Crop Protection 95 (2017) 14–21

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

Role of crop competition in managing weeds in rice, wheat, and maize in India: A review

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A R T I C L E I N F O

Article history:
Received 7 April 2016
Received in revised form
5 July 2016
Accepted 8 July 2016
Available online 16 July 2016

Keywords:
Crop competition
Spacing
Density
Direction of sowing
Weed competitive cultivars

A B S T R A C T

In India, the three staple food crops viz., rice, wheat, and maize, contribute more than four-fifths of the total food grain production. Among the several factors limiting their productivity, weeds account for about 40%. In order to meet the requirements of growing population, it is essential to improve productivity by reducing such unwarranted losses. Managing weeds with crop competition is an eco-friendly approach. Once the mechanisms of competition are understood, further improvements in weed control could be gained by manipulating other agronomic practices. The choice of cultivars, crop density, seeding rate, direction of planting, and intercropping could be exploited to enhance crop competitiveness against weeds. The variation in competitiveness and weed suppression among cultivars has been documented in rice, and to a lesser extent in wheat and maize. Research has demonstrated that the integration of crop competitiveness with other methods, such as the use of herbicides and manual weeding, is successful in managing weeds. However, in India, greater efforts are needed to exploit crop competitiveness for managing weeds in rice, wheat and maize. The success of these approaches relies on proper understanding of the biology and ecology of weeds, to identify weak points in their life cycle.

1. Introduction

Rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), and maize (*Zea mays* L.) are the three main food crops in India, fundamental to national food security. Together these crops occupy 42.2% of the gross cropped area in India, and contribute 85.7% to the total food grain production (Directorate of Economics and Statistics (2015)). With increasing population and improvement in purchasing power, the demand of food is rising, and it is projected that, by 2050, the global annual demand for these three cereals will be around 3.3 billion tones (FAO, 2016). In India, approximately 100 million tonnes of wheat would be required by 2030 and 120 million tonnes by 2050 (Tiwari et al., 2011; DWR, 2015). It is estimated that the demand for rice in India will be 121.2 million tonnes by the year 2030, and 137.3 million tonnes by the year 2050 (Mohapatra et al., 2013). The current maize production of 24.3 million tonnes has to be increased 3.25 times by 2050 (IIMR, 2015).

Food security in India is threatened by shrinking land holdings, climate change, environmental degradation, vulnerability of crops to biotic- and abiotic-stresses and stagnating yields. India is the world's second largest producer of rice and wheat, and the eighth largest producer of maize. The crop productivity (in 2013) in India is low for rice (3.66 t ha^{-1}), maize (2.45 t ha^{-1}), and wheat (3.15 t ha^{-1}) as compared to global averages of 4.53, 5.52 and 3.26 t ha^{-1} (FAO stat 2016), and needs to be increased to meet the food grain requirements of the growing population. Among several factors responsible for low productivity of these crops in India, weeds are a major biological constraint that limits the production of rice by 10–100%, wheat by 10–60%, and maize by 30–40% (Rao et al., 2014; Yaduraju et al., 2015). Thus improvements in productivity and total production of crops can be achieved by combating weeds. Integrated weed management (IWM), which is a science-based decision-making process that coordinates the use of macro- and micro-environmental information, weed biology and ecology, is the key in effective, efficient, and economical

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http://dx.doi.org/10.1016/j.cropro.2016.07.008
0261-2194/

management of weeds in Indian agro-ecosystems (Rao and Nagamani, 2010; Rao and Chauhan, 2015). IWM uses all available technologies to control weeds by the most economical and ecologically viable methods (Rao and Nagamani, 2010, 2013; Rao and Ladha, 2013).

In India, the high cost and scarcity of labour, and cost effective as well as timely control of weeds have increased use of herbicides for weed control in almost all crops (Rao et al., 2014). With increasing incidences of weeds developing resistance to commonly used herbicides, growing concerns about the environment, and increased public interest in environmental conservation, efforts are needed to identify the components of IWM that have minimum adverse effects on the environment.

Increased crop competition is a fundamental cultural weed management method which has been in use for decades. Variations in the competitive ability of many crops, specifically rice, have been documented (Zhao, 2006). Crop interference refers to the competition exerted by a crop on weeds. Improved crop competitiveness can be achieved by growing weed-competitive cultivars (robust early growth, fast ground coverage, allelopathic nature etc.), and adjustments in crop density, seed rate, and direction of planting to make efficient use of space, light, moisture, nutrients etc., by the crop rather than weeds.

