Indian Journal of Weed Science **46**(1): 1–13, 2014

Research needs for improving weed management in rice

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Received: 16 December 2013; Revised: 3 February 2014

ABSTRACT

Weeds are the most important biological constraints to increasing rice productivity in Asia. They are managed by using herbicides; however, reliance on herbicides alone is not sustainable in the long run. There is thus, a need to develop sustainable weed management strategies in different rice-based cropping systems. The development and adoption of improved weed management strategies must form an integral part of sustainable rice production. Improved weed management techniques in rice should focus on shifting the crop-weed balance in favour of rice by integrating possible cultural, physical, and biological weed management tools with judicious use of herbicides. Together, these approaches may be used as components of an integrated package in the future to slow down the evolution of new weed problems in rice production. The improved weed management approaches should aim to reduce the weed seed bank before crop sowing and reduce weed emergence and weed growth in rice.

Key words: Improved management, Research need, Rice, Weed management

Rice (*Oryza sativa* L.), the staple food of more than 60% population of the world, plays a crucial role in the economic and social stability of the world. The resources for rice production-land, water, nutrients, and labour-are becoming scarce. Therefore, meeting the rice demand of the burgeoning population is a great challenge in the future. In rice production, weeds are one of the major yield-limiting biological constraints worldwide. Losses caused by weeds in rice vary in different countries because the nature, extent, and intensity of weed problems depend on the ecology in which the crop is grown and situations such as hydrology, land topography, establishment methods, *etc.* Management practices of farmers to control weed also differ in different countries, and this explains the variation in losses caused by weeds in different countries. The dimension of the problem can be ascertained with the following examples. In India, about 33% of rice yield losses are caused by weeds (Mukherjee 2004), while in Sri Lanka, weeds accounted for 30-40% of yield losses (Abeysekera 2001). In world rice production, about 10% of the total yield is reduced by weeds (Oerke and Dehne 2004). Globally, pests have a potential to reduce rice yield by 40%, of which weeds account for 32%. Annually, 10 million tonnes of rice produce are lost in China due to weed competition. This quantity of rice is sufficient to feed at least 56 million people for a year. Weeds are the universal pests in rice, causing losses that exceed tolerable levels in all seasons (Moody and Cordova 1985). Therefore, it is imperative that investment in weed management practices be made to reduce yield losses caused by weed competition. Total loss caused by weeds are tied up with cultural practices pertaining to weed control, land preparation, weed control expenses, and reduction in yield quantity and quality. Rice is cultivated in various ecosystems from irrigated to shallow lowland, mid-deep lands, deep water to uplands. In most of the Asian countries, including India, rice is cultivated mainly by manual transplanting of seedlings in puddled conditions. Weed control in puddled transplanted rice is done by a combination of pre-emergence herbicides, hand weeding, and water management.

The increase in production cost, shortage of labour, increased wages, and decreased water availability resulted in a shift from transplanting to direct seeding in many Asian countries. In India, dry-seeded rice is extensively practiced in the northwest Indo-Gangetic Plains because dry-seeded rice in this region provides the highest opportunity to attain optimal plant density and high water and labour productivity (Chauhan *et al.* 2012b). However, weeds are a serious problem in dry-seeded rice because dry tillage practices and aerobic soil conditions are favourable for germination and growth of weeds, which can cause grain yield losses from 50 to 90% (Chauhan and Johnson 2011, Chauhan *et al.* 2011, Prasad 2011). With the adoption and development of dry-seeded rice, good crop growth can be obtained, but the lack of sustained flooding can cause great losses from weeds. Since weeds are a major constraint to dry-seeded rice cultivation, the success of dry-seeded rice warrants the

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intensive use of herbicides. Herbicides have been proven effective in many cases, but intensive herbicide use can cause environmental contamination and induce herbicide resistance in weeds (Heap 2012). Therefore, to sustain rice production, effective weed management strategies are required. Researchers are now taking an interest in exploring non-chemical (cultural) methods of weed control because of increased use of herbicides, risk of herbicide resistance, rising costs of production, and concerns about environmental pollution (Chauhan 2012a, b).

Rice and rice weeds have similar requirements for growth and development. They compete for limited resources such as nutrient, moisture, light, space, *etc*. Most of the weeds, being C_4 plants, have higher adaptability and faster growth than rice, a C_3 crop. Weeds dominate the crop habitat and rice yield potential is reduced. Proper weed control in rice, especially dry-seeded rice, is achieved by using both pre- and post-emergence herbicides. But the use of herbicides brings about environmental problems because farmers lack knowledge about the proper use of herbicides. Currently, herbicides with ALS inhibitors are used in dry-seeded rice, which have high selection pressure and may exacerbate the problem of herbicide-resistant species. The constant shift in weed population dynamics that goes with the introduction of new herbicides has always been a prelude to the development of new and more potent herbicides. When a particular herbicide is applied, susceptible weeds are controlled and their population decreases, but the number of tolerant weeds increases. Also, even in single weed species, intra-specific variation in ecological characteristics or herbicide susceptibility is often observed in rice fields, leading to a decrease in herbicide efficacy. This problem can be solved only by implementing integrated weed management (IWM) in rice, which can go a long way to sustain rice production.

