plants in genus *Peganum*, one of the group of plants in the semi-arid regions of the world. These compounds showed significant potential to manage weeds in crops.

Allelochemicals – soil system

The soil is a living and dynamic system. The living system can influence the functions of allelochemicals in time and space. Soil chemical properties are significantly altered by any cropping system through moisture and nutrient uptake and the amount and quality of crop residue (Sainju and Alasinrin 2020, Wozniak 2020). The bioavailability of allelochemicals in the soil is dependent on processes such as adsorption, leaching and degradations by abiotic and biotic factors. The clay types, organic matter, and soil pH can affect the bioavailability of allelochemicals in the soil and the details were revived by Kobayashi (2004).

The soil can adsorb and modify the fate of allelochemicals. For instance, sorgoleone binds strongly to soil colloids because it is a highly lipophilic allelochemical, with a log (log octanol- water partition coefficient) of 6.1 (Trezzi *et al.* 2016). The allelopathic compounds l-3,4dihydrox phenylalanine and catechin are also strongly adsorbed by soil colloids, possibly due to the catechol group present in these molecules (Furubayashi *et al.* 2007).

Reduced allelopathic potential of benzoxazinoid compounds 2-aminophenoxazin-3-one and DIBOA (2,4-dihydroxy-(2H)-1,4-benzoxazin-3(4H)-one) have been reported due to their adsorption by soil colloids (Teasdale *et al.* 2012). The chemical compounds that are not adsorbed onto colloids or minerals are usually in the soil solution. Thus, they can be absorbed by plants or leached (Kobayashi 2004, Kong *et al.* 2007, Li *et al.* 2013). Kong *et al.* (2007) reported that flavonoids with a high mobility in the soil profile were less phytotoxic than those with reduced soil mobility with rice plants. Similarly, an analysis of ten potential allelochemicals revealed an inverse relationship between soil mobility and their toxic effect on target plants (Li *et al.* 2013).

Tharayil *et al.* (2006) demonstrated the role of preferential sorption to soil in altering the chemical composition of plant exudates in a silt loam soil using representative mixtures of plant phenolic acids, namely, hydroxybenzoic acid, vanillic acid, coumaric acid, and ferulic acid. Removal of organic matter substantially decreased the sorption affinity of all phenolic acids. The soil sorption properties of some individual allelochemicals have previously been studied. A detailed description of preferential sorption to soil has been reported and reviewed (Bhowmik 2018).

Gimsing *et al*. (2009) reported mineralization of the allelochemical sorgoleone in soil. Wei et al. (2017) reported soil microbial utilization, enzyme activities and nutrient availability responses to *Biden Pilosa*.

The allelopathy of *Imperata cylindica* may support the invasiveness of the species (Kato-Noguchi 2021). Kato-Noguchi (2022) reported root exudate of *Imperata cylindrica* released into the rhizosphere and surrounding environments containing allelochemical that can alter the microbial community.

The role of sorption to soil in modifying the bioavailability of components in complex allelochemical mixtures is still not well understood. Soils can alter the phytotoxicity of plant secondary metabolites by changing their bioavailability, persistence, and fate under field conditions. Sorption is one of the prominent factors affecting the phytoavailability of allelochemicals in soil.

Allelochemicals - microbial activity

The fate of allelopathic compounds in soil may be altered by soil microorganisms. Phenolic acids are readily converted from one structure to another with different phytotoxicities (e.g., ferulic acid to vanillic acid) by soil-borne microbes (Blum 1998, Inderjit 2001, 2005). Schmidt and Ley (1999) suggested that carbon-limited soil organisms would rapidly mineralize phenolic compounds due to their higher energy content on a per weight basis than simple sugars. Zikmundová *et al*. (2002) studied the biotransformation of the phytoanticipins BOA and HBOA by four endophytic fungi isolated from *Aphelandra tetragona*. It was shown that the metabolic pathway for HBOA and BOA degradation leads to o-aminophenol as a key intermediate.

Microbes can deactivate water soluble allelochemicals released soon after cover crop residue incorporation (Jilani *et al*. 2008). As agricultural soils are not sterile, it is important to understand how microbial activity moderates allelopathic potential of cover crop residues (Blum 1998, Inderjit 2005). Mohler *et al*. (2012) showed that unsterilized live soil (*i.e.*, with a natural microbial community) reduces seedling germination rates when cover crop residues are incorporated, and the combined effect of residues and live microorganisms is greater than the effect of either of these components alone.

Allelochemicals in the soil may be degraded and altered, reducing their efficacy. In non-sterilized soil, for instance, DIBOA showed a half-life of 43h. However, 2-aminophenoxazin-3-one (APO), the fungal degradation product of DIBOA, has a low mineralization rate and therefore, a half-life greater than 90 days (Macías *et al*. 2005). In addition, some flavonoid glycoside molecules exuded by rice plants can suffer high mineralization by soil microorganisms, resulting in a glycosylated compound. Flavonoid glycosides and a glycoside have a half-life of 2 h and 30 h, respectively, suggesting a higher allelopathic activity for the second group (Kong *et al*. 2007). The biodegradation of the sorgoleone quinone ring is relatively slow, with only 21% being mineralized 77 d after incubation in soil. However, the sorgoleone methoxy group was biodegraded within a few days, particularly in soils with a low colloid content (Gimsing *et al*. 2009).

Lou *et al*. (2016) reported interactions between allelochemicals and the microbial community affecting weed seed germination following cover crop residue incorporation into the soil. Qu *et al*. (2021) invasive species allelopathy may decrease plant growth and microbial activity. Scavo *et al*. (2019) showed the importance of agronomic, nutritional and ecological relevance in the soil system. In contrast, Mishra *et al.* (2013) reported beneficial role of microbial contributor in reducing the allelopathic effects of weeds. Zhang et al. (2019) showed soil microbial metabolic activity and carbon utilization in rhizosphere soil of rape seed (*Brassica napus* L.).

Many researchers isolated secondary metabolites and identified in the leachate, exudates, and extracts. An excellent review of literature on allelochemicals of *Imperata cylindrica* on microbial community has been published by Kato-Nogochi (2022). Greenhouse and field studies showed that *Imperata* cylindrica altered the microbial community in the rhizosphere soil and affected the growth of several crop plants. This type of research needs to be planned to establish any role of microbial community.

Allelochemicals - availability

A less attention has been made in the fact that the allelochemicals may be released as mixtures with other compounds (Wu *et al*. 2002). Soils may also influence the relative activity of allelochemicals in combinations. Because allelochemicals are generally exuded in mixtures of metabolites that often include other allelochemicals (Uren *et al*. 2001), preferential sorption of compounds onto the soil matrix could further alter availability.

The disappearance of allelochemicals was delayed when present in a multi-solute mixture from both soils. This slow disappearance of allelochemicals in a mixture could be due to the combined effect of preferential degradation, where compounds with a stable ring structure and without a 3-C (acrylic) side chain are less susceptible to degradation, and competitive sorption, where less hydrophobic molecules are displaced into soil solution (Tharayil *et al.* 2008).

The interaction of allelochemicals in the soil matrix remains as one of the least understood areas in the research on allelopathy (Tharayil *et al.* 2006). Most of the allelopathic interactions take place in the soil, where allelochemicals are exuded through roots (Bias *et al.* 2006) or are released during decomposition of plant litter (Bonanomi *et al.* 2006, Siqueira *et al.*, 1991). Thus, soil matrix forms the primary medium for the transport of allelochemicals from a donor to a receiver plant. During this transportation, the soil matrix is capable of altering the bioavailability of allelochemicals by various processes including sorption and chemical and microbial degradation (Dalton 1989, Tharayil *et al.* 2006, Ohno 2001). Because allelochemicals are secreted in quantities far less than needed to overwhelm the soil processes, at the field level, the soil matrix becomes the governing factor in the allelopathic activity. Thus, in many cases allelochemicals are not found in phytotoxic quantities under field conditions (Tharayil *et al.* 2008).

CLIMATE CHANGE

Climate change can disrupt food production and availability with current agricultural practices. Projected increases in temperature, changes in precipitation patterns, occurrence of extreme weather events and reductions in water availability may all result in reduced agricultural productivity (Raj *et al.* 2022). Climate change involves rising temperatures (Tubiello *et al.* 2007, Gillet *et al.* 2011) and altered precipitation patterns, leading to tribalities of summer droughts. Weeds are influenced by these altered abiotic conditions (Duke *et al.* 2009, Singer *et al.* 2013). Rising atmospheric CO_2 is likely to alter the competition between weeds and crops (Gray and Brady 2016). Thus, weed management will likely to be altered or challenged.

Bois *et al.* (2013) discussed the climatic change on biotic interactions of pants. Changes in temperature and precipitation will also affect the species phenology in ways that we do not understand. Peters et al. (2014) while reviewing the impacts of climate change on weeds in agriculture, indicated that changes in the species composition and new species introductions are favored under climate change. Thus, facilitate major ecological and agronomical implications. Climate change has significant impacts on the distribution of species and alters ecological processes that result from species interactions (Gomez-Ruiz and Lacher Jr, 2019). Duke *et al.* (2009) reported responses of insect pests, pathogens and invasive plant species to climate change in the forest areas of northern North America. Soil microbes alleviate allelopathy of invasive plants (Li *et al.* 2015).