Interspecific competition in crop-weed competition is defined as the competition between two species (crop vs. weed) occurring at low weed densities so that individual weeds do not compete with each other but do compete with the crop. Zhao (2006) categorized two components of weed competitiveness viz., weed tolerance and weed-suppressive ability. Weed tolerance is the crop's ability to maintain high yield despite weed competition, while weed-suppressive ability is the ability of the crop to suppress weed growth through competition. Both components have equal significance in terms of weed management.

Plastic stem-elongation responses to the ratio of red: far-red wavelengths enable plants to match their phenotype to local competitive conditions (Weinig and Delph, 2001). Liu et al. (2009) opined that crop-weed competition under cultivated conditions is triggered by these wavelengths of light from neighbouring plant species, followed by a series of complex physiological processes, which are not necessarily the direct consequence of resource competition viz., nutrients, water etc. These developments in plant eco-physiology and competition with neighbouring plants have thrown light on plant morphogenesis and development, and especially the perception and adjustment of plant communities to available resources (Merotto et al., 2009).

Competition-density effects and alteration in the size structure of the plant population are considered as intraspecific competition in crop-weed interactions (Park et al., 2003). In this review, an analytical analysis is presented of the role of crop competitiveness in managing weeds in the three major food crops of India, viz., rice, wheat, and maize, including an evaluation of the various strategies that can be adopted towards enhanced crop-weed competitiveness.

2. Rice weed flora

Major weeds associated with rice include several grasses viz., *Dactyloctenium aegyptium* (L.) Willd., *Echinochloa crus-galli* (L.) Beauv., *E. colona* (L.) Link, *Leptochloa chinensis* (L.) Nees, *Cynodon dactylon* L., *Digitaria sanguinalis* (L). Scop., and *Eragrostis pilosa* (L.) P. Beauv.; sedges viz., *Cyperus rotundus* L., *C. difformis* L., *Cyperus iria* L., *C. compressus* L., and *Fimbristylis miliacea* (L.) Vahl.; and broad leaf weeds viz., *Commelina benghalensis* L., *Caesulia axillaris* Roxb., *Eclipta prostrata* (L.) L., *Euphorbia hirta* L., *Portulaca oleracea* L., *Trianthema portulacastrum* L., *Lindernia* sp., *Brachiaria muctica* (Forssk.) Stapf., *Ipomoea aquatic* Forssk., *Marsilea minuta* L., *Nymph aeanouchali Burm.f.*, *Pistia stratiotes* L., *Veronica anagallis-aquatica* L., *Ranunculus sceleratus* L., *Ammannia baccifera* L., *Physalis minima* L., *Eclipta alba* L., *Phyllanthus niruri* L., *Ludwigia* spp. L., *Trianthema monogyna* L., etc. (Payman and Singh, 2008; Singh et al., 2008; Chauhan et al., 2011; Kumar et al., 2013; Singh, 2013; Kaur and Singh, 2014).

Major weeds associated with rainfed rice in India are *A. baccifera*, *Chara zeylanica* kl.ex.willd, *Cyperus iria*, *C. difformis*, *C. microiria*, *Echinochloa* spp., *F. miliacea*, *Hydrolea zeylanica* (L) Vahl., *Hydrodictyon reticulatum* L., *Lindernia ciliate* (Colsm.) Pennell, *Ludwigia parviflora* L., *Marsilea quadrifolia* L., *Monochoria vaginalis* (Burm.f.) C.Presl, *Paspalum* spp., *Sphenoclea zeylanica* Gaertn., *Spirogyra condensate* (Vaucher) Kutz., *Nittella hyalina* (De Candolle) C. Agardh and *Spilanthes acmella* (L.) murr (Duary et al., 2015a).

Major weeds associated with transplanted rice in India are *A. baccifera*, *Alternanthera sessilis* L., *Bergia capensis* L., *Caesulia axillaris* L., *E. colona*, *E. crus-galli*, *Eclipta alba*, *Ischaemum rugosum* Salisb., *D. sanguinalis*, *C. difformis*, *C. rotundus*, *C. iria*, *F. miliacea*, *S. acmella*, *S. zeylanica*, *L. parviflora*, *L. ciliate*, *Leersia hexandra* L., *L. chinensis*, *L. parviflora* and *M. quadrifolia* (Kabdal et al., 2014; Parthiban and Ravi, 2014; Das et al., 2015; Duary et al., 2015b).