In this review, we describe some of the present approaches and possible future strategies to manage weeds in rice. However, the main focus is on direct-seeded rice systems.

Knowledge of weed ecology and biology

Knowledge of the behaviour of weed species in a region, such as time of germination of weeds, period of fruit setting, emission of first vegetative organ, *etc.* is critical in weed management. In the present scenario, weed management strategies should focus on preventing the build-up of a weed seed bank. Because of the complexity of weed flora, this is not easy; however, knowing under what conditions weed seeds germinate and grow may help farmers improve their weed management practices. With adequate knowledge of the germination requirements of weed seeds, weeds can be controlled by stimulating germination at a time when seedlings can be easily killed or by providing an environment that induces very low germination (Chauhan and Johnson 2010b). The most important survival mechanisms of weeds are seed dormancy and germination. The seed bank in the soil builds up through seed production and dispersal; it is depleted through germination, predation, and decay. Seedling emergence and weed population dynamics are influenced by the differential vertical distribution of weed seed bank in the soil, the consequences of differences in availability of moisture, diurnal temperature, light exposure, and predator activities at different soil depths (Chauhan *et al.* 2006, 2007).

Cultural control

Flooding is commonly used as the primary cultural weed control method to suppress weeds in puddled transplanted rice; however, flooding effect on weeds is species-specific (Chauhan and Johnson 2010b, Singh 2010). Some weed species, such as *Leptochloa chinensis* (L.) Nees, *Eleusine indica* (L.) Gaertn., and *Eclipta prostrata* (L.) may be encouraged by alternate wetting and drying in puddled as well as dry-seeded rice. Sedges primarily compete for nutrients as their root systems are fibrous. Similarly, grass weeds also pose serious competition for soil water and nutrients, apart from that for CO_2 and light. Broad-leaved weeds have less competition for nutrients with rice because their deep root systems explore the deeper layer for minerals. *Echinochloa* species poses serious competition for light because of its height, whereas weeds with short stature [*e.g. Monochoria vaginalis* (Burm. f.) Kunth] offer little competition for light. Management and environmental factors greatly influence weed distribution in upland rice. Soil moisture content in the upper 0-15 cm soil layer affects the emergence patterns of weeds. All the weeds do not emerge at one time but rather in several flushes.

Weed seed bank in rice

Very limited information is available on the persistence of weed seed banks. For example, the long-term fate of the seeds that remain in the seed bank and the management practices that deplete the seed bank are not well understood. There is a need for research to address this key knowledge gap in our understanding of the ecology of important rice weeds, including weedy rice. To develop a viable weed management technology, a better understanding of weed ecology, the basis for competitiveness, phenology, physiology, and biochemistry, and threshold population is required, and it is toward this goal that the research programme needs to be reoriented.

Tillage reforms: Tillage influences weed growth by altering the soil conditions for germination and emergence through several ways: uprooting, dismembering, burying them deep enough to prevent emergence, and moving seeds both vertically and horizontally in the soil (Clements *et al.* 1996, Hartzler and Owen 1997, Swanton *et al.* 2000). Weed management is thus greatly influenced by any change in intensity or frequency of tillage. As tillage is reduced, the density of certain annual and perennial weeds can increase, so effective weed control techniques are required to manage weeds successfully (Moyer *et al.* 1994). Harrowing and puddling are done for a range of reasons, including weed control. Precision land levelling, obtained with laser-directed equipment, has made an important contribution to weedy rice management in European rice production (Ferrero and Videtto 2007). Level or regulatory sloping fields enable appropriate water management, which limits weed growth and guarantees uniform emergence of weeds. This in turn makes herbicide application more effective.

A large proportion of the weed seed bank remains on or close to the soil surface after crop planting in zero-till systems, which may promote greater emergence of weed species that require light to germinate (Chauhan *et al.* 2009). Weed seeds present on the soil surface after crop sowing may be more favourable for granivore fauna, such as ants and other insects. Hulme (1994) suggested that weed seeds remaining on the soil surface are most vulnerable to surface-dwelling seed predators, while burial makes seeds largely unavailable. Therefore, seed predation could be used as an important tool in weed management systems where newly produced weed seeds remain on the soil surface as in, for example, zero-till systems (Baraibar *et al.* 2009, Chauhan *et al.* 2010). In contrast, tillage redistributes the weed seeds stored in superficial chambers by destroying the nests of weed seed predators (Baraibar *et al.* 2009). Westerman *et al.* (2003) reported that germination and emergence of weed seeds are reduced and seed predation may be responsible for the larger part of these losses. Thus, herbicide use, risk, and cost and demand for labour can be reduced by integrating seed predation with other weed control methods. These results suggest that the size of the weed seed bank can be reduced significantly by seed predation. Weed seed predators can be encouraged by retaining crop residues in the field as they serve as forage to them (Chauhan *et al.* 2010). Since no additional cost is required to apply such approaches, these can be combined with existing practices as a component of an IWM package (Chauhan *et al.* 2010). Future research may look into ways of integrating weed seed predation in existing weed management systems where chemical herbicides are used widely.