Root exudates in rhizosphere interactions with plants have been studies over the years (Bias *et al.* 2006). The general expected higher atmospheric temperature and lower/altered precipitations would constitute environmental stresses affecting plant growth and development. In addition, the expected plant stresses may result in less or more production of allelochemicals in plant. The information on allelochemical production in plants under increased temperature or CO_2 or under altered precipitation is very limited.

Effects of increased atmospheric CO_2 on C_3 and C_4 weed species and crops have been established (Ziska and Bounce 1997, Ward *et al.* 2001). Rising atmospheric temperature on weed and crop growth and development have been reported over the years. Studies on the effects of higher temperature on allelopathic effects of weeds on crops are limited. This type of management practices would be altered under higher temperature or altered precipitation ranges. Teasdale *et al.* (2012) reported expression of allelopathy in the soil environment as soil concentration and activity of benzoxazinoid released by rye cover crop residue.

Chadha *et al.* (2019) showed that soil moisture regimes influenced growth, photosynthetic capacity, leaf biochemistry and reproductive capabilities of the invasive agronomic weed *Lactuca serriola*. Medina-Villar *et al.* (2020) reported that environmental stress under climate change reduces plant performance yet increases the allelopathic potential of an invasive shrub. The varying effects of temperature and photosynthetic photon flux density on the expression of allelopathy was demonstrated by growth analysis (Bhowmik and Doll 1983). Similar studies could be conducted to show any allelopathic activity as influenced by temperature variations, altered moisture conditions in the soil. Bajwa (2005) reported various effects of arbuscular mycorrhizae (AM) and effective microorganisms (EM) in various plant under allelopathic stress. Environmental stress such as rising temperature any influence plant growth enhancing or decreasing production of allelopathic compounds.

Altered precipitation leads to dry or wet conditions to soil and can influence the growth of plants. Mausbach (2022) demonstrated the effects of water stress on growth and fecundity of velvetleaf (*Abutilon theophrasti*). *Abutilon threophrasti* can survive equator larger than 50% FC continuous water-stress conditions, although with reduced leaf number, plant height, and growth index compared with 75% and 100% FC. And these factors may induce production of allelochemicals.

ALLELOCHEMICALS - CHALLENGES

We currently have numerous examples of allelopathic effects on weed suppression either by allelochemicals or by joint action of residue and its altered chemicals. Many crop residues or cover crop residues have been used in crop production. Today, we are still looking for other allelopathic plants or weed species. We have made significant advances in this direction over the last several decades. However, we still have a long way to go in terms of using allelochemicals or developing plant cultivars that would be used for complete weed management. This approach would be more challenging as we face rising atmospheric CO_2, temperature and altered precipitation.

Using allelochemicals for successful weed management may have limitations. Some of these in implementing natural products or allelochemicals for effective weed management include: (i) allelochemicals are present in very low concentration, (ii) compounds have generally short half-lives, (iii) narrow spectrum weed selectivity, and (v) may have high cost of production.

The environmental fate of allelochemicals is a complex issue that is affected by the donor and receiver target plant species, as well as soil and environmental variables that affect the fate and functions of the chemicals in the soil complex. Knowledge concerning the variation in these factors is essential to use the allelopathic relationship among plants in agroecosystems to promote weed management. Some of the research areas include:

- Identify allelopathic plant species
- Isolate and identify compounds in relation to mode of action
- Determine the stability of allelochemicals in soil
- Identify microbial role in allelopathic activity
- Production of allelochemicals as affected by temperature and CO_2 and PPFD
- Establish allelopathic activity in weed suppression or control in cropping system

Despite many challenges in implementing the allelopathic concept in weed management, there is tremendous scope for exploring allelopathy phenomena for successful weed management. The bioavailability of allelochemicals under field conditions must be established for its effective role in weed management. Continued research on these areas is important and we must invest our resources in exploring allelopathy as a complimentary component in successful weed management.

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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 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.

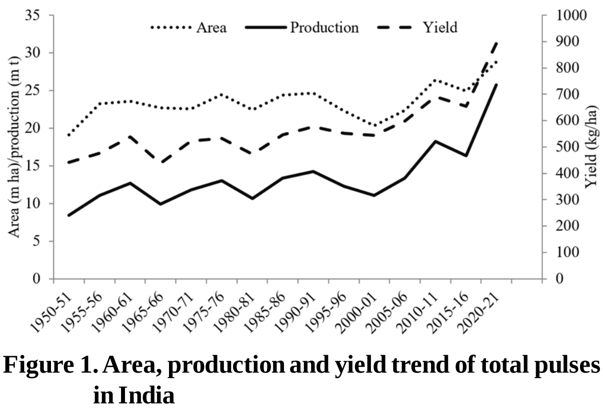

Figure 1. Area, production and yield trend of total pulses in India

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

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.

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REVIEW ARTICLE

Weed management in oilseed crops- a review

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ABSTRACT

Oilseed crops are slow growing during the initial growth period. In oilseeds, weeds caused yield reduction by 15-60 percent. Hence it is very essential to control weeds during the critical period of crop-weed competition. Weed management options in the majority of oilseed crops are limited, therefore, adoptions of multiple options of weed management using 'little hammers' considering preventive, cultural, mechanical, chemical, and biotechnological approaches are important. Integrated weed management (IWM) is a system approach to minimize weed populations below the economic threshold level. Among different weed management practices, cultural practices minimized the crop-weed competition up to large extent. Further, mechanical measures and herbicidal weed management are 'large hammers' or single large methods of weed control, but that may lead to the development of another level of problems like shift in weed flora, development of difficult-to-control weeds, issues of herbicide resistance, establishment of perennial weeds, *etc*. Thus, the aforesaid problems can be overcome by suitably adopting IWM, since it mixes the use of different available weed control methods in a balanced way by managing the weeds effectively, and sustainably provides higher production without harming the environment.

Keywords: Castor, Groundnut, Linseed, Niger, Oilseed crops, Sesame, Soybean, Sunflower, Weed management

INTRODUCTION

Globally, about 374000 plant species are currently known. Once anyone grows plant species for economic purposes, invariably a variety of unwanted vegetation establishes and competes with the economic species for available resources. These unwanted and competitive plants are termed "weeds". Plant species grown for economic purpose has to encounter various biotic and abiotic stresses. Among these stresses, biotic stress causes yield loss by 20-40% Ghosh *et al.* (2021). Among biotic stresses, weeds are a major one and alone can cause a yield loss of 45% in the world context (Katiyar and Singh 2015) and 37% in the Indian context. Apart from weeds in India, yield loss due to insect-pests accounts for 29%, diseases 22%, and other pests 12% (Yaduraju 2006; Mishra *et al.* 2021). As per the study conducted at ICAR-Directorate of Weed Research, Jabalpur, India yield loss of about US$ 11 billion due to weeds in ten major field crops has been estimated (Gharde *et al.* 2018). This figure further increases when other crops and the indirect effect of weeds are taken into consideration.

India has achieved self-sufficiency in food production, but in reality, it can only be achieved by assuring a balanced diet to individuals. Oilseeds plays important role in human health as the oilseeds are rich in protein, and in addition, they contain a high level of fat. Oilseeds add important nutritional value to the diet due to high-quality protein and or vegetable oil, together with oil soluble vitamins like vitamin A. Oilseeds not only provide food- and nutritional-security but also provides raw materials to manufacturing industries. The major oilseeds crops are soybean, sunflower, rapeseed, cotton, groundnut, *etc*. and oil content ranges from about 20% in soybean to over 40% in sunflower, linseed (37-47%), rapeseeds (35-46%) and groundnut (46-51%). Among oilseed crops, soybean, rapeseed-mustard, and groundnut stand 1st, 2nd and 3rd place, respectively in terms of area of cultivation. Crop-wise acreages, production, and productivity are stated in **Table 1**.

In crop production, biotic and abiotic stress are major yield-limiting factors. The yield loss caused by biotic stress ranges from 20-40% (Ghosh *et al.* 2021). Weeds are considered a major biotic stressor which accounts for 37% of yield loss followed by insect pests (29%), disease (22%), and other pests (12%) (Mishra *et al.* 2021). Weeds are unwanted plants that grow simultaneously with crops and offer severe competition for below-ground resources like nutrients and water, and above-ground resources like space and gases (Rao *et al.* 2014; Choudhary and Dixit 2021). Weeds are considered to be unwanted plants for various reasons, they grow profusely and

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Table 1. Area, production, and productivity of oilseed crops in India [https://www.sopa.org/ (2019-20)]

Crop	Area (m ha)	Production (mt)	Productivity (kg/ha)
Rainy season			
Soybean	12.19	11.22	920
Groundnut	4.83	9.95	2062
Sesame	1.62	0.66	407
Castor seed	1.05	1.84	1752
Niger seed	0.14	0.04	301
Winter season			
Rapeseed & mustard	6.86	9.12	1329
Sunflower	0.23	0.21	921
Linseed	0.18	0.12	667
Safflower	0.05	0.04	808
	27.14	33.20	

reproduce aggressively. They need to be controlled effectively and on time in order to prevent loss or diminished crop yields. The major weeds of oilseed crops are detailed in **Table 2**. Weeds have the capabilities to adapt and grow even in adverse conditions and occupies areas that are not occupied by crop cultures. Many of the weeds have better below-ground parameters (longer, deeper, and heavier roots) allowing them to excerpt water and nutrients from deeper soil profiles (Choudhary *et al.* 2021). The yield loss caused by weeds under moisture stress conditions varies, in dryland, it ranges from 10-98% and sometimes complete crop failure (Ramamoorthy *et al.* 2004). In India, yield loss due to weeds varies with the cropping season, the highest in summer (36.5%) followed by the rainy season (31.5%) and the lowest in winter (22.7%) in some cases can cause complete devastation of the crop. Under adverse situations, weed problems are further aggravated and severe. Under this situation, weeds uptake more moisture and nutrients from the soil profile and are meagerly available to the crop plants resulting in lean and thin, and weak growth and can cause crop yield loss by 37-79% (Singh *et al.* 2016).

