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Review article

Sustainable weed management in direct seeded rice culture: A review

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Abstract

The weed-rice ecological relationship is very complex and dynamic. Weed distribution and successions are always affected by management and environmental factors. Weed spectrum and degree of infestation in rice field are often determined by rice ecosystems and establishment methods. Due to high weed pressure, weed management in direct seeded rice has been a huge challenge for the researchers and farmers as well. Integrated weed management approach based on critical period of crop weed competition, involving different direct and indirect control measures, has been developed and widely adopted by farmers to overcome weed problem in direct seeded rice in a sustainable way. Although a number of sulfonylurea herbicides, diquat, paraquat, glyphosate quinclorac, MCPA have been found to be suitable alternatives to the old herbicides like 2,4-D, a less herbicide-dependent weed management strategy must be developed to reduce the risk of developing herbicide resistance in weeds. Weed control methods must be sought that are friendlier to the environment and substantially reduce the cost of weed management to farmers. Weed-competitive and allelopathic rice varieties, seed priming for increased weed competitiveness, higher seeding density should be considered as a management strategy. In order to devise a sustainable weed management strategy for direct seeded rice, detailed studies need to be done on the biology and ecology of notorious rice weeds, particularly *Oryza sativa* L. (weedy rice), *Echinochloa* spp., *Leptochloa chinensis* (L.) Nees, *Limnocharis flava* (L.) Buch. *Commelina benghalensis, Ipomoea aquatic, Cyperus iria* and *Fimbristylis miliacea*.

Keywords: Direct-seeding rice, rice weeds, weed management, weed resistance, weed shifting.

Abbreviations: MCPA- 2-methyl-4-chlorophenoxyacetic acid, CP-Crtitical period, DSR- Direct seeded rice.

Introduction

Rice (*Oryza sativa* L.) is the leading cereal of the world (Ashraf et al., 2006), and more than half of the human race depend on rice for their daily sustenance (Chauhan and Johnson, 2011). It is the primary source of income and employment for more than 100 million households in Asia and Africa (FAO, 2004a). World's rice demand is projected to increase by 25% from 2001 to 2025 to keep pace with population growth (Maclean et al., 2002), and therefore, meeting ever increasing rice demand in a sustainable way with shrinking natural resources is a great challenge. Weed is as old as agriculture, and from the very beginning farmers realized the interference of weed with crop productivity (Ghersa et al., 2000), which led to the co-evolution of agroecosystems and weed management (Ghersa et al., 1994). Weeds are the greatest yield-limiting constraint to rice (WARDA, 1996). The risk of yield loss from weeds in direct-seeded rice is greater than transplanted rice (Rao et al., 2007). Ramzan (2003) reported yield reduction up to 48, 53 and 74% in transplanted, direct seeded flooded and direct seeded aerobic rice, respectively. Aerobic rice is subject to much higher weed pressure with a broader weed spectrum than flood-irrigated rice (Balasubramanian and Hill, 2002). In tropic, average rice yield losses from weeds is 35% (Oerke and Dehne, 2004), while in direct seeded aerobic rice, yield penalty is as high as 50-91% (Rao et al., 2007). Sunil et al. (2010) as stated, season-long weed competition in direct seeded rice may cause yield reduction up to 80%. Weed problem is sought to be addressed from two basic points of view: weed control and weed management (Ghersa et al., 2000). Control approach only emphasizes on reduction of weed pressure and the management approach, by contrast, focuses on keeping weed infestation at a level compatible with environmentally and economically sustainable production (Radosevich et al., 1997). However, different weed control options are available for rice. Physical control are eco-friendly but tedious and labor-intensive (Roder and