Major weeds associated with direct seeded rice in India are *Alternanthera* sp, *E. colona*, *E. crusgalli*, *E. stagnina*, *L. chinensis*, *F. mileacea*, *C. iria*, *C. difformis*, *L. perennis*, *Lindernia crustacea* L., *M. vaginalis* and *Sphaeranthes indicus* L. (Prameela et al., 2014).

2.1. Weed-competitive cultivars

Compared with direct-seeded rice (DSR), the transplanting rice tends to have fewer weeds and lower associated yield losses (Rao et al., 2007). The puddling of soil, followed by stagnation of water, coupled with greater competitiveness of transplanted vigorous rice seedlings; provide effective weed control in the early vegetative crop growth stage (Rao et al., 2007; Mahajan and Chauhan, 2013). Conversely, in dry DSR, this type of environment is not available, and the rice and weeds emerge simultaneously, which often results in greater weed competition at the early stages, leading to yield reduction if weeds are not controlled. Despite these drawbacks, the area under DSR in India is increasing mainly because of the scarcity of water and increased cost of labour and energy (Rao et al., 2015).

Crop cultivars with greater seedling vigour, fast early growth and rapid canopy closure have greater ability to suppress weeds through resource competition, and have received growing attention over the past decades. As a result of evolution and rapid expansion of herbicide-resistant weeds, environmental concerns, opportunities in organic farming and smallholder farmers without access to herbicides, the interest in breeding crops with improved weed suppression ability is growing (Worthington and Reberg-Horton, 2013). Such cultivars could curtail weed seed production and future weed infestation, providing a low cost tool in weed management regimes (Kumar et al., 2013). As rice established by direct seeding is a weak competitor against weeds, identification of weed-competitive cultivars would help in sustaining rice productivity, particularly for resource-poor farmers. To cope with the problem of increased weed pressure in DSR, more attention has been directed towards the use of competitive cultivars in DSR (Chauhan, 2012; Mahajan and Chauhan, 2011).

A few of the rice plant characteristics associated with weed competitiveness are: plant height, early canopy cover, high tiller density, vertical leaf orientation, high biomass accumulation at the early crop stage, high leaf area index and high specific leaf area during vegetative growth, early vigour, and greater root biomass and volume (Saito et al., 2010). Diversity in cultivars in terms of morphology, canopy structure, and growth rate is an opportunity for weed management. However, information on the architectural traits enhancing the competitiveness of rice cultivars (including hybrids) against weeds is rather lacking.

Rice cultivars PR-120, IR88633, and IR83927 were found to be strong weed competitors in dry-seeded rice (Mahajan et al., 2014). Cultivars Vandana, Kalinga-III, and RR-151-3 showed weed competitive ability under upland dry-seeded conditions, and higher yield potential under suboptimal weed management conditions (ICAR, 2007). Cultivar Prabhat, with hanging lower leaves, significantly reduced biomass and density of *Echinochloa* spp. and *Cyperus* spp. at almost all stages of rice growth (Kumar et al., 2013). At 60 days after transplanting, the competitive rice hybrid PHB 71 had a greater smothering effect on the grassy weeds *Echinochloa* spp., *Cynodon dactylon*, *F. miliacea*, and *Cyperus* spp. than the poorly competitive cultivar NDR 359, but had no effect on density of the broad-leaved weeds *A. baccifera* and *L. parviflora* (Shukla et al., 2015).

Early maturing rice cultivars have smothering effects on weeds through improved vigour and rapid canopy closure (Mahajan et al., 2011). Under dry-seeded aerobic rice cultivation, PR 115 (125 days duration) demonstrated weed competitive ability against sedges, while PR 114, a long-duration rice cultivar (145 days) with slower initial growth than PR 115, suffered higher yield losses due to weeds (Singh and Bhullar, 2015). On the basis of various experiments conducted in India, Prasad (2011) reported that the traditional tall cultivars exert a greater smothering effect on weeds. Although weed competitiveness of tall plants is higher, these are more prone to lodging and often have lower yield potential than the modern semi dwarf varieties. As a compromise, the development of cultivars of intermediate height, that resist lodging and have higher yield than the tall cultivars, could be desirable for weed control in DSR systems. Alternatively, rather than stature (tallness), cultivars with greater early ground cover may be more desirable. With the availability of modern tools in genetic engineering, concerted efforts are underway to develop rice cultivars with weed-competitive traits for DSR systems (Mahajan and Chauhan, 2013).