Importance of weed management in oilseed crops

The majority of oilseed crops are slow growing during their initial stage of development. This invites the weeds to emerge and establish, and compete for available resources. This ultimately reduces the crop yield and deteriorates the quality of the final product. An estimation was made using available literature that among ten major crop cultivation technologies sowing window contributes 23.0% to crop yield followed by weed management 17.2% and improved varieties (15.9%) and the rest technologies are in single digit (**Table 3**).

Table 2. Commonly infested annual weeds of oilseed crops in India

Weeds	Grasses	Broad-leaved	Sedges
Rainy season			
Dinebra retroflexa	√		
Digitaria sanguinalis	√		
Cynodon dactylon	√		
Panicum repens	√		
Echinochloa colona	√		
Setaria viridis	√		
Cenchrus biflorus	√		
Xanthium strumarium		√	
Euphorbia geniculata		√	
Amaranthus viridis		√	
Portulaca oleracea		√	
Conyza aegyptiaca		√	
Tribulus terristris		√	
Corchrus rarvensis		√	
Trianthema monogyna		√	
Cyperus rotundus			√
Cyperus iria			√
Winter weeds			
Avena fatua	√		
Cynodon dactylon	√		
Chenopodium album		√	
Chenopodium murale		√	
Argemone maxicana		√	
Anagallis arvensis		√	
Asphodelus tenuifolius		√	
Boerhavia spp.		√	
Brassica kaber		√	
Brassica sinensis		√	
Chrozophera perviflora		√	
Cirsium arvensis		√	
Euphorbia geniculata		√	
Euphorbia hirta		√	
Fumaria parviflora		√	
Lathyrus aphaca		√	
Medicago denticulata		√	
Melilotus alba		√	
Melilotus indica		√	
Melotropicum indicum		√	
Parthenium hysterophorus		√	
Physalis minima		√	
Solanum nigrum		√	
Spergula arvensis		√	
Vicia hirsuta		√	
Cyperus spp.			√

Crop weed competition and yield loss

Crop weed competition is a negative aspect where individuals compete for the resources available at the site, while both suffer and one suffers less which has better adaptability *i.e.* weeds. The competition between crops and weeds is presented in a line diagram (**Figure 1**) which is responsible for considerable yield loss in agriculture ecosystems (**Table 4**), and this varies based on the species, their

Table 3. Technology's contribution to crop yield

Technology	% Contribution
Land preparation	7.0
Organic manure	4.7
Improved varieties	15.9
Optimum seed rate	7.9
Time of sowing	23.0
Line sowing	9.6
Crop geometry	3.0
Fertilizers	8.3
Weed management	17.2
Plant protection	3.4

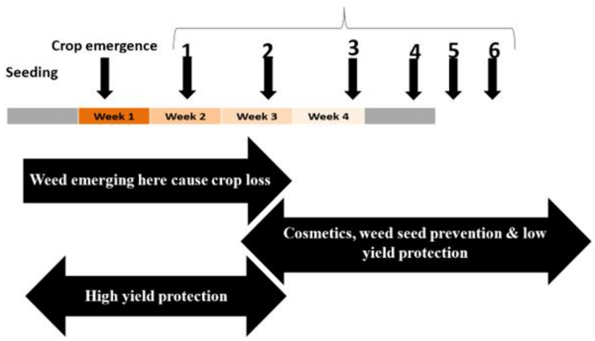

Figure 1. Critical period of crop weed competition

densities, duration of weed competition, and soil and climatic factors prevailing at the site. Initial one-third part of the life of the crop is critical where the maximum competition took place and suffers maximum and attain irreversible losses. However, weeds emerging after the critical weed-free period will less effect on yield, but management efforts after the critical weed-free period may make harvest more efficient, reduce weed seed bank and reduce weed problems in subsequent years. The reduction in the economic yield of oilseed crops due to crop weed competition is presented below (**Table 4**).

Nutrient mining by weeds in oilseed crops

Nutrients are important resources required to complete the life of a crop. Excessive growth of weeds offers competition for nutrients. The majority of the weeds compete aggressively for soil N and K. Weed accumulates more nutrients from the soil profile and thus has higher nutrient content than the crop plants (Reddy *et al.* 2018). Weeds and the majority of oilseed crop have extensive root system they can uptake water and nutrients from deeper layer and complete life, still, they pose a serious threat to crops (Berger *et al.* 2008). Most of the oilseeds are grown under limited moisture, and under the condition, limits the nutrient uptake by plants even though they are available in plenty. However, plant expenses more energy to develop and proliferate the root system for better extraction of water and nutrients from the deeper soil profile. The nutrients mining by weeds is detailed in **Table 5**.

Water extraction by weeds in oilseed crops

Under limited water availability, soil moisture is a limiting factor, presence of weeds offers more competition to the crops. Normally, weed plants take three times higher water than crop plants to accumulate a unit quantity of biomass Mishra and Choudhary (2022). The transpiration coefficient of weeds is far more than that of crop plants thus offering more stress to the crop plants (**Table 6**). The majority of weeds have a deep root system and they can uptake water from a deeper soil profile (Maganti

Table 4. Critical period of crop weed competition and yield loss due weeds in oilseed crops days after sowing (DAS)

Crop	Critical period	Reference	Yield loss (%)	Reference
Sesame	15-45 DAS	Duary and Hazra (2013)	15-40	Mishra (1997)
Groundnut	21-56 DAS	Everman *et al.* (2008)	15-75	Priya *et al.* (2013)
Sunflower	30-45 DAS	Reddy *et al.* (2008)	54.6	Wanjari *et al.* (2001)
Castor	30-60 DAS	Mishra (1997)	30-35	Mishra (1997)
Safflower	15-45 DAS	Mishra (1997)	35-60	Mishra (1997)
Rapeseed & mustard	15-40 DAS	Sekhawat *et al.* (2012)	10-58	Banga and Yadav (2001)
Linseed	20-45 DAS	Mishra (1997)	30-40	Mishra (1997)
Soybean	30-45 DAS	Chhokar and Balyan (1999)	74	Chhokar and Balyan (1999)

Table 5. Nutrient mining by weeds in different oilseed crops

Crop	Nutrient removal (kg/ha)			Reference
	N	P_2O_5	K_2O	
Sesame	45	6.9	36	Bhadauria *et al.* (2012)
Groundnut	15-39	5-9	21-24	Harikesh *et al.* (2021)
Sunflower	42	15.5	45.4	Sumathi *et al.* (2009)
Castor	45-60	3-9	35-88	Kalaichelvi and Kumar (2016); Nayak *et al.* (2016)
Safflower	15-28	2-5	15-45	Tewari *et al.* (2008)
Rapeseed & mustard	20-22	2-3	10-12	Mukherjee (2014); Kalita *et al.* (2017)
Linseed	30-32	2-3	11-13	Dwiwedi and Puhup (2019)
Soybean	26-65	3-11	43-102	Sharma *et al.* (2016)

Table 6. Transpiration coefficient and water use efficiency (WUE) values for various weeds (Norris 1996; Mishra and Choudhary 2022)

Weed species	C_3 or C_4	Transpiration coefficient	WUE
Xanthium strumarium	C_3	415	3.41
Bromus intermis	C_3	977	1.02
Chenopodium album	C_3	658	1.52
Polygonum aviculare	C_3	678	1.47
Panicum capillare	C_4	254	3.94
Portulaca oleracea	C_4	281	3.56
Amaranthus retroflexus	C_4	305	3.28
Salsola tragus	C_4	314	3.18

et al. 2005). However, water loss from soil profile also depends on the types of weeds, their densities, root structures, weed physiology, and weed competition period (Shoup and Holman 2010). Thus, the adoption of suitable weed management is a prerequisite in adverse climatic situations to get optimum crop yields.

Strategies for weed management in oilseed crops

It is important to understand the biology and ecology of the weeds and the time period of crop weed competition for successful weed management in oilseed crops. There are many factors like local situations, environmental conditions, labour availability, weed pressure, and nature of the crop, those need to be taken into consideration while planning weed management strategies. However, weed management is an approach in which weed prevention and weed control have companion roles. Weed management is the combination of the techniques of prevention, eradication, and control to manage weed in a cropping system or environment.

There are many methods by which weed severity can be minimized, that are **Table 7.**

The selection of weed management practices largely depends on the availability of resources, costing of methods, and environmental conditions. Chemical methods of weed control are very effective in certain cases and have great scope provided the herbicides are cheap, efficient, and easily available.