Keobulapha, 1997). Other problems include delayed weeding due to unavailability of labor (Johnson, 1996), damage to the rice seedlings and mistaken removal of rice seedlings (Moody and Cordova, 1985). Biological control by using different bio-agents (Smith, 1992) and mycoherbicides (Thi et al., 1999) are practiced in irrigated lowland rice, but these may not be effective under aerobic soil conditions. Chemical control, on the contrary, is the most effective, economic and practical way of weed management (Marwat et al., 2006; Hussain et al., 2008; Anwar et al., 2012a). Many researchers working on weed management in direct seeded rice opined that herbicide may be considered to be a viable alternative/ supplement to hand weeding (Mahajan et al., 2009; Pacanoski and Glatkova, 2009; Chauhan and Johnson, 2011; Anwar et al., 2012a). In China, aerobic rice cultivation is completely dependent on herbicides (Wang et al., 2002). But, intensive use of herbicides may result in development of resistant weed biotypes (Heap, 2006), crop phytotoxicity (Begum et al., 2008a) and public health hazard (Phuong et al., 2005). The other option left is cultural weed control through adoption of different agronomic practices including tillage (Rao et al., 2007), competitive cultivar (Zhao et al., 2006a), seeding density (Guillermo et al., 2009; Anwar et al., 2011), water management (Hill et al., 2001; Rao et al., 2007), fertilizer management (Buhler, 2002; Blackshaw et al., 2005), seed invigoration (Harris et al., 2002; Ghiyasi et al., 2008; Anwar et al., 2012b), mulching (Singh et al., 2007a). Although those agronomic tools help to increase competitive ability of crop against weeds (Liebman et al., 2001), and at the same time are eco-friendly and economic, but may not provide acceptable level of weed control, especially under aerobic soil conditions, where weed pressure is very high. A single weed control approach may not be able to keep weeds below the threshold level of economic damage, and may results in shift in the weed flora, resistance development and environmental hazards. Therefore, adoption of diverse technology is essential for weed management because weed communities are highly responsive to management practices (Buhler et al., 1997). Besides, farmers are now becoming increasingly interested in more inclusive weed management strategy to reduce herbicide dependence (Blackshaw et al., 2005). Therefore, while addressing environmental concern, all the methods that are ecologically and economically justifiable should be integrated in a comprehensive way, known as integrated weed management (IWM). The IWM involves the selection, integration, and implementation of effective weed control means with due consideration of economics, environmental, and sociological consequences (Buchanan, 1976). Concern over long-term efficacy of herbicide dependent weed management has reinforced the need for IWM (Wyse, 1992). A substantial impact of IWM on rice farming has been documented by many researchers (Ho et al., 1990; Azmi and Baki, 2002; Sunil et al., 2010; Jayadeva et al., 2011). Our review aims to sum up earlier work on different sustainable weed management approaches in direct seeded rice.

Rice culture systems

Rice farming is practiced in several regions and under a wide range of agro-climatic conditions. Over the centuries, naturally occurring selection pressure like submergence, drought and biotic stresses has widely diversified the rice ecosystem (FAO, 2004b). Traditionally, rice has been cultivated in flooded conditions mostly for irrigation and effective weed control (Bouman, 2003). But due to shortage of farm labor along with physical and economic scarcity of water, flood irrigated rice has been replaced by different less labor dependent and water saving production systems. Khush, (1997) has categorized rice land ecosystems into four types. According to FAO (2007), irrigated, rainfed lowland, upland and deep water rice area have been estimated as 56.9, 30.9, 9.4 and 2.8% worldwide. In Asia, 58.6% of rice growing area is under irrigated, 32.1% under rainfed lowland, 6.7% under upland and 2.6% under deepwater cultivation system. Thus, among the four rice ecosystems, irrigated rice is the main system, in terms of both area coverage and production. Irrigated rice occupies more than 50% of world rice area supplying more than 75% of global rice demand (FAO, 2007). Unfortunately, this most important rice ecosystem is being increasingly endangered due to water scarcity threatening the world food security.

Weed problem in rice

Noxious weed community in rice field

Rice weed community appears as a complex ecological entity. Despite the drastic intervention required for land preparation, rice fields can be colonized by aquatic, semi-aquatic and terrestrial weeds (Fernando, 1980). About 350 species have been reported as weeds of rice, of which grasses are ranked as first followed by sedges and broadleaf weeds (Holm et al., 1977). Different rice ecosystems and cultural practices mostly determine dominant weed species/group, rice-weed competition and eventually, the weed control strategy (De Datta and Balatzar, 1996). Moody (1991) stated, abundance of different weed species is greatly influenced by land preparation, rice seeding method, water management and edaphic factors. A list of major weeds found in rice fields in Asia has been presented in Table 1 (IRRI, 2003).