2.2. Crop row spacing

The outcome of competition between crop and weeds growing in association will be determined by a variety of processes, including the spatial distribution of individuals, the resources being competed for, and the ability of the species to compete for these resources (Freckleton and Watkinson, 2001). The weed competitiveness of modern high-yielding, semi-dwarf cultivars could be improved using suitable agronomic manipulations, such as changing the crop planting arrangement (Mahajan and Chauhan, 2011). A marginal increase in rice row spacing from 15 to 20 cm failed to curtail the weed population in DSR (Payman and Singh, 2008). Conversely, because row spacing influences crop canopy cover which in turn controls light penetration to weed seeds at or near the soil surface, the emergence of many weed seedlings will be reduced as a consequence of narrow crop row spacing (Bradley, 2006).

In most parts of India, broadcasting is still a commonly used method for sowing dry- and wet-seeded rice (Chauhan, 2013). To overcome the problem of lower and uneven germination, a higher seed rate is often used. In a thin crop stand, weeds flourish due to the lack of crop competition. It is generally observed that high crop density with narrow row spacing leads to increased weed suppression i.e. lower weed density and biomass in DSR (Phuong et al., 2005; Kaur and Singh, 2014). A spacing of 15 cm was found to be ideal for weed suppression in DSR (Pande et al., 1974), with higher weed incidence under wider inter row spacing (Pillai and Sreedevi, 1980). With an increase in row spacing of DSR from 15 to 30 cm, weed biomass increased significantly (Kaur and Singh, 2014).

Weeds can be smothered by making changes in plant arrangements with bidirectional sowing. Mahajan and Chauhan (2011) observed that the paired row planting pattern (15–30–15-cm row spacing) in dry-seeded rice greatly facilitated weed suppression and reduced weed biomass through modification in the rice canopy structure, and also resulted in increased yield compared with the normal row planting system (23-cm row spacing). A uniform planting geometry of 20 cm resulted in lower weed density compared to 20 cm $\times$ 10 cm and 25 cm $\times$ 25 cm, due to mutual competition between weed species (Joshi et al., 2015). Narrow row planting with increased crop density shifted the competitive balance in favour of the crop. All planting geometries had a similar population of broadleaf weeds, but the sedge *C. iria* and the grass *E. colona* were more effectively controlled in high density, uniform planting arrangements (Joshi et al., 2015). In transplanted rice, seedlings are usually transplanted in a random manner or in squares. Changes in plant geometry (e.g., transplanting in a triangular manner or in paired rows) may help cultivars suppress weeds more effectively. Grain yield remained the same at 20 cm or 30 cm row spacing in weed-free environments (Chauhan, 2012), whereas in weedy or partially weedy conditions, narrow row spacing resulted in significantly higher grain yield than in wider row spacing. Crops planted in narrow rows had a shorter critical period for weed control than crops planted in wider rows (Chauhan and Johnson, 2011).

2.3. Rice seeding rate and density

Higher seed rates are generally used in DSR to smother weeds (Dixit et al., 2010). A lower than optimum plant density leaves space for the growth of weeds, and in many situations, results in less uniform ripening and poor grain quality. On the other hand, a very high plant stand reduces the number of productive tillers and may increase lodging. Only limited information on managing weeds through the use of seeding rates is available under Indian conditions.

Although Payman and Singh (2008) did not observe the benefit of increasing seed rate on weed suppression at 90 days after sowing in DSR, Walia et al. (2009) and Mahajan et al. (2010) found a linear reduction in weed biomass with increased seed rates up to a threshold level. Weed biomass was significantly affected by seed rate and it decreased significantly with each successive increase in seed rate (Kaur and Singh, 2014). *Echinochloa* spp. and *Cyperus* spp. densities in DSR were lowest when sown at 50 kg ha^{-1} with 15–20 cm row spacing, and were highest at a lower seed rate of 20–30 kg ha^{-1} with wider row spacing of 30 cm (Kaur and Singh, 2014). Mahajan et al. (2010) reported that rice seed rate in DSR did not influence the density of *E. colona*, while the density of sedges was decreased by 35% with 240 kg ha^{-1} as compared with 15 kg ha^{-1} rice seed rate. Chauhan et al. (2011) also reported a significant reduction in weed biomass with an increase in the seeding rate of rice from 15 to 125 kg ha^{-1}. Recently, Mukherjee (2015) observed reduction in weed density and weed biomass in rice with seed rate of 100 kg ha^{-1}, due to rapid canopy closure and reduced weed competition. Thus, a high seeding rate could facilitate control of weeds depending on the biology of the weeds and the rice cultivars. Further, in a weed-free environment, variable seed rates of rice may not influence grain yield (Chauhan, 2012).