Chemical method of weed management

The selectivity exhibited by certain chemicals to cultivated crops in controlling their associated weeds without affecting the crops forms basis for the chemical weed control. Such selectivity may be due to differences in morphology, differential absorption, differential translocation, differential deactivation, *etc*. Herbicides offer great scope for minimizing the cost of weed control irrespective of the situation and offer a good weed control alternative to cultural or mechanical methods in oilseed crops. However, herbicide-based weed management is relatively poorly developed in the majority of oilseed crops (except soybean and groundnut). Use of herbicides provides broad-spectrum weed control with higher selectivity. Use of pre-emergence (PE) herbicide assumes greater importance given their effectiveness from the initial stages of crop growth and later emergence can be tackled by applying selective post-emergence (PoE) herbicides (Choudhary *et al.* 2021; Choudhary and Dixit 2021). The pre-requisite for a chemical method of weed management is scouting the field and based on weeds herbicides need to be chosen. Likewise, the following 5Rs (right source, right herbicide, right dose, right time, and right application method) are also equally important to get the best control. The list of herbicides commonly used for weed control in oilseed crops is listed in **Table 8**.

Table 7. (A): Preventive measures and (B): curative measures (eradication and control measures) (Choudhary 2022)

Weed control methods				
(a) Preventive	(b) Curative			
	Control			
	Mechanical	Cultural	Biological	Chemical
• Sowing of weed-free seeds. • Use of clean implements. • Removal of weeds along the canal and irrigation channel. • Care in transplanting seedlings/plantlets. • Use of well-rotten manure. • Avoiding passing of cattle. from weed-infested areas. • Crop management practices. • Enforcement of Weed Laws. • Quarantine methods and use of pre-emergence herbicides.	-Tillage -Hoeing -Hand weeding -Digging -Mowing -Burning -Mulching -Soil solarization	-Selection of crops and varieties -Stale seedbed -Sowing window -Planting geometry -Crop rotation -Use of compost or manure -Cover or smother crop -Water management, -Intercropping -Nutrient management -Orientation of sowing/transplanting	-Plants-parasites -Predators and - Pathogens	Detailed below

While using herbicide one has to be very careful, as residues from the application of herbicides to previous crops can cause a problem in oilseed crops *e.g.*, atrazine applied to a previous maize crop can reduce soybean stand and yield. Likewise, imazethapyr applied during rainy season crops may reduce the plant stand of mustard and seed yield. Some herbicides are effective in the temperate region but their efficacy is comparatively less in the tropical and sub-tropical regions and sometimes may be toxic also such as metribuzin and bentazone. Therefore, herbicides must be tested under different agro-

Table 8. List of herbicides for use in oilseed crops

Crop	Herbicide	Dose (kg/ha)	Time of application	Reference
Soybean	Metribuzin	0.50	PE	Malik *et al.* (2005); Rathore *et al.* (2006); Panda *et al.* (2015); Choudhary and Kumar (2016); Patel *et al.* (2016); Saharan *et al.* (2016); Sharma *et al.* (2016); Parmar *et al.* (2016); Thirumalaikumar *et al.* (2017); Choudhary and Choudhury (2018); Virk *et al.* (2018); Andhale and Kathmale (2019); Jadhav and Kashid (2019); Patel *et al.* (2021); Meena *et al.* (2022); Binjha *et al.* (2022)
	Pendimethalin + imazethapyr	1.00	PE	
	Diclosulam	0.022-0.026	PE	
	Metolachlor	1.00	PE	
	Sulfentrazone	0.72	PE	
	Sulfentrazone + clomazone	0.35+0.375	PE	
	Na-acifluorfen + clodinafop	0.245	PoE	
	Imazethapyr	0.10	PoE	
	Propaquizafop + imazethapyr	0.125	PoE	
	Imazethapyr + imazamox	0.070	PoE	
	Haloxyfop-methyl	0.108-0.135	PoE	
	Fomesafen + quizalofop	0.180+0.045	PoE	
	Quizalofop + chlorimuron	0.0375+0.009	PoE	
	Fluthiacet-methyl	0.0136	PoE	
	Chlorimuron + fenoxaprop	0.009 + 0.08	PoE	
	Fomesafen + fluazifop	0.22-0.25	PoE	
	Bentazone	0.96	PoE	
Groundnut	Pendimethalin	0.678	PE	Malunjkar *et al.* (2012); Choudhary *et al.* (2016); Shweta *et al.* (2016); Poonia *et al.* (2016); Dixit *et al.* (2016); Singh *et al.* (2017); Kumar et al (2019); Kumar *et al.* (2020); Patel *et al.* (2020); Mudalagiriyappa *et al.* (2021); Regar *et al.* (2021); Sridhar *et al.* (2021); Charitha *et al.* (2022); Lakshmidevi *et al.* (2022)
	Diclosulam	0.022-0.026	PE	
	Imazethapyr	0.10-0.15	E PoE	
	Fenoxaprop	0.079	PoE	
	Fluazifop-p-butyl	0.125-0.25	PoE	
	Fomesafen + fluazifop	0.22-0.25	PoE	
	Imazethapyr + imazamox	0.07	PoE	
	Propaquizafop + imazethapyr	0.125	PoE	
	Imazethapyr + chlorimuron	0.10+0.024	PoE	
	Quizalofop + imazethapyr	0.0328+0.0626	PoE	
Rapeseed and mustard	Pendimethalin	0.678	PE	Mukherjee (2014); Kumar *et al.* (2012); Banga *et al.* (2004); Bazaya *et al.* (2004); Yadav and poonia (2005); Sarkar *et al.* (2005); Choudhary *et al.* (2016); Choudhary and Bhagawati (2019); Singh *et al.* (2020); Chisi *et al.* (2021); Yernaidu *et al.* (2022) Mishra *et al.* (2021); Mishra and Choudhary (2022); Choudhary and Meena (2022)
	Oxyfluorfen	0.15-0.25	PE	
	Oxadiargyl	0.09	PE	
	Napropamide	1.125-1.406	PE	
	Isoproturon	1.00	PE or PoE	
	Quizalofop	0.04-0.05	PoE	
Sesame / niger	Butachlor	1.00-1.50	PE	Moorthy *et al.* (2004); Mathukia *et al.* (2015); Babu *et al.* (2016); Gupta and Kushwah (2016); Singh *et al.* (2018); Sahu *et al.* (2019); Mishra *et al.* (2021); Mishra and Choudhary (2022); Joshi *et al.* (2022)
	Oxadiazon	0.50-1.00	PE	
	Pendimethalin (30 and 38.7%)	0.50-0.75 & 0.678	PE	
	Isoproturon	1.00-1.50	PoE	
	Propaquizafop	0.10	PoE	
	Fluazifop	0.25	PoE	
Linseed	Pendimethalin	0.75-1.00	PPI and PE	Devendra *et al.* (2016); Dwivedi and Puhup (2019); Mishra *et al.* (2021); Mishra and Choudhary (2022)
	Butachlor	1.00-1.50	PE	
	Oxadiazon	0.50-1.00	PE	
	Propaquizafop	0.10	PoE	
	Isoproturon	1.00-1.50	PoE	
Sunflower	Pendimethalin	0.75-1.00	PPI and PE	Reddy *et al.* (2008); Sumathi *et al.* (2010); Nagmani *et al.* (2011); Baskaran and Kavimani (2014); Mohapatra *et al.* (2020); Mishra *et al.* (2021); Mishra and Choudhary (2022)
	Oxadiargyl	0.10	PE	
	Quizalofop	0.04-0.05	PoE	
Safflower	Pendimethalin (30% EC)	0.75-1.00	PPI and PE	Tewari *et al.* (2008); Mishra *et al.* (2021); Mishra and Choudhary (2022)
	Pyroxasulfone	0.1175	PE	
	Sulfentrazone	0.105	PE	
Castor	Metolachlor	1.0-1.5	PE	Kalaichelvi and Kumar (2016); Naik *et al.* (2016); Mishra *et al.* (2021); Mishra and Choudhary (2022)
	Pendimethalin	1.5-2.0	PE	
	Quizalofop-ethyl	0.05	PoE	
	Fenoxaprop-p-ethyl	0.05	PoE	

PPI- Pre-plant incorporation; PE- Pre-emergence; PoE- Post-emergence. The above herbicides should be integrated with hand weeding to remove the weeds that escaped/emerged after the application of herbicides climatic conditions and doses may be standardized as per crops and weeds.

Management of broomrape in Indian mustard and dodder in niger

Broomrape is a major weed of mustard. Seed coating of mustard seeds with 1.0 ppm of chlorsulfuron or triasulfuron provides 70-98% control of *Orobanche aegyptiaca* but the efficacy of seed treatment with sulfosulfuron was poor. Post-emergence application of glyphosate at 25 and 50 g/ha with 1% solution of $(NH_4)_2SO_4$ at 25 and 55 DAS showed promise with 63-100% control of this weed in large scale at farmers' fields (Poonia 2015; Singh *et al.* 2020). Glyphosate dose range is very limited. Over dosing of glyphosate, may leads to 15-35% toxicity to mustard in terms of marginal leaf chlorosis, slow leaf growth and bending of apical stems and stunting with a yield penalty. Bleaching of a few leaves of mustard may occurred with a 50 g/ha dose at 55 DAS, which can recovered within 20 days resulting in no loss in yield. Apart from these, based on irrigation availability crop rotation with wheat, barley and chickpea, delayed sowing (25 October -10 November) with higher seed rate, use of organic manures with increase N fertilizers and hand removal are also found effective in managing broomrape in mustard (Rao and Chauhan 2015). Dodder is an annual obligate stem parasite belonging to Cuscutaceae. Cuscuta is a major limitation for cultivation of niger [*Guizotia abyssinica* (L.f.) Cass.] in India. Application of pendimethalin 1.0 kg /ha as PE followed by hand removals were found to be effective in management of dodder.