Weed succession in rice ecosystems

Weed species replace one another through succession and vary considerably in composition and species dominance from one rice ecosystem to another (Kosaka et al., 2006; Juraimi et al., 2011). The repeated use of a particular herbicide greatly influences weed species dominance and composition. A noxious weed *E. crus-galli* was found to be dominant in plots repeatedly applied with 2,4-D amine (Azmi and Baki 2006). On the other hand broadleaved Monochoria *vaginalis* became dominant when propanil, benthiocarb, pretilachlor, quinclorac, fenoxaprop ethyl were used repeatedly. Weed succession and distribution pattern in rice fields are governed by spatio-temporal aspects, water management and cultural practices (Azmi and Baki, 2002). For example, in Malaysia, *Echinochloa cruss-galli* complex, *Leptochloa chinensis*, *Ischaemum rogosum* and *Paspalum vaginatum* were not so prevalent and dominant in the 1970's but became widespread in the 1990's (Azmi et al., 1993). The advent of direct seeding and insufficient water supply are perceived as factors responsible for the shift in weed species dominance and diversity in rice ecosystems. Moreover, changes from traditional transplanting to direct seeding culture (1980's onward) resulted in drastic changes of weed flora from easy- to difficult- to-control weeds like weedy rice (Azmi and Baki, 2002). Weed succession is also affected by seasonal changes. Chin, (2001) reported that in Vietnam, *Leptochloa chinensis* density in the summer-autumn season is higher than in winter-spring season. Extensive use of herbicides has been reported to promote shifts in the weed population (De Datta and Baltazar, 1996; Azmi and Baki, 2002). Examples from Malaysia and the Philippines showed

Table 1. Major weeds in rice fields in Asia.

Serial no.	Scientific name	Family
	Grass	
1.	*Echinochloa colona*	Poaceae
2.	*Echinichloa crus-galli*	Poaceae
3.	*Digitaria setigera*	Poaceae
4.	*Eleusine indica*	Poaceae
5.	*Echinochloa glabrescens*	Poaceae
6.	*Ischaemum rugosum*	Poaceae
7.	*Digitaria ciliaris*	Poaceae
8.	*Oryza sativa* (weedy rice)	Poaceae
9.	*Leptochloa chinensis*	Poaceae
10.	*Paspalum distichum*	Poaceae
	Sedge	
1.	*Cyperus iria*	Cyperaceae
2.	*Cyperus difformis*	Cyperaceae
3.	*Cyperus rotundus*	Cyperaceae
4.	*Fimbristylis miliacea*	Cyperaceae
	Broadleaf	
1.	*Monochoria vaginalis*	Pontederiaceae
2.	*Ipomoea aquatica*	Convolvulaceae
3.	*Sphenoclea zeylanica*	Sphenocleaceae
4.	*Ludwigia octovalvis*	Onagraceae
5.	*Ludwigia adscendens*	Onagraceae
6.	*Eclipta prostrata*	Asteraceae
7.	*Commelina benghalensis*	Commelinaceae

(Source: IRRI, 2003)

that continuous use of post emergence herbicides (such as 2, 4- D) to control broadleaf weeds and sedges has led to complete dominance of grassy weeds, while long term use of pretilachlor, propanil and molinate has suppressed grassy weeds at the cost of increased dominance of broadleaf weeds and sedges (Ho, 1994). Ecological shift of weeds from annuals to perennials have been occurred in Japan due to continuous use of herbicides (Shibayama, 1996).

Rice yield loss due to weeds

Weed is a major yield limiting factor in rice culture and yield losses are numerous. Globally, actual yield losses due to pests have been estimated ~ 40%, of which weeds caused the highest loss (32%) (Rao et al., 2007). Yield losses are largely dependent on the season, weed species, weed density, rice cultivars, growth rate, management practices and rice ecosystem. Azmi and Baki (1995) estimated that the yield loss caused by grasses (mainly *E. crus-galli*), broadleaved weeds and sedges was 41, 28 and 10%, respectively. Weedy rice cannot be harvested and it reduces yield because it matures earlier than cultivated rice, shatters and lodges easily (Azmi and Rezaul 2008). Furthermore, weedy rice at 35% infestation can cause total yield loss of about 60%, and under serious infestation, yield loss of 74% has been recorded in direct seeded rice (Azmi and Abdullah, 1998). In 2004, yield loss equivalent to RM90 million was estimated due to weedy rice infestation in direct seeded rice in Malaysia (Azmi and Rezaul 2008). However, water regimes in rice fields might determine the extent of yield loss due to weed completion. On average, rice yield loss due to weed ranges from 