Optimum crop density is necessary for the efficient utilization of solar radiation and other resources. A lower than optimum crop density enables weeds to establish and grow more quickly. A change in crop density modifies the crop micro climate and also the canopy structure. Wherever the weed problem is severe, a slight adjustment in crop density was found to increase the crop competitiveness, especially in low-input and dry land production systems. An increase in the rice density from 47 to 71 plants m^{-2} decreased weed density in DSR up to 40 days after sowing (Nayak et al., 2014). A quantum increase in density of rice from 22 to 44 hills m^{-2} significantly reduced competition from *L. chinensis* (Aulakh and Mehra, 2008). The reverse was also true; an increase in density of *E. colona* from 50 to 400 plants m^{-2} significantly reduced the LAI, biomass production as well as grain yield of rice due to competition (Babu, 2012).

2.4. Integrating rice competitiveness with other weed control methods

Crop–weed competition is comprised of both resource dependent and resource independent processes (Page et al., 2010). A careful combination of other field management practices such as fertilizer dose, source, placement and timing may be effective in reducing yield losses in rice and DSR in particular. Competitive rice cultivars with differential morphological characters and light interception-related traits play a vital role in crop-weed competition (Chauhan, 2012), and therefore such competitive cultivars may form a component of an IWM strategy (Mahajan et al., 2013).

A study of the integration of two rice cultivars (PR 115 and Punjab Mehak 1) with two planting patterns (uniform rows [23-cm row spacing] and paired rows [15-, 30-, and 15-cm row spacing]) under aerobic conditions revealed that weed biomass was not affected by the planting pattern of Punjab Mehak 1; however, for PR 115, weed biomass was greater in rice grown in uniform rows than in paired rows (Mahajan and Chauhan, 2013). A weed competitive cultivar 'Prabhat' in association with butachlor at 1.5 kg ha^{-1} post emergence (PE) plus 2,4-D at 0.5 kg ha^{-1} PE recorded minimum weed biomass and highest rice yield; a result similar to hand weeding twice (Singh et al., 2004). An increase in plant density of transplanted rice from 22 to 44 hills m^{-2} along with the application of pyrazosulfuron (0.015 kg ha^{-1}) significantly suppressed weeds such as *L. chinensis* (Aulakh and Mehra, 2006). Enhanced competitiveness of dry-seeded rice against weeds was observed with 100 kg ha^{-1} seed rate + oxyfluorfen at 0.25 kg ha^{-1} (3 days after sowing) (Angiras and Sharma, 1998).

Information on the integration of different management strategies for weed management in rice is not available for Indian conditions. The management of volunteer rice seedlings is also an issue for further research in DSR-based cropping systems. For effective use of crop competition to manage weeds in Indian rice production systems, it is necessary to characterise the morphological and physiological traits of emerging weed species, such as weedy rice occurring in different parts of India.

3. Wheat weed flora

The introduction of high yielding dwarf wheat cultivars during the early 1960s changed the spectrum of weed flora from dominance of broadleaf weeds to a mixed flora of broadleaf and grassy weeds by the early 1970s, and subsequently the dominance of grass weeds, especially *Phalaris minor*, towards the late 1970s (Chhokar et al., 2012). Grassy species such as *Phalaris minor* Retz. and *Avena fatua* L., and broad leaf weeds such as *Rumex dentatus* L., *Medicago denticulata* L. and *Anagallis arvensis* L., have become the major weeds of irrigated wheat in rice-wheat systems of the north western plains of India (Balyan and Malik, 2000; Chhokar et al., 2006). The predominant weeds associated with conventional till wheat are *P. minor*, *Poa annua* L., *Polypogon monspeliensis*, *Avena ludoviciana*, *Rumex dentatus*L., *R. spinosus*, *A. arvensis*, *Convolvulus arvensis* L., *Malva parviflora*, *M. denticulata*, *Chenopodium album*, *Vicia sativa*, *Lathyrus aphaca*, *Circium arvense* (L.) Scop., *Melilotus alba*, *Coronopus didymus*, *Polygonum plebejum*, and *Spergula arvensis* (Singh et al., 2015). *P. minor* is predominant in medium to heavy textured soils, whereas *A. fatua* is more prevalent in light textured soil under non rice-wheat rotation. Both *P. minor* and *R. dentatus* are highly competitive weeds and can cause drastic yield reductions under heavy infestation. An increased infestation of *M. denticulata*, *Convolvulus arvensis*, and *Cirsium arvense* has occurred due to continuous use of the herbicide isoproturon. In irrigated wheat of India, *P. minor* among grass weeds, and *R. dentatus* and *M. denticulata* among broad-leaved weeds, are of major concern. The evolution of resistance in *P. minor* (Malik and Singh, 1993; Chhokar and Malik, 2002; Chhokar and Sharma, 2008) against isoproturon has made it the single most serious weed species limiting wheat productivity in the north-western plains of India.