Weed response to herbicides

Weed control percentages are intended as a guide for comparing alternatives. Percentages are estimated based on favourable conditions. The herbicides can be chosen based on efficacy of the herbicide. Some of the herbicides, their controlling ability, and choice patterns are given below in **Table 9**.

Biological method of weed management

Using living organisms such as competitive plants, insects, pathogens, and other animals for weed control is considered under the biological method. There are two popular methods (classical approach and the augmentative or bioherbicide approach) employed in the biological control of weeds. These methods are sustainable and risk-free. However, it takes a longer time to get optimum results and largely depends on population build-up and density. Parthenium emerging in oilseed crops can be controlled by the release of Mexican beetle (*Zygogramma bicolorata*) (Kumar 2009). Kaur *et al.* (2014) reported the rust fungi, *Puccinia abrupta* var. partheniicola and *Puccinia xanthii* var. parthenii-hysterophorae, can be used to control Parthenium. Likewise, *Bactra verutana* was another insect bioagent used against *Cyperus rotundus*.

Biotechnological method of weed management

Herbicide-resistant crops can be used in weed management as biotechnological approach. Use of herbicides with a similar mode of action for an extended period can develop resistance in many weeds. ICAR-DWR (2017-18) has already reported that *Commelina communis* and *Echinochloa colona* are not being controlled by imazethapyr (an ALS-inhibiting herbicide) in soybean fields of Madhya Pradesh. Similarly, many more complaints have been received from farmer's fields that imazethapyr is unable to control certain weeds of greengram and blackgram crops, which were killed earlier. Several biotechnological techniques have been adopted for developing herbicide-resistance in crop plants. Plant transformation by transfer of cloned genes in susceptible plants through an engineered vector technique is a common method (Chacko *et al.* 2021).

Integrated weed management in oilseed crops

Dependence on herbicides alone for weed management is not encouraged due to the problems in the environment and resistance development in weeds. Therefore, a system that combines two or

Table 9. Response of herbicide on % weed control

Grade	% control	Extent of control	Choice of herbicide
E= Excellent	90-95%	Usually over 90% seldom 100%	Best choice for weed
G=Good	80-90%	Sometimes under 80% seldom over 90%	Usually satisfactory
F=Fair	65-80%	Sometimes under 65% seldom over 80%	Sometimes unsatisfactory Moderate infestation
M=Marginal	40-65%	Seldom over 65% and Erratic	Seldom satisfactory Light infestation only
P=Poor	-	Usually under 40 or no control	Not recommended

more weed control measures and other good crop husbandry practices should be practiced to increase effectiveness and efficiency Chakraborthy (2020). opined that integrated weed management is a cost-effective, sound, reliable practice that can be easily and effectively adopted by a farmer as a part of any sound management practice (Rao and Nagamani 2010; Chakraborthy 2020). Buhler (1992) revealed that combining rotary hoeing followed by cultivation with herbicide gives better weed control and higher soybean yield over non-combined herbicides. Application of PE provides broad-spectrum weed control of initial flush, but later some weeds get emerged and offer severe competition with crops for resources, thus they need to be managed by adopting other management practices suitable for the crop. Care must be taken that weeds do not need to go to seed, that harvesting equipment is not transporting weed seeds, and that clean seed is used for all crops in the rotation; is an integral part of a weed program.

Based on the research carried out in India, some of the important integrated weed management practices have been compiled that provides excellent weed control, higher crop yield, more returns, and no injury to the crop. However, herbicides must be selected based on the existing weed flora, as some of the herbicides are good on some weeds but not effective against some other weeds.

Soybean and groundnut

Application of pendimethalin 0.678 kg/ha or imazethapyr + pendimethalin 1.00 kg/ha or diclosulam 0.02 kg/ha or oxyfluorfen 0.18 kg/ha (PE) followed by premix of imazethapyr + imazamox 0.07 kg/ha or fluazifop-p-butyl + fomesafen 0.25 kg/ha or propaquizafop + imazethapyr 0.125 kg/ha or sodium-acifluorfen + clodinafop-propargyl 0.245 kg/ha or haloxyfop-p-ethyl 0.135 kg/ha (PoE) along with need-based hand weeding provides broad-spectrum weed control, higher seed yield and net returns in soybean and groundnut.

Sesame and niger

Application of pendimethalin at 0.75 kg/ha or oxadiazon 0.50 kg/ha (PE) followed by propaquizafop 0.10 kg/ha or fluazifop 0.25 kg/ha (PoE) and need-based hand weeding was effective for weed management in sesame and niger.

Sunflower

Application of pendimethalin at 1.0 kg/ha or oxadiargyl 0.125 kg/ha (PE) followed by propaquizafop 0.062 kg/ha at 15-20 DAS (PoE) and need-based hand weeding was effective for weed management in sunflower.

Linseed

In irrigated linseed crops, sequential application of pendimethalin 1.0 kg/ha (PE) followed by metsulfuron-methyl 0.004 kg/ha (PoE) or clodinafop + metsulfuron-methyl at 0.06 + 0.004 kg/ha at 2-3 leaf stage of weed and need-based hand weeding for higher weed control efficiency, linseed yield and economic returns.

Mustard

Application of pendimethalin 1.0 kg/ha or oxadiargyl 0.09 kg/ha (PE) followed by quizalofop 0.05 kg/ha at 15-20 DAS (early PoE) or fluazifop-p-butyl 0.125 kg/ha at 25-30 DAS (PoE) provided broad-spectrum weed control, increased mustard seed yield and higher net returns.

Castor

Application of pendimethalin 1.0 kg/ha or metolachlor 0.5-1.0 kg/ha (PE) followed by hand weeding provided broad-spectrum weed control, increased castor seed yield and higher net returns.

Conclusion

Weed interference causes substantial yield reduction in oilseed crops. Although, severity largely depends on the density of weeds, duration of the competition, types of weed flora, *etc*. Thus, it is important to keep the weed density below the threshold level to minimize yield loss. Similarly, to avert economic loss, weed control should be followed to minimize weed density during the first four weeks of growth period. Relying on a single method may lead to various problems such as shift in weed flora, development of herbicide-resistance, emergence of perennial weeds, establishment of tough-to-kill weeds, *etc*. Under the circumstances, the adoption of integrated weed management considering 'little hammers' such as cultural, mechanical, chemical, biological and biotechnological interventions judiciously without any adverse effect on the environment together effectively managing the weeds that do not pose serious yield penalty. Integrated weed management should also minimize weed seed recruitment and deplete the weed seed bank. Accordingly, integrated weed management can be considered to be effective, efficient, and sustainable for oilseed crops.

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REVIEW ARTICLE

Herbal herbicide: A low-cost and eco-friendly tool for weed management in smallholder farming

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ABSTRACT

Weeds have been recognized as a major biotic constraint towards achieving higher crop productivity as well as quality. With the current crop protection measures, weeds cause nearly one-third of the crop losses among all the crop pests. The effective approach to combat the weed menace is the need-based use of herbicides. Because of widespread growing concern over the environmental aspects of commonly used herbicides as well as their untimely availability, development of weed resistance, *etc*., the need for the use of conveniently available and biodegradable herbicides is very much imperative. Researchers currently search for novel alternatives to the synthetic herbicides, which would be biodegradable and environment-friendly. Common plants and their metabolites become a source of compounds that can be utilized directly as natural herbicides or as lead structures for the herbicide discovery. These herbal herbicides in judicious combination with other weed management methods would be a potential tool to combat weed menace, especially by the smallholder farmers in rural areas in general, and organic or natural farming in particular.

Keywords: Crop losses, Herbal herbicide, Integrated weed management, Organic farming, Smallholder farmer, Weeds

INTRODUCTION

Weeds have been one of the major impediments to crop production since the dawn of human civilization. A significant quantum of crop harvest is lost each year due to inadequate, ineffective and untimely weed management. Huge losses in crop yields as well as crop quality take place due to weeds, which have an impact on food security and safety. The extent of crop yield losses varies due to weeds, depending on the crop and related agro-ecological conditions. In India, the average annual yield losses due to various crop pests are projected to be approximately ₹ 600 billion (Singh 2005), with weeds alone responsible for the greatest losses. However, weed damage to crops receives less attention than the damage from other pests. Weeds have a direct impact on crop productivity and quality, and they also substantially reduce the input use efficiency. The uncontrolled weeds utilize most of the expensive inputs like fertilizers and irrigation water that would otherwise be used to maximize the potential yield (Yaduraju and Mishra 2004 and 2005). Gharde *et al*. (2018) estimated total actual economic loss of about USD 11 billion due to weeds alone in 10 major crops of India *viz*. groundnut (35.8%), soybean (31.4%), greengram (30.8%), pearlmillet (27.6%), maize (25.3%), sorghum (25.1%), sesame (23.7%), mustard (21.4%), direct-seeded rice (21.4%), wheat (18.6%) and transplanted rice (13.8%) using the data from 1581 on-farm research trials conducted by ICAR - All India Coordinated Research Project on Weed Management between 2003 and 2014 in major field crops in different districts of 18 states of India. They found that potential yield losses were high in case of soybean (50–76%) and groundnut (45–71%). Greater variability in potential yield losses were observed among the different locations (states of India) in case of direct-seeded rice (15–66%) and maize (18–65%).