Climate change and weeds in rice

In the wake of climate change, weed communities in rice may also be affected. Weed species distribution and prevalence within weed and crop communities will be influenced by changes in atmospheric CO_2, rainfall, and temperature. Competitiveness in rice over C_4 weeds (*e.g., Echinochloa glabrescens* Munro ex Hook. F.) could be increased with elevated CO_2 alone (Alberto *et al.* 1996). However, the simultaneous increase in CO_2 and temperature favours the C_4 species. Climate change can also influence the chemical and mechanical weed management operations in rice. Under high-temperature conditions, C_4 plants (mostly weeds) have a competitive advantage over C_3 plants (rice) (Yin and Struik 2008). The increased concentration of CO_2 may have positive effects on rice competitiveness over C_4 weeds (Fuhrer 2003, Patterson 1995). But this is not always true. Potvin and Strain (1985) reported that, in several weed species, elevated CO_2 has been found to increase tolerance for low temperature. At the Directorate of Weed Science in Jabalpur, India, studies on the effect of CO_2 enrichment on weed species revealed that some weeds, such as *Echinochloa colona* (L.) Link, responded to elevated CO_2, but others, such as *Cyperus rotundus* L. and *Eleusine indica*, did not.

Ziska *et al.* (2010) reported that weedy rice responds more strongly to increasing levels of CO_2 than does cultivated rice. The authors suggest that weedy rice may become a more problematic weed in the future. In field conditions, the rate of emergence of weed seedlings increased with increases in CO_2 concentrations (Ziska and Bunce 1993). Under erratic rainfall conditions also, a similar change in weed flora can be expected because of climate change. Any type of environmental stress on a crop due to a sudden change in climate may increase its susceptibility to attacks by insects and pathogens; it thus becomes less competitive with weeds. These aberrant weather conditions not only increase weed competitiveness but also enhance weed seed germination in several flushes, making weed management more difficult. An increase in CO_2 level in the atmosphere may increase the tolerance of weeds for glyphosate (Ziska *et al.* 1999), a pre-plant herbicide used to kill weeds before crop sowing. Such information suggests that glyphosate efficiency in the future may decrease with increase in CO_2, thereby posing a threat in areas where weeds are controlled with the stale seedbed technique.

Rotation of establishment methods, crops and herbicides

There are three different kinds of direct-seeded rice systems: dry-seeded, wet-seeded, and water-seeded. Dry-seeded rice can be sown after tillage or under zero-till conditions. Because of the availability of rice cultivars tolerant of anaerobic conditions, it is possible to increase the area under water seeding also, as in eastern India. In water-seeded rice systems, however, aquatic weeds are likely to be problematic. Because of the availability of transplanters, mechanical rice transplanting is being practiced in zero-till and non-puddled (tillage in dry soil conditions) conditions in India (Kamboj *et al.* 2013). In such conditions, however, weed infestation may increase faster than in puddled conditions. Rice establishment methods affect the level of weed infestation and the species composition in the crop. However, such information on weed shifts, as a result of the adoption of a particular establishment method, is limited in different cropping systems. Knowledge on the shifts in principal weeds under a particular establishment method could help reduce the buildup of seed banks by using other establishment methods.

Crop rotation is an important tool of IWM. The long-term weed population dynamics is affected by the choice and sequencing of crops. Consequently, weed management is affected. The key component of weed management in traditional farming was the rotation of different crops with different life cycles. Plant establishment or seed production by weeds can be prevented by different planting and harvest dates of these crops, which provide more opportunities for farmers to control weeds (Rao 2011). Grasses and sedges in the rice-wheat cropping system can be controlled to a great extent by sequences involving summer cowpea for fodder or *Sesbania* for green manure, resulting in significantly lowest weed populations (Singh *et al.* 2008).

Continuous growing of a single crop or different crops having similar management practices give certain weed species the chance to become dominant in the cropping system. With passage of time, these weed species become hard to control (Chauhan *et al.* 2012b). For instance, grass weed species, such as *Alopecurus myosuroides* Huds and *Bromus* species, dominate in continuous cereal cropping with reduced tillage in temperate regions (Froud-Williams 1983). Crops with different management practices may help in disrupting the growth cycle of weeds (Chauhan 2013). When there is a fallow period in any crop rotation, it can be exploited to stimulate the emergence of problem weeds. These weeds are then controlled by non-selective herbicides. Different crops have different management practices, which is a key weed management tool: disturbing the growth cycle of weeds and thus preventing selection of weed flora toward increased abundance of problem species (Karlen *et al.* 1994). One particular weed species cannot become unmanageable when different crops with different management practices are grown in crop rotation (Locke *et al.* 2002).