3.1. Weed competitive cultivars

Careful selection of a competitive crop/cultivar can potentially suppress weed growth without sacrificing crop yield. Crop cultivars often differ in their competitive ability against weeds. Wheat cultivars that are fast growing, or early canopy forming and quick spreading during the early stages, are less susceptible to weed competition. Taller wheat cultivars have greater *P. minor* suppression ability (Paul and Gill, 1979). The improved short-statured cultivars are more susceptible to weed competition (Challaih et al., 1986), even though they are high yielding under weed-free conditions. Compared with wheat cultivars,HD 2009, WH 291, and S 308, the wheat cultivars WH 147 and HD 2285 have been highly competitive against *A. fatua*, which itself is a strong competitor due to its deep and extensive root system and early maturity (Balyan et al., 1991). Chauhan et al. (2001) found that HD 2687 and PBW 343 were more competitive than WH 542 and WH 157. The cultivar PBW 343 is among the more weed-competitive cultivars in India (Vincent and Quirke, 2002), possibly due to higher number of tillers (Mahajan et al., 2004). It is important to note that the most competitive cultivars were not always the highest yielding cultivars in weed-free conditions. However, the magnitude of yield loss under weedy conditions was greater in the high yield-potential dwarf wheat cultivars, compared with taller weed-competitive cultivars (Challaih et al., 1986).

3.2. Crop row spacing

Narrower row spacing improves crop competition for limited resources due to a rapid canopy closure, reduced weed seedling growth, and eventually reduced weed seed bank in the soil. Borger et al. (2010) observed that the reflection of far-red photons by the stem of one plant lowered the red to far red photon ratio of light experienced by the stems of neighbouring plants, which triggered an increase in stem elongation. As the crop canopy closed, mutual shading further increased competition for photosynthetic light. A row spacing of 15 cm reduced weed density and dry matter production (Kumar et al., 2008). Row spacing of 17 cm significantly reduced weed biomass over a row to row spacing of 20- and 22.5-cm in bread wheat (Chaudhary et al., 2015).

3.3. Seeding rate of wheat

Maintaining optimum plant populations is an important component of the wheat crop's ability to compete with weeds. While environmental and economic factors dictate the choice of seeding rates, a higher seeding rate can give the crop an edge against weeds due to increased crop competitiveness (Singh et al., 2013). Use of a high seed rate has been shown to significantly influence weed density and its biomass by securing an optimum wheat crop population (Meena et al., 2010).

Increasing wheat seeding rates has been shown to decrease the dry weight of weeds from 135 to 96 g m^{-2} (Yadav et al., 2001). An increase in seed rate by 50% (150 kg ha^{-1}) improved competitiveness of wheat and reduced the dry matter accumulation of *P. minor* by 35%, compared with a seed rate of 100 kg ha^{-1} (Bhullar and Walia, 2004). Similarly, doubling the seed rate decreased the dry weight of weeds in wheat (Sharma and Singh, 2011).

3.4. Planting direction

Planting direction has a significant effect on weed population and crop growth. Crop rows oriented at a right angle to the sunlight direction may suppress weed growth through greater shading of weeds in the inter-row space. In Western Australia, weed biomass of wheat oriented in an east–west direction was reduced by half, as compared to wheat sown in a north–south direction (Borger et al., 2010). Light interception by the crop canopy was 28 and 18% greater in wheat oriented east–west compared with the north–south crop orientation. In India, the north-south row direction of wheat planting shaded the ground better than east-west rows, and thus may be useful in reducing weed emergence (Chhokar et al., 2012). Bidirectional sowing of wheat, using same seed rate, had fewer weeds compared to unidirectional sowing (Singh et al., 2012). Dry matter accumulation of weeds in wheat was highest under unidirectional sowing at row spacing of 22.5 cm, and significantly lower under bi-directional row orientation, followed by north-south row orientation, and then cross sowing at 22.5 cm × 22.5 cm (Chaudhary et al., 2013).