A clear understanding and knowledge regarding weeds and their management can be helpful in addressing certain challenges related to food security and safety. In India, various weed control methods are in use, based on the socio-economic conditions of farmers. Manual weeding is still the most common way to manage weeds in the country although it is tiresome, time-consuming, ineffective, and

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practically uneconomical. There is also a declining trend on the use of draught animals for land preparation and intercultural operations. Wage rates have been increasing dramatically over the last two decades. The reduced labour availability at the peak time of agricultural operations compels the farmers to look for alternative weed management options as the farmers frequently fail to address the weed problems with their current weed management techniques. Significant crop losses occur due to either delayed weeding or omitted weeding. As a result, there is a greater need for low-cost, time-saving, and effective weed management solutions under various agro-ecological situations (Duary and Mukherjee 2013). To deal with the weed problems, the intense use of herbicides is being preferred by farmers during recent years. But exclusive reliance on the use of synthetic herbicides has resulted in emerging environmental concerns, including herbicide residue in soil, water and plants (especially fruits and vegetables); toxicity to animals and humans; shift in weed flora; and evolution of resistant weeds (Mukhopadhyay 1992 and 1993, Gautam and Mishra 1995, Duary 2010).

Innovations and interventions are imperative for effective weed management so as to eliminate or avert the environmental risks and health concerns. Since the herbicides have the relatively higher potential to cause unfavourable environmental contaminants, there is a growing need for using the environmentally safer herbicides which would be either equally or even more effective and selective than the currently available synthetic herbicides. Researchers have been searching for novel, bio-degradable and environment-friendly alternatives to the synthetic herbicides. In this context, herbal herbicides can play a greater role. There has been an increasing interest in the use of allelopathic plants for weed management at the national and international levels. The compounds released by these allelopathic plants (allelopathic chemicals/allelochemicals) can either be directly utilized for weed management or alternatively their chemical contents be utilized for developing new herbicides with novel chemistries. As an essential prerequisite of the sustainable agricultural practices, the inputs currently provided by non-renewable chemical resources should be replaced by the biologically based renewable and naturally available products. To make the weed management solutions more sustainable and eco-friendlier, there is a need to judiciously switch from using chemical herbicides to that of the herbal herbicides or phytochemicals with herbicidal properties.

CONCEPT OF HERBAL HERBICIDE

There exist many plant species in and around our surroundings. Some of these have allelopathic potentials. There is a range of plants that herbivores do not graze, browse, nibble or relish in other ways, and these plants are also not afflicted with insects and pathogens. These plants include those with the aromatic, cosmetic, antibiotic, empirical remedial, medicinal, preservative, repellent, and other properties. These plants, in whole or in part, have herbicidal and other properties. These plants exude attractants (water/alcohol soluble products) or release some active chemicals into the environment through exudation, leaching or decomposition (Kumar and Varshney 2009), which inhibit the germination and growth of nearly all types of annual weeds both in transplanted and direct-sown crops in both aerobic and anaerobic soils. The bioactive compounds or phytochemicals or plant extracts with herbicidal properties are called herbal herbicides, also known as phytoherbicides (Bhowmick *et al.* 2016). Moreover, the herbal herbicides will act as natural herbicides for combating the weed problems in organic and sustainable agricultural systems. **Table 1** lists some examples of such plants although it is not the exhaustive one.

TYPES OF HERBAL HERBICIDES

Herbal herbicides from plant extracts

Plant extracts are excellent candidates to replace synthetic compounds that render toxic and carcinogenic effects. Hence, plants extracts can be used in various ways, including food industries (Balasubramaniam *et al.* 2022; Ramakrishnan *et al.* 2022), human health benefits and medicines (Abubakar and Haque 2020; Proestos 2020), antimicrobial purposes (Alzoreky and Nakahara 2003; Gonelimali *et al.* 2018; Palombo 2011), and also as herbal herbicides (Hasan *et al.* 2021). Aqueous plant extracts of several plant species have shown good potency against many weed species as herbal herbicides (Carrubba *et al.* 2020, Caser *et al.* 2020, Elisante *et al.* 2013, Hasan *et al.* 2021, Perveen *et al.* 2019, Wang *et al.* 2019). Such water-based extracts are considered easy to prepare and less damaging to the environment as compared to the chemical herbicides.

Herbal herbicides from plant allelochemicals

Plants often produce a class of semiochemicals called allelochemicals or phytotoxins which inhibit the growth of nearby plants while allelopathy refers to the

Table 1. Common plant sources having herbicidal properties

Scientific name	Common name	Family	Salient features	References
Ailanthus altissima	Tree of heaven	Simaroubaceae	Deciduous tree	Kozuharova *et al.* (2022)
Acacia auriculiformis	Sonajhuri	Fabaceae	Evergreen tree	Bhowmick *et al.* (2016)
Adhatoda vasica	Vasaka	Acanthaceae	Small evergreen, sub-herbaceous bush	De and De (2000)
Ailanthus altissima	Tree of heaven	Simaroubaceae	Deciduous tree	Heisey (1997)
Andrographis paniculata	Kalmagha	Acanthaceae	Annual herbaceous plant	Nagaraja and Deshmukh (2009)
Annona squamosa	Ata	Annonaceae	**S**mall, well-branched tree or shrub	De and De (2000)
Antigonon leptopus	Sandwich island climber / Anantalata	Polygonaceae	Flowering plant	De and De (2000); Mandal and De (2005)
Azadirachta indica	Neem	Meliaceae	Tree	De and De (2000)
Centaurea diffusa	Diffuse knapweed	Asteraceae	Herbaceous, perennial weed	Quintana *et al.* (2009)
Calotropis gigantean	Akand	Apocynaceae	Large shrub or small tree	De and De (2000); Bhowmick *et al.* (2014), Bhowmick *et al.* (2016)
Chromolaena odorata	Bitter bush	Compositae	Weed	Nornasuha and Ismail (2013)
Cymbopogon nardus	Citronella grass	Cardiopteridaceae	Herb	Somala *et al.* (2022)
Cymbopogon citratus	Lemon grass	Poaceae	Fast growing, perennial aromatic grass	De and De (2000)
Drimys winterii	Winter's bark or canelo	Winteraceae	Slender tree	Verdeguer *et al.* (2011)
Eucalyptus sp.	Eucalyptus	Myrtaceae	Large tree	Bhowmick *et al.* (2016)
Holarrhena antidysenterica	Kurchi	Apocynaceae	Medicinal herb	De and De (2000); Mandal and De (2005)
Ipomoea batatus	Sweet potato	Convolvulaceae	Dicotyledonous plant	De and De (2000)
I. carnea	Ban kalmi	Convolvulaceae	Vine	De and De (2000)
Lantana camara	Lantana	Verbinaceae	Perennial herb	Darana (2013)
Leucas aspera	Set drone	Lamiaceae	Annual herb	Islam and Kato-Noguchi (2013)
Mikania micrantha	Bitter vine	Asteraceae	Perennial herbaceous vine	Nornasuha and Ismail (2013)
Nigella sativa	Black caraway	Ranunculaceae	Annual herb	Zribi *et al.* (2018)
Peumus boldus	Chilean plant	Monimiaceae	Evergreen tree	Verdeguer *et al.* (2011)
Senna (*Cassia*) *tora*	Sickle pod	Caesalpinaceae	Annual leguminous weed	Dolai *et al.* (2015); Bhowmick *et al.* (2016)
Tabarnaemontana coronaria	Siulicop	Apocynaceae	Medicinal plant	Mandal and De (2005)
Tagetes erecta	Mexican marigold	Asteraceae	Annual plant	Dolai *et al.* (2015); Wichittrakarn *et al.* (2013)
T. patula	French marigold	Asteraceae	Annual plant	Ramachandra Prasad *et al.* (2010)
Vitex negundo	Nisinda	Lamiaceae	Large aromatic shrub	De and De (2000)

direct or indirect chemical effect of one plant on the germination, growth or development of neighboring plants (Cheng and Cheng 2015). Some of the important chemically diverse plant allelochemicals include alkaloids, phenols, terpenoids, glucosinolates, isothiocyanates, steroids, proteins, purine-based compounds, macrocyclic polyethers, *etc*. (**Table 2**). There are several crop varieties like rice, wheat, sorghum which have the ability to suppress weed by allelopathy (Jabran 2017; Masum *et al*. 2018; Shamsur *et al*. 2019). The phenomenon of allelopathy can be practically utilized for weed control in the form of crop rotations, intercropping, allelopathic mulches, and a spray of allelopathic plant water extracts. Sorghum (*Sorghum bicolor*) and sunflower (*Helianthus annuus*) are well known allelopathic crops, which contain a number of allelochemicals that are toxic to weeds (Bajwa *et al*. 2015; Cheng and Cheng 2015; Jabran *et al*. 2015; Shamsur *et al*. 2019; Sathishkumar *et al.* 2020).