With crop rotation, growers can use new herbicides and this practice helps to control problematic weeds in rice. In Southeast and South Asia, weedy rice is becoming a serious weed problem in rice monoculture systems (Chauhan and Johnson 2010c, Chauhan 2013). This may even become a more problematic weed species when rice is grown with conservation agricultural techniques. In rice-rice-rice or rice-rice cropping systems, rotating one rice crop with an upland crop, such as maize, soybean, sesame, mungbean *etc.* in the dry season may significantly help in reducing the seed bank of weedy rice in the soil. In these upland crops, the emerged seedlings of weedy rice can be killed by using a combination of different herbicides, which otherwise would not be used in a rice crop because of the non availability of selective herbicides to control weedy rice in the conventional rice system (Chauhan 2013). Greater herbicide effectiveness may be achieved when crops as well as herbicides are rotated. Combining herbicides and sequential treatment and herbicide mixture with cultural, mechanical, and bio-control methods will reduce the chance of undesirable ecological shifts to tolerant weed species, minimize the chance of an accumulation of herbicide residue in the soil, and reduce the weed seed population in the soil. To make the approach most effective, preventive weed control must precede and accompany standard weed control practices. Information on the role of crop rotation in suppressing the build-up of weed populations in rice monoculture systems is very limited in India.

Agronomic approaches

Plant geometry: Weed flora can be smothered by making changes in plant arrangement with bidirectional sowing. In a thin crop stand, weeds get a favourable environment and so they flourish well. This results in grain yield reduction and also an increase in the soil weed seed bank, paving the way to weed infestation during the following season. In most parts of India, broadcasting is still commonly used to sow dry-seeded rice or wet-direct-seeded rice (Chauhan 2013). However, with this seeding method, it is difficult to recognize weedy rice seedlings from cultivated rice seedlings until the plants reach flowering stage. In such a situation, use of row-seeded rice will be a better option than use of broadcast rice as weedy rice seedlings emerging between the rows can be easily distinguished. Manual and mechanical weeding is much easier to perform in row-seeded rice than in broadcast rice.

In a crop-weed ecosystem, by maintaining narrow row spacing, the crop provides a more smothering effect on weeds as less space is available for weeds to flourish. The light regime created at the ground level by the thick crop canopy is also low. With the help of high crop density per unit area, weeds can be suppressed by maintaining the dominant position of crop plants over weeds through a modification in canopy structure. Sunyob *et al.* (2012) reported that weed dry matter production was significantly affected by plant spacing of rice at different stages. Narrow plant spacing decreased weed biomass, increased weed suppression, and ultimately, increased the rice yield. Phuong *et al.* (2005) reported that favourable conditions for the crop are produced with higher plant density and narrow row spacing in rice, enabling it to compete with weeds and to give higher yield. Twin planting in rice reduced the weed biomass in dry-seeded rice and resulted in an increase in yield (Mahajan and Chauhan 2011). More weed biomass was produced using a row spacing of 30 cm as compared with that produced in 15 cm or 10-20-10-cm paired rows (Chauhan and Johnson 2011). Grain yield remained similar at different row spacing (20 cm or 30 cm) in weed-free environments (Chauhan 2012a). However, in weedy or partially weedy conditions, narrow row spacing provided a significantly higher grain yield than did wider row spacing. Besides, in crops planted in narrow rows, the critical period for weed control was usually less than that for crops planted in wider rows. The rice crop's ability to compete against weeds for light can be increased with cultural management practices, such as reduced crop row spacing (Chauhan and Johnson 2010c).

In India, the agronomic aspects (crop geometry, row, *etc*.) of crop competitiveness are yet to be exploited as a component of IWM in direct-seeded rice systems. Narrower row spacing, for example, improves the competitiveness of crops with weeds by developing faster canopy cover and allowing less light penetration through their leaves. 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. Different rice genotypes (including hybrids), depending on their architectural traits, may perform differently at different plant geometry. However, such information is not available and there is a need to evaluate the performance of rice cultivars planted using different geometric schemes in different environments. Results from such research may guide the design of better transplanters and sowing drills.

Seeding rate: The impact of weeds on crops can be reduced by increasing crop density. Increasing crop competitiveness through the use of high crop density is a possible technique for weed management, especially in low-input and organic production systems or when herbicide resistance develops in weeds. At low crop density, crop cover early in the growing season is usually low and a large amount of resources is available for the weeds. These conditions enable weeds to establish and grow quickly. In a previous study in India and the Philippines, increases in seeding rate of rice from 15 to 125 kg/ha decreased weed biomass significantly (Chauhan *et al.* 2011). It was due to rapid canopy closure and reduced weed competition. Thus, high seeding rate could partly control weeds. However, the effectiveness of high seed rates in controlling the weed problem is dependent on the biology of weeds and rice cultivars present in the field. Moody (1977) reported that biomass of broadleaved weeds, grasses, and sedges significantly decreased as seeding rate increased from 50 to 250 kg/ha. Grain yield may not be influenced with increasing or decreasing seed rate in a weed-free environment (Chauhan 2012a, b).