3.5. Integrating wheat competitiveness with other methods

Efforts were made to integrate wheat competitiveness with other methods to obtain better weed control. Reduced weed growth and increased wheat yield were observed with narrower row spacing (15 cm) and reduced doses of herbicides (Prakash et al., 1986). Ahuja and Yaduraju (1989) reported cross sowing of wheat and placement of fertilizer below seed as more effective in controlling weeds and increasing yield, compared to unidirectional sowing and broadcast fertilizer application. The use of a competitive cultivar coupled with closer or cross sowing is suggested to further reduce herbicide usage (Chhokar et al., 2012).

3.6. Maize weed flora

Weeds are one of the major production constraints in maize (Lal and Saini, 1985; Sharma and Thakur, 1998; Pandey et al., 1999; Deshmukh et al., 2009). Maize grown during summer or rainy season is commonly infested with a range of weeds, such as *E. colona*, *C. rotundus*, *Commelina benghalensis*, and *T. portulacastrum* during early stages of the crop growth, and *D. aegyptium* towards tasseling and crop maturity (Saini and Angiras, 1998). Rao et al. (2009) documented *E. colona*, *Dinebra retroflexa* (Vahl) Panzer, *Panicum repens* L., *C. dactylon*, and *L. chinensis* among grasses; *C. rotundus* among sedges; and *Chrozophora rottleri* (Geisel) A. Juss. Ex Spreng., *T. portulacastrum*, *Digera arvensis*, *Merremia emerginata* (Burm. f.) Hall. F., *Phyllanthus niruri*, and *Euphorbia hirta* L. among broadleaf weeds in clay loam soils of Guntur, Andhra Pradesh. Kiran and Rao (2014) noticed 21 weed species (7 grasses, 3 sedges, and 11 broadleaf) in the Krishna zone of Andhra Pradesh, of which *E. colona* was the most prevalent, followed by *P. repens*, *T. portulacastrum* and *D. arvensis*. Maize is also grown during the winter season in some parts of the country where it is often infested with *Brachiaria* spp., *Asphodelus tenuifolius* Cav., *Indigofera glandulosa* L., *Panicum coloratum* L. and *D. egyptium* among grass weeds; *Digera arvensis* Forsk, *Amaranthus viridis* L., *Acanthospermum hispidum* DC., *Launaea nudicaulis* L., *Euphorbia hirta* L., *C. album* L., *Portulaca oleracea* L., and *Celosia argentea* L. among broadleaf weeds; and the sedge like *C. rotundus* L. (Mathukia et al., 2014).

3.7. Weed competitive cultivars

Maize was more competitive against *C. dactylon* (L.) Pers. when established (Ramakrishnan and Kumar, 1971), indicating the significance of initial crop competitiveness for weed management. Plant height, leaf development rate, leaf area index, and crown leaf distribution are among the traits in maize considered to be important in light-competitiveness against weeds. A study in the USA indicated that plant height was the most predictive trait for weed suppressive ability and crop tolerance (Zystro et al., 2012). The use of competitive cultivars in maize in India, as a component of IWM, is almost non-existent and needs to be included in the future.

3.8. Crop row spacing

Reducing row spacing to half the standard distance has been shown to reduce weed biomass by 39–68% in maize (Mhlanga et al., 2016). Reduced weed biomass has been recorded at 45 cm × 25 cm spacing compared with 60 cm × 19 cm spacing, due to greater crop competitiveness in the former case (Thavaprakaash et al., 2011). Narrow row spacing (45 cm) and high plant density of maize (90,000 plants ha^{-1}) produced a significantly higher leaf area index, dry matter accumulation, and higher N, P, and K uptake by the crop compared to wider spacing (Pandagare et al., 2010). Sunitha et al. (2011) reported lowest density, dry weight, and nutrient uptake of weeds and the highest leaf area index, dry matter production, and nutrient uptake of maize at the planting pattern of 60 cm × 20 cm (83,333 plants ha^{-1}).