The majority of past allelopathic research has focused on the detrimental effects of living plants or their residues on plant growth. Recent research on identifying novel secondary products isolated from plants, as phytochemicals with allelopathic potential (Cragg and Newman 2013; Ndam *et al*. 2014), offer promising scope for the biological control of weeds as well. The synthetic herbicide 'mesotrione' (callisto®), is derived from leptospermone, a compound isolated from the bottle brush plant (*Callistemon citrinus*) (Araniti *et al*. 2015). The ability to develop more herbicides from allelopathic compounds is limited by several factors. Allelopathic

Table 2. Allelochemicals for inhibiting weed seed germination and weed seedling growth

Allelochemicals	Allelopathic plants	Target weeds	References
Ailanthone	Tree-of-heaven (*Ailanthus altissima*)	*Lepidium sativum, Raphanus sativus, S. officinalis, S. rosmarinus*	Caser *et al.* (2020)
Alkaloids	Jimson weed (*Datura stramonium*)	*Cenchrus ciliaris, Notonia wightii*	Lovett and Potts (1987)
Artemisinin	Sweet wormwood (*Artemisia annua*)	*A. retroflexus, I. lacunose, P. oleracea, A. annua, Lemna minor, Pseudokirchneriella subcapitata*	EI Bazaoui *et al.* (2011)
Catechin	Spotted knapweed (*Centaurea stoebe*)	*Arabidopsis thaliana, Festuca idahoensis*	Bais and Kaushik (2010)
1, 8- cineole	Purple sage (*Salvia leucophylla*), Eucalyptus (*Eucalyptus* sp.)	*E. crus-galli, Cassia occidentals, Lolium rigidum*	Topal *et al.* (2007); Subramanyam *et al.* (2013)
Glucosinolates*, Isothiocyanates**	Brassicaceous plants (*Brassica* sp.)*, Radish (*Raphanus sativus*)**	*S. aspera, M. inodora, A. hybridus, E. crus-galli, A. myosuroides, C. bursapastoris, C. arvensis, Cuscuta* spp., *D. carota, H. incana, S. polyceratium*	Soltys *et al.* (2013)
Juglone	Black Walnut (*Juglans nigra*)	*S. arvensis, C. arvense, Papaver rhoeas, Lamium amplexicaule, Triticum vulgare, Hordeum vulgare*	Julien and Griffiths (1998)
Leptospermone	Lemon bottlebrush (*Callistemon citrinus*), Broom tea-tree or manuka tree (*Leptospermum scoparium*)	*E. crus-galli, D. sanguinalis, Setaria glauca, Avena sativa, Brassica juncea, Rumex crispus*	Dayan *et al.* (2011); Soltys *et al.* (2013)
Momilactone	Rice (*O. sativa*), Moss (*Hypnum plumaeform*)	*E. colona, A. lividus, D. sanguinalis, P. annua*	Motmainna *et al.* (2021)
Pelargonic acid	Rose Geranium (*Pelargonium roseum*)	*Digitaria ischaemum, Physalis angulata, Amaranthus spinosus, Cyperus esculentus*	Webber *et al.* (2014)
Polyacetylenes	Russian knapweed (*Centaurea repens*)	*T. aestivum, Glycine max, L. minor*	Minto and Blacklock (2008)
Quinones	*Black cumin* (*Nigella sativa*)	*S. lycopersicum*	El-Najjar *et al.* (2011)
Sarmentine	Long pepper (*Piper longum*)	*E. crus-galli, A. retroflexus, D. sanguinalis, Leptochloa filiformis, Taraxacum* sp. *C. album, P. annua, I. purpurea, S. arvensis, R. crispus*	Dayan *et al.* (2011)
Sorgoleone	Sorghum (*Sorghum bicolor*)	*P. minor, C. didymus, C. rotundus, S. nigrum, A. retroflexus, A. atrtemisifolia, C. obtusifolia*	Subramanyam *et al.* (2013); Thi *et al.* (2015)

compounds tend to be short-lived in the environment, complex and unpredictable (Schandry and Becker 2020; Zhang *et al.* 2021). Additionally, they are often non-selective in their control, expensive to synthesize, and in some cases, present potential mammalian toxicity with carcinogenic and allergenic concerns (Clemensen *et al.* 2020; Wink 2018). Despite these limitations, the herbicides based on allelopathic compounds often represent novel target sites in managing pesticide resistance, and they are water soluble and are perceived as more environmentally benign as compared to the chemical herbicides (Clemensen *et al.* 2020; Macias *et al.* 2003; Nishida 2014).

Several plant-based compounds possess a specific inhibiting activity against weed growth without causing any detrimental impact on crops due to differences in sensitivity to a specific receptor in different plant species or families (Hasan *et al.* 2021). The target-oriented phytotoxic compounds may lead to chlorosis or burning of leaves, reduction in chlorophyll content, cellular respiration, oxidative damage, plant growth reduction, mitotic inhibition, etc. (Hasan *et al.* 2021; Muñoz *et al.* 2020). However, hardly any systematic study has been conducted to elucidate the biochemical or physiological pathway followed by a range of plant extracts used as herbicidal agents.

EVIDENCE-BASED BIO-EFFICACY STUDIES FOR WEED MANAGEMENT USING HERBAL HERBICIDES

In a study on the wet season rice, *Calotropis* was found to be more effective than mechanical weeding at 30 days after transplanting (DAT).

Ipomoea and *Antigonon* also reduced weed growth, whereas higher grain yields were achieved with the use of *Annona*, followed by *Vitex* and *Holarrhena*, which were significantly superior to *Azadirachta*, pretilachlor and *Adhatoda*. The usage of *Adhatoda* was found to be as good as mechanical weeding (MW) and weed-free treatments. *Calotropis*, *Ipomoea* and *Antigonon* were found to be less effective in producing higher grain yield of rice (De and De 2000), whereas the use of *Ipomoea*, *Vitex*, MW (30 DAT) and *Cymbopogon* was equally effective as the weed-free check with minimal weed density at 42 DAT (Mandal and De 2001; Mandal *et al*. 2002). Next best treatments were the usage of *Calotropis* and *Annona*, which remained significantly superior to butachlor. Use of *Vitex* registered minimum weed biomass and remained at par with weed-free check and MW, and it was superior to butachlor. *Ipomoea* and *Calotropis* lowered the weed biomass in an equally manner as butachlor, and were followed by *Cymbopogon* and *Annona*. Similar results of *Annona* were also reported earlier (De and De 2000).

In a study, green leaves of the selected plants (150-200 kg/ha) were chopped, macerated and incorporated into the soil at the time of final puddling in transplanted rice or land preparation in other crops (Mandal and De 2005; Mandal *et al*. 2002). It was observed that incorporation of chopped and macerated leaves of *Tabernaemontana* caused 34% yield advantages and ranked second best in terms of net returns, whereas *Holarrhena* and *Antigonon* had fetched net returns exceeding those attained with MW (Mandal and De 2005). Hence, *Antigonon*, *Holarrhena* and *Tabernaemontana* may replace the traditional MW methods in rapeseed.

One hand weeding (HW) at 15 DAT in combination with two rounds of cono weeding (CW) at 25 and 35 DAT was found comparable with the pre-emergence (PE) application of pretilachlor 500 g/ha at 1 DAT followed by (*fb*) CW twice at 25 and 35 DAT, and use of herbal extract (water extract of *Calotropis* stem and leaf at 50 ml/l) at 1 DAT (PE) *fb* CW twice at 25 and 35 DAT, in the system of rice intensification (SRI). An integrated approach involving MW (CW), manual weeding (HW), and/or herbicide (pretilachlor) in judicious combination with the herbal herbicide (*Calotropis*) would be effective for sustainable weed management to improve rice productivity (Bhowmick *et al*. 2014).

Nagaraja and Deshmukh (2009) studied the phytotoxic effect of *Andrographis paniculata* (king of bitter / kirata / kalmagha) on growth and metabolism of *Parthenium hysterophous*. They reported that the powdered leaves, stems and roots of *Andrographis* could adversely affect the growth and physiology of *Parthenium* up to 60 days after sowing (DAS). Hence, *Andrographis* may be a suitable herbal herbicide against *Parthenium*.

Field experiment was conducted to find out a suitable solution for managing *Parthenium* with the use of different bio-agents including Mexican beetle (*Zygogramma bicolorata*) at 35 nos./plant, sowing of Mexican marigold (*Tagetes erecta*) along with *Parthenium* in 50 : 50 proportion, sowing of sickle pod (*Cassia tora*) in 50 : 50 proportion, and inoculation of Brinjal Mosaic Virus (BMV). The beetle insect and BMV did not exhibit satisfactory performance whereas *C. tora* and *T. erecta* significantly minimized weed growth possibly due to the release of allelochemicals. Because of widespread availability of sicklepod and marigold, common people can easily use these plants for controlling the obnoxious weed *Parthenium* (Dolai *et al*. 2015). *Parthenium* intensity was reduced in association with the plant species *C. tora* and *T. erecta* (Pawar *et al.* 2010). French marigold (*T. patula*) did not allow *Parthenium* to grow with it (Ramachandra Prasad *et al*. 2010). *T. erecta* displays strong allelopathic and herbicidal potential on seed germination and seedling growth of wild peas (*Phaseolus lathyroides*) as reported by Wichittrakarn *et al.* (2013). Furthermore, aqueous extracts from leaf may have a greater inhibitory effect on seed germination and seedling growth, *fb* those of root, flower and stem extracts.