In many Asian countries (e.g., Vietnam and Sri Lanka), high seeding rates (up to 150 kg seeds/ha) are used mainly in a broadcast rice crop but, in other parts of the world (e.g., South America), growers use high seeding rates in a mechanized row-seeded rice crop also. In weedy rice-infested areas (e.g., in Malaysia), the use of high seeding rates helped to reduce the problem of weedy rice (Chauhan 2013). Weed growth is encouraged with low plant density and high gaps and, in many cultivars, it also results in less uniform ripening and poor grain quality. Therefore, it can be concluded that high seeding rates may help control weeds and reduce yield losses caused by weeds if no or partial weed control is expected (Mahajan *et al.* 2010). However, such information on the use of high seeding rate in managing weeds is very limited in Indian conditions. In some situations, the very high plant density tends to reduce productive tillers, increase lodging, minimize full benefits from nitrogen (N) application, and increase the chances of rat damage. Therefore, there is a need to evaluate the effect of high seeding rates on weed management and rice productivity, especially where herbicide use is limited or less effective.

Fertilisation: Crop fertilization can be used as an important component of IWM. It is observed that N fertilisation plays a vital role in establishing the competitive balance between weeds and rice (Raun and Johnson 1999, Camara *et al.* 2003). Weed growth in rice fields is affected by fertilisation. Some sedges, such as *Eleocharis kuroguwai* Ohwi dominated on low-fertility soils (Guh 1974). A lower population of *Cyperus iria* L. in transplanted rice was obtained at higher N rates (80-120 kg/ha) than at lower (40 kg/ha) (Mishra *et al.* 2001). N application has a negative effect on the germination and growth of *Striga* seeds in the soil. On the other hand, the susceptible host is favourably affected by N application as N enables the host plant to tolerate or avoid the effect of *Striga*. Kayeke *et al.* (2007) reported that the number of *Striga* seedlings was reduced by 100% in the 6th and 12th weeks with application of N at the rates of 25 or 50 kg/ha. Under good N fertilisation, the rice plant grew vigorously and thus an unfavourable environment was created for *Striga* germination and development. It enabled the host plant to avoid the effect of *Striga* probably by delayed haustorium attachment and by poor production of germination stimulants.

Nitrogen application without proper weed management, however, provides a favourable environment to enhance the vigour and competitive ability of weeds. Although improved nutrient status may improve crop competitiveness, some weeds become more successful than crops in utilizing the available excess nutrients (Raun and Johnson 1999). Other authors also report that nutrient absorption is faster and higher in weeds than in crop plants (Iqwal and Wright 1997, Ali *et al.* 2003, Blackshaw *et al.* 2005), suggesting that, in the presence of high weed density, crop growth may be suppressed by increased weed growth due to fertilisation. Therefore, manipulation of crop fertilisation is an important agronomic practice that can be used in weed management (Cathcart *et al.* 2004, Blackshaw *et al.* 2005, Mahajan and Timsina 2010). However, the effect of fertilisation, especially N, on weed interference with crop growth is not fully understood (Zoschke and Quadranti 2002), especially in the newly emerged direct-seeded rice systems.

Rice cultivars

Weed-competitive cultivars: The selection of cultivars plays a vital role in crop-weed competition because of the differential morphological characters of cultivars. The competitive ability of rice cultivars is associated with light interception-related traits (Chauhan 2012a, b). Variation in many crops, including rice, in terms of ability to compete with weeds, has been documented (Gibson and Fischer 2004, Zhao 2006). Therefore, the use of competitive cultivars may be an important IWM strategy (Mahajan *et al.* 2013). The rice plant characteristics associated with weed competitiveness are plant height, together with high canopy cover at the early stage of growth, high tiller density, droopy leaves, high biomass accumulation at the early crop stage, high leaf area index and high specific leaf area during vegetative growth, rapid canopy ground cover, and early vigour.

Generally, weed competitiveness in tall plants is higher but they tend to lodge and often have low yield potential. Semi-dwarf cultivars also have the same ability to compete with weeds. These cultivars have higher yield potential than tall cultivars. Therefore, intermediate height may be a more desirable trait for direct seeding in suppressing weeds (Fischer *et al.* 2001, Fukai 2002). Fischer and Gibson (2001) examined the competitive ability of rice cultivars with *Echinochloa colona*, *E. phyllopogon* (Stapf) Koss, *E. oryzoides* (Ard.) Fritsch, and *Brachiaria decumbens* Stapf. It was observed that, to achieve a high level of competitiveness, it is not necessary to develop highly erect cultivars (normally susceptible to lodging); modern high-yielding, semi-dwarf cultivars are also able to compete with weeds efficiently. Gibson *et al.* (2001) reported that *E. oryzoides* and *E. phyllopogon* infestation was effectively suppressed by competitive rice cultivars in California and such cultivars may thus help reduce herbicide dependency and decrease selective pressure for resistance. Early-maturing rice cultivars and rice hybrids also have a smothering effect on weeds due to their improved vigour and early canopy cover (Chauhan and Johnson 2010a). The effectiveness of competitive cultivars in weed suppression can be increased with agronomic manipulations. Changing the plant spacing pattern and the time of sowing, for example, might be helpful in providing supplemental weed control when herbicide inputs are reduced (Mahajan and Chauhan 2011).