3.9. Maize seeding rate and density

A significant reduction in biomass of the dominant weed *T. monogyna* was observed with an increase in maize seed rate from 75 to 150 kg ha^{-1}, from 30 to 60 kg ha^{-1} for cowpeas, and from 37 + 15 to 75 + 30 kg ha^{-1} for maize + cowpeas intercropping (Brar et al., 1984). A maize seed rate of 24 kg ha^{-1} resulted in lower weed biomass when compared with 16 kg seeds ha^{-1} (Sarma and Gautam, 2010). Research conducted worldwide has reported that a 26–99% reduction in weed biomass could be achieved by increasing the maize planting density by 200% the standard rate (Mhlanga et al., 2016). Kumar and Walia (2003) also reported lower dry matter accumulation of weeds with maize crop density of 90,000 plants ha^{-1}, compared to a crop plant density of 75,000 ha^{-1}. Significantly lower weed density and biomass, and consequently higher green cob and green fodder yield, were recorded with a crop density of 1,11,111 plants ha^{-1}, compared with 83,333 and 74,074 plants ha^{-1} (Arvadiya et al., 2012).

3.10. Integration of crop competitiveness with other methods

Theoretically, weed management using integration of crop competitiveness with other methods envisages the manipulation of best agronomic practices, adjustment in row spacing (crop density and uniformity within rows), and use of competitive cultivars. However the integration of these methods depends on the field-situation, especially the amount, intensity and distribution of rainfall. Variation in the amount of herbicide needed for effective weed management was observed in a study with transgenic maize hybrids having both insect protection and herbicide-tolerant traits. In this study, transgenic 900 M Gold required post-emergence application of glyphosate at 1800 g ha^{-1} in comparison to herbicide dose of 3600 g ha^{-1} required for the transgenic Hishell (Ravisankar et al., 2012). In order to increase the competitiveness of crops in maize agro-ecosystems, wide row spacing in maize can be used to grow short duration legumes which not only acts as a smother crop, but also gives additional yield (Shah et al., 2011). The intercropping of maize with pea or chickpea (Sharma and Banik, 2013), blackgram (Shekhawat et al., 2001; Tripathi et al., 2005), or soybean (Channabasappa and Nanjappa, 1994) effectively suppressed weeds. The weed smothering efficiency was reported to be influenced by planting geometry, and was highest with maize + blackgram in 1:1 row proportion; which was remarkably higher than maize + blackgram in 2:2 and 2:1 row proportions (Dwivedi and Shrivastava, 2011). However, Singh et al. (2005) observed that paired planting of maize and soybean (2:2) was more effective in controlling weeds than alternate planting of maize + soybean (1:1). Paired rows of maize + soybean in 2:2 row proportion (Kithan and Longkumer, 2014), and baby corn + pea or baby corn + chickpea in 2:2 row proportion (Sharma and Banik, 2013), resulted in lower weed biomass, higher yield, net returns, and a positive benefit:cost ratio. In organic maize production, increasing the competitiveness of maize by intercropping with soybean, plus one mechanical weeding (20 DAS), or two mechanical weedings (20 and 40 DAS), were effective non-chemical weed management options (Saini et al., 2013).

Narrow spacing and higher plant density, along with either paraquat application at 0.75 kg ha^{-1} or two hand weedings, resulted in lower weed biomass and better crop growth under no-till conditions (Pandagare et al., 2010); whereas two hand weedings at 25 and 45 DAS with a high seed rate (24 kg ha^{-1}) reduced weed growth under tilled conditions (Sarma and Gautam, 2010). Integration of manual weeding, intercropping with soybean, plant density of 75,000 plants ha^{-1}, and fertilizer application at 50% of the recommended rate, resulted in the lowest weed biomass (Angiras and Singh, 1988), decreased nutrient uptake by weeds, and increased uptake by maize and soybean (Angiras and Singh, 1989).

4. Conclusions

Improving crop competitiveness against weeds would provide a low-cost and safe tool for ecological weed management. Crop competitiveness can be increased using any cultural practice that facilitates rapid crop growth and quicker soil surface cover to reduce light, space and other resources available to weeds. Competitive cultivars, increased seed rate, narrower row spacing, and a paired-row planting pattern have been shown to enhance crop competitiveness against weeds in rice, wheat and maize. Keeping in view the limited information available in India on this aspect for these important crops, and more research efforts are needed to explore different ways of enhancing crop competitiveness, and integrating crop competitiveness with other weed management options, to profitably and ecologically manage weeds in Indian agro-ecosystems.

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