Essential oil of *Peumus boldus* at all concentrations of 0.125-1.000 µl/ml is highly phytotoxic against annual weeds such as *Amaranthus hybridus* and *Portulaca oleracea* by inhibiting their seed germination and seedling growth whereas that of *Drimys winterii* only affects germination of *Portulaca* at the highest concentration (0.5-1.0 µl/ml). This suggests the possible use of essential oil from *P. boldus* as a natural herbicide for weed management in tropical and subtropical crops (Verdeguer *et al*. 2011).

Since aqueous methanol extract of *Leucas aspera* can significantly inhibit the seedling growth of timothy, jungle rice and barnyard grass, *Leucas* plant extract may have allelopathic properties (Islam and Kato-Noguchi 2013). Leaf extract of *Lantana camara* inhibits the germination per cent of *Bidens pilosa*, and leaf extracts at 1, 5 and 10% concentrations are comparable with MW and synthetic herbicide oxyfluorfen, but higher and significantly different as compared to lantana leaf extracts at 20% concentration (Darana 2013). Aqueous leaf extract and leaf debris of *Chromolaena odorata* and *Mikania micrantha* incorporated into the soil shows significant effect on total germination, germination indices and seedling growth of *Ageratum conyzoides* both in the laboratory and greenhouse conditions (Nornasuha and Ismail 2013).

According to Sondhia and Varshney (2009), significant inhibition of growth of major world's worst weeds (*P. hysterophorus*, *Vicia sativa*, *Ischaemum rugosum*, *Convolvulus arvensis*, *Echinochloa colona*, *Lathyrus sativa*, *Phalaris minor*, *Cyperus rotundus, Avena ludoviciana, etc*.) is possible with the use of phytochemicals / extracts isolated from different plants / weeds at the concentration range of 0.5-5.0 ppm and complete inhibition at 5-10% extracts. Crude ethanol extracts (70%) from the leaves of *Chromolaena odorata* as an early post-emergence application exhibit the highest inhibitory activity on the germination and growth of *Echinochloa crus-galli* seedlings (Poonpaiboonpipat *et al.* 2021).

Ghosh *et al.* (2020) studied with different botanical extracts of *Tectona grandis* (leaf), *Eucalyptus cameldulensis* (leaf), *Bambusa vulgaris* (root and leaf), *Calotropis procera* (young twigs), *Cucumis sativus* (matured plants), and young plants of *Parthenium hysterophorus*, *Blumea lacera*, *Ageratum conyziodes*, *Ocimum sanctum*, *Physalis minima*, *Cyperus difformis* and *Echinochloa colona* in mixed combination with 0.25% Tween 80 surfactants. In rapeseed and soybean, *Eucalyptus* leaf extract gives 11.2% higher seed yield over weedy check. Botanical treatments like *Ageratum conyzoides* extract gives higher growth and yield in sesame and blackgram while *Ocimum sanctum* extract among the botanicals in greengram displays higher harvest index, oil content and also soil nutrient status. Botanicals are reported to inhibit mostly the grassy weed species and give higher yields due to weed management with the help of natural phenol based allelochemicals (Ghosh *et al.* 2015 and 2020). Annual planning for weed management along with the use of botanical herbicides in integration with the MW is more eco-safe and cost-effective option for weed management under the system of crop intensification (Ghosh *et al.* 2015).

In a study with different intercrops for weed management in cotton under rainfed condition, the relative neighbour effect (RNE) value for each intercrop was assessed to correlate the abundance of different allelochemicals released from intercrops with their bio-efficacies for weed suppression. As evidenced from the RNE values, intercrops with high levels of phenolic, terpenoid, and other allelochemicals specific to sunnhemp, pearl millet, and sesame can be positively correlated with weed suppression. An effective weed management in cotton is possible if it is intercropped with pearl millet, sesame and sunnhemp due to the combined effect of allelochemicals (fatty acids, fatty acid methyl esters, terpenoids and phenolics) released from those intercrops which proved to be toxic to the weed flora. (Verma *et al.* 2021). Allelopathic compounds of wild plants (*Tithonia diversifolia* and *Thevetia peruviana*) may be an effective alternative for promoting growth and imparting resistance of tomato crop (Fangue-Yapseu *et al.* 2021).

The allelopathic potential of certain weed and crop species can influence the growth and distribution of associated weeds and the yield of desired plants (Inderjit and Keating 1999). For example, *Ailanthus altissima* produces an allelopathic compound called alianthone, which inhibits the growth of other plants (Heisey 1997) like garden cress (*Lepidium sativum*), redroot pigweed (*Amaranthus retroflexus*), yellow bristlegrass (*Setaria pumila*), barnyard grass (*Echinochloa crusgalli*), pea (*Pisum sativum* cv. *Sugar Snap*) and maize (*Zea mays* cv. *Silver Queen*). Likewise, several plant secondary metabolites (allelochemicals) possess good herbicidal activity. These allelochemicals provide novel chemistries that can be manipulated in order to produce commercial herbicides (Bhowmick and Mandal 2001). Some examples of commercially developed herbicides (based on natural chemistry) are 'cinmethylin' (a herbicidal analogue of 'cineole', widespread in plants), 'benzazin' (based on the natural product 'benzoxazinones'/'hydroxamic acids' derived from poaceaeous plants), 'quinclorac' (based on 'quinolinic acid' from *Nicotiana tabacum*), *etc*. (Hatzios 1987). One more important example is 'leptospermone', which is a purported thermochemical in lemon bottlebrush (*Callistemon citrinus*). Although it has been found to be too weak as a commercial herbicide, a chemical analog of it, 'mesotrion' (trade name 'callisto'), has been found to be effective. It is sold to control broadleaved weeds in corn but also seems to be an effective control for crabgrass in lawns. Corn gluten meal (CGM) is used for the natural PE weed control in turfgrass, which reduces germination of many broadleaved weeds and grasses (McDade and Christians 2000).

These examples demonstrate that the structures of naturally occurring phytotoxins can serve as leads for the synthesis of new successful herbicides. Thus, the secondary metabolites of plant species with allelopathic activities offer an excellent potential to develop new herbicide formulations or as a guide towards identifying active compounds to obtain natural / herbal herbicides. Greater research efforts need to be made to study the effect of plant-derived compounds or the allelopathic effect of phytochemicals for identifying them as herbal herbicides. Till then, the commonly available plants may be utilized directly by the rural farmers for successful weed management in different crops and cropping systems.

PROSPECTS AND LIMITATIONS OF USING HERBAL HERBICIDES

Use of herbal herbicides for weed management may have certain prospective benefits (Bhowmick *et al.* 2016). Some of these are as follows:

1. They don't necessarily display a toxic effect on the non-target organisms including human beings and animals.
2. There is limited scope for the development of resistance in weeds.
3. There is no scope for the residue build up in the environment.
4. They are bio-degradable.
5. They may act as plant growth promoters in addition to their herbicidal activities.
6. Smallholder farmers can easily explore the use of herbal herbicides as per natural and local availability.
7. Weed control techniques are inexpensive.

Despite having multiple benefits, use of herbal herbicides may be constrained for widespread adoption by the farmers because of certain limitations (Bhowmick *et al.* 2016), including (1) slow rate of weed suppression or extermination by herbal herbicides, (2) their variable efficacies or sometimes even little or negative toxicity and instability under field conditions (based on soil and environmental conditions), (3) possible requirements for bulk applications for improving field effectiveness and performance, (4) lack of specific mode of action and also no systemic activity (limited absorption and translocation) unlike synthetic chemical herbicides, (5) inadequate research efforts for the discovery and development of novel herbal herbicides with greater bio-efficacies, and (6) requirements for need-based integration with synthetic herbicides and other tactics for broad-spectrum weed control.

CONCLUSION

Weed-related crop losses are still very common and can place a huge financial strain on farmers. Herbicide usage minimizes crop-weed competition effectively and increases farm labor efficiency, but it comes out with the risks in terms of environmental pollution, human health hazards, herbicide resistance development, and much reliance on inputs that must be purchased. New eco-friendly alternatives are required to combat the threat of weeds as they continue to evolve resistance to synthetic herbicides. Therefore, proper attention must be placed on using non-chemical weed control methods, ranging from adjusting crop cultivation systems to biological ones, as well as developing, identifying, and employing herbal herbicides. The potential use of secondary plant products as natural or herbal herbicides has initiated scientific curiosity in light of recent developments in plant biochemistry. Although it may or may not control all kinds of weeds, rural farmers can readily use such natural plant sources as herbal herbicide. Thus, herbal herbicides should be viewed as complementing adjuncts in an integrated weed management (IWM) system rather than as a current replacement for broad-spectrum herbicides and other weed control strategies. The IWM strategy using herbal herbicides and other techniques in a strategic combination would be a cost-effective and environmentally acceptable solution resolve to the weed problems and related issues in smallholder farming in general, and organic or natural farming systems in particular.

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