There are two components of weed competitiveness: weed tolerance and weed-suppressive ability (Jannink *et al.* 2000, Zhao 2006). Weed tolerance is the crop's ability to maintain high yield despite weed competition, whereas weed-suppressive ability is the ability of the crop to suppress weed growth through competition. Since yield stability and the prevention of weed seed production and subsequent seed bank build up are desirable in crops growing in association with weeds, both components are important (Jordan 1993). Because the use of weed-competitive cultivars is a cost-effective method with minimum environmental pollution, more attention has been given by researchers to the use of competitive cultivars for weed management in direct-seeded rice systems (Chauhan 2012a, Mahajan and Chauhan 2011). However, in transplanted rice, there was less emphasis on weed-competitive traits in as much as seedling size advantage and puddling, followed by stagnation of water, provide effective weed control (Mahajan and Chauhan 2013). In dry-seeded rice crops, this type of environment is not available; therefore these crops face crop-weed competition at the early stages and suffer from heavy yield losses, if weeds were not controlled. In summary, the development of weed-competitive cultivars is a useful tool in managing weeds in rice. This could prove to be a cost-effective component of an overall IWM program in rice, especially in newly emerging direct-seeded systems. There is a strong need to evaluate rice traits responsible for weed-competitiveness in favourable as well as unfavourable environments in India.

Allelopathic cultivars: Crop allelopathy refers to the process of releasing chemical compounds, called allelochemicals, by living and intact roots of crop plants, which adversely affect the growth of other plant species (Belz 2007, Farooq *et al.* 2011). Allelopathy holds promise as a possible component in IWM. Some crops such as sorghum, pearl millet, and maize have the ability to reduce the weed population by allelopathy, thereby reducing weed biomass. For example, pearl millet shows residual weed suppression in the following crop. Therefore, these fodder crops can be grown before the rice crop in some cropping systems (Narwal 2000).

Rice plants release toxic allelochemicals (either as root exudates or sourced from decaying plant materials) that can suppress and kill weeds. *Heteranthera limosa* (Sw.) Willd. and other aquatic weeds are controlled by these allelochemicals. Dilday *et al.* (1991) reported that, out of 10,000 rice accessions tested in the United States, approximately 4% exhibited some allelopathic activities. Weed suppressiveness and allelopathy, however, may be confounded and they may coexist in the same cultivar. Progress has been significant in isolating rice allelochemicals (Rimando *et al.* 2001) and locating genes controlling allelopathic effects of rice (Jensen *et al.* 2001). Olofsdotter (2001) reported that both monocot and dicot weed species can be suppressed by allelopathic rice. The potential of some allelopathic rice cultivars to inhibit weed growth is up to 40% and this has been shown by planting *Echinochloa crusgalli* (L.) Beauv. together with various allelopathic rice varieties in the greenhouse (Mattice *et al.* 1999). Quantitative trait loci, which are associated with rice allelochemicals against *E. crus-galli*, have been identified (Jensen *et al.* 2001). This is an important step toward breeding allelopathic rice cultivars. Many studies suggest that farmers in rice-cultivating countries would be benefited by the success in breeding new rice cultivars with high weed-suppressing ability and this will play a vital role in sustaining agricultural production (Khanh *et al.* 2007, Jamil *et al.* 2011). However, more research is needed along this area.

Herbicides

Herbicides, being one of the most important tools for weed management, are a must in rice cultivation. Azmi *et al.* (2005) reported that unavailability and increasing cost of labour and the pressing need to raise yield and maintain profits on a progressively limited land base have forced farmers to seek substitutes for manual weed control. Herbicides proved to be one such alternative, as they provide superior weed control and are more energy- and labour-efficient than manual or mechanical methods of weed management. Farmers consider several factors, such as weed control spectrum, lack of crop injury (selectivity), cost, environmental impacts, *etc.* before selecting a weed management system using herbicides. Because cultural and mechanical weed control methods are time-consuming, cumbersome, and laborious, farmers rely more on herbicides. In addition, weeds tend to regenerate from roots or rhizomes that are left behind during manual or mechanical weeding, and these can be controlled only by the use of herbicides.

Direct seeding provides a favourable environment for the growth of sedges, such as *Cyperus difformis* L., *C. iria*, *C. rotundus*, and *Fimbristylis miliacea* (L.) Vahl (Azmi and Mashor 1995, Mortimer and Hill 1999, Gressel 2002). Some weed species, such as *E. colona* and *E. crus-galli*, escape from hand weeding as they are difficult to distinguish from rice at the early stage, thus reducing rice yield in the current season and producing weed seeds that can infest crops in subsequent seasons (Chauhan 2012a,b). Singh (2008) reported that these weeds severely affected rice growth, sometimes resulting in complete crop failure of the crop. It is important to include systematic herbicide in weed management options with this changing scenario of weed composition in dry-seeded rice systems.

Available are several pre-emergence herbicides that reportedly provide a fair degree of weed control when applied alone or supplemented with hand weeding (Chauhan 2012a, Mahajan and Chauhan 2011, Chauhan and Opeña 2013). These herbicides include butachlor, thiobencarb, pendimethalin, oxadiazon, oxyfluorfen, and nitrofen. However, with pre-emergence herbicides, some difficulties are encountered: application duration is limited and at the time of application, adequate soil moisture is required. The use of post-emergence herbicides was better option in these situations. Singh *et al.* (2006) suggested that both pre- and post-emergence herbicides can effectively suppress weeds in dry-seeded rice, if these are properly used.

In dry-seeded rice systems, the sequential spray of pre-emergence application of pendimethalin (1 kg/ha), followed by bispyribac-sodium (30 g/ha) at 15 days after sowing was found effective for weed management (Mahajan *et al.* 2009). In direct-seeded systems, especially in aerobic rice systems where a broad range of weeds is present, there is a need to use mixtures of different compatible herbicides (Chauhan 2012b). However, some weed species are not controlled effectively even after using herbicide mixtures. Moreover, some weed species [e.g., *Rottboellia cochinchinensis* (Lour.) W.D. Clayton] keep emerging throughout the crop season because of their high degree of seed dormancy. In such situations, other weed management strategies, such as high seeding rates or hand weeding should be integrated with herbicide use to control them.

In spite of the aforementioned advantages of herbicide use, injudicious and continuous use of a single herbicide over a long period of time may result in the development of resistant biotypes, shifts in weed flora, and negative effects on the succeeding crop and the environment (Chauhan *et al.* 2012a). Several issues, such as food safety, groundwater and atmospheric contamination, increased weed resistance to herbicides, destruction of beneficial organisms, and concerns about endangered species, have also been related with the indiscriminate use of herbicides. In India, due to the continuous use of butachlor and anilofos in rice, particularly in northwest India, the weed flora is shifting to sedges, such as *Cyperus* sp., *Scirpus* sp., *Fimbristylis* sp., and *Eleocaris* sp., and broadleaved weeds, such as *Caesulia auxillaris* Roxb. Such information suggests the need to rotate herbicides and integrate herbicide use with other weed management strategies.

Herbicide-resistant rice

The evolution of herbicide resistance is now a common and undesirable feature of most cropping systems; around 310 herbicide-resistant (HR) biotypes across 183 weed species have been reported (www.weedscience.org). Herbicide-resistant weed species have been reported in countries with high herbicide adoption rates, including the Philippines, Malaysia, Japan, Sri Lanka, Thailand, Korea, Colombia, Costa Rica, Italy, Portugal, Spain, France, Greece, North and Central America, and Australia (Rao 2011).

Biotechnology plays a vital role in the genetic engineering of plants for herbicide tolerance. In direct-seeded rice systems, the development of HR rice cultivars is essential as herbicides are continuously used in these systems. The development of a non-transgenic HR cultivar would be a classical, safe, and yet novel and effective means of weed management through the application of new-generation herbicides that are highly effective, non-toxic, and rapidly biodegradable (Mahajan and Chauhan 2013). In direct-seeded rice systems, HR rice can solve the problem of weeds, especially weedy and wild rice. The main benefits from introducing HR rice are as follows: (1) it solves the problem of managing weeds, specifically those associated with rice(weedy rice); (2) it provides an alternative to currently used herbicides, with new ones having better environmental profiles and greater efficiency; (3) it provides the solution to the problem of controlling weeds that have already developed resistance to current herbicides; and (4) it enables the adoption of resource conservation technologies by improving weed management options.

In direct-seeded systems, weed problems can be controlled dramatically with the use of HR rice and it will reduce the need to puddle soils and keep them continuously submerged (Malik *et al.* 2003). Three HR rice systems have been developed: imidazolinone-, glufosinate-, and glyphosate-resistant cultivars (Gealy *et al.* 2003). Glufosinate- and glyphosate-resistant rice cultivars were developed through transgenic technologies. Imidazolinone-resistant rice was developed through chemically induced seed mutagenesis and conventional breeding. Growing rice containing transgenes that impart resistance to post-emergence, nonselective herbicides such as glyphosate and glufosinate allows farmers use of no-till cultural practices, which may potentially reduce the total amount of herbicide released in the environment while controlling nearly the entire spectrum of weed species (Duke 1999). These properties make these herbicides safer and environmentally compatible. Therefore, HR rice offers a new way of conferring selectivity and enhancing crop safety and production (Chauhan *et al.* 2012b, James 2011). The use of non-transgenic HR rice cultivars developed by seed mutagenesis could be used as an effective weed management strategy in direct-seeded systems.

HR rice can be used to control weeds that proliferate in conservation (minimum) tillage systems, for example, perennial weeds, such as *Cyperus* spp. Some weeds (parasitic broomrapes and witchweeds) cannot be controlled by herbicides or there are no readily usable selective herbicides for their control. Such problems can be controlled by the use of HR rice cultivars. Therefore, HR rice should be part of IWM to improve our agricultural ecosystems.

Integrated weed management

Several weed management strategies have been discussed in the previous section. However, the use of any single strategy cannot provide effective, season-long, and sustainable weed control as different weeds vary in dormancy and growth habits. Effective and sustainable weed management involves the combined use of preventive, cultural, mechanical, chemical, and biological weed control techniques in an effective and economical way. Aside from this, herbicide use moves the agroecosystem to low species diversity with the possibility of new problem weeds occurring. There is a need for an ecological approach to control weeds instead of relying totally on chemical control methods. The use of clean crop seeds and seeders and field sanitation (irrigation canals and bunds free from weeds) can be included as a component of IWM for effective weed management.

The efficiency of applied herbicides and competitiveness against weeds can be improved by integration of improved agronomic practices, timeliness of operations, optimum fertilisation and water management, and incorporation of crop residues in the soil (Chauhan *et al.* 2012b). Brar and Walia (2001) revealed that high N rate (180 kg/ha), along with a plant density of 44 plants/m^2, provided superior weed control. A pre-emergence spray of pendimethalin at 1 kg/ha plus one hand weeding at 25 days after sowing in rice + green gram intercropping provided effective weed control and caused a significant improvement in yield in both crops (ICAR 2007). Aulakh and Mehra (2006) recorded effective control of *L. chinensis* with increased crop density from 22 to 44 plants/m^2, coupled with pyrazosulfuron at 0.015 kg/ha. Sharma and Singh (2008) reported that, among different weed control treatments, IWM including criss-cross sowing plus one hand weeding plus herbicide provided better results than those obtained from only one weed control method, that is, two hand weedings and no weeding. It is imperative that IWM strategies be evaluated, considering available resources and locations.

Decision-making tools

Decisions for weed control must be made on the basis of knowledge of the biology and phenology of weeds in the field in order to design rotation scheme where each crop naturally suppresses weeds in the subsequent crop. Herbicide use and application rate must be decided based on what weeds are expected in the field (for pre-emergence herbicides) or are present in the field (for post-emergence herbicides). Progressive farmers now understand that the more varied the control mechanisms used in a rotation, the longer the duration of each desired effect would be. Research is needed to develop effective decision-making tools for weed management in rice.

The trend of replacing transplanted rice by direct-seeded rice is increasing because of water and labour scarcity. This change removes the suppressive advantage of standing water. In these situations, problems of weed management may become more important because of the emergence of new weeds and consequently the change in composition of the weed flora. To achieve effective, long-term, and sustainable weed control, IWM strategies that target the prevention of weed invasion, recruitment, and reproduction need to be developed. These strategies may include stale seedbed practice, crop rotation, weed seed predation, use of crop residue as mulch, combination of optimal fertilizer schedule, summer ploughing, land preparation, modifying plant geometry, planting time, seeding rate, and use of weed-competitive cultivars. Knowledge of weed ecology and biology can prove to be very effective tools for IWM.

Future issues and strategies

Although herbicide-based weed management systems have been proven to be beneficial to the agricultural community in many ways, continuous use of herbicides creates an environment that encourages weed resistance to herbicides, weed population shifts, and off-site movement of herbicides. Therefore, rice producers face the challenge of using herbicides and other inputs in such a way that prevents adapted species from reaching troublesome proportions. Other major areas for future IWM research are further described.

Rice cultivars with high competitive ability: India needs rice cultivars that can form an early dense canopy, leaving less space and light for weeds. In this case, germination and subsequent growth of weed seedlings is reduced due to restricted light availability at the soil surface. Although the vigorous, early vegetative growth of a cultivar has been identified as the key characteristic for increasing crop competitiveness, there is still a need to learn about the characteristics that impart competitiveness, the component traits of vegetative vigour, possible trade-offs, and the relative importance of these in different cropping environments and management systems. Many scientists think that root competition has a vital role in the interaction between rice and weeds, which suggests the need to study root characteristics of rice cultivars in relation to weed competition, especially in nutrient- and water-stressed environments.

Herbicide-resistant rice cultivars: Herbicide-resistant rice cultivars are an effective option in the IWM program. However, there are risks of gene flow from HR rice to their wild relatives (e.g., weedy rice) and of HR biotypes of weeds. Risk management strategies must therefore be seriously considered. Equally critical is the development of stewardship guidelines for the use of HR rice cultivars.

Exploiting the potential of biocontrol: The bioherbicide approach of weed control is based on the ability of natural enemies to cause sufficient damage to weeds to reduce their adverse effects on crop yield. In some developed countries, including the USA, Canada, and the UK, several biocontrol agents have been successfully patented and commercialized, Collego Devive, Elgo, Casst, Anisomycin, Bialophos, and AAL toxin. Foliar application of conidial suspensions of *Curvularia tuberculata* Jain and *Cyperus oryzae* Bugnicourt is used to kill *C. difformis*, *C. iria*, and *F. miliacea*. However, there is very low abundance of these natural enemies at the particular time required to control the weed in a specific agricultural situation. This explains why their potential has not been harnessed to support weed management strategies. There is a need to explore the role of biocontrol in IWM systems in rice as it provides a cheaper and more effective eco-friendly means for addressing the prevalent weed problems in agriculture as well as in other ecosystems.

Herbicide application technologies: To improve the efficacy of applied herbicides and to reduce the cost of weed management, low-cost and highly efficient herbicide application technologies should be adopted. These may include spray equipment and nozzles, herbicide carriers, adjutants, and the like. Moreover, further research is needed on herbicide mixtures for delaying resistance, reducing the cost of weed management, and providing more options in the weed control spectrum. There is a need to develop decision tools for different IWM options, including the choice of herbicide use and establishment methods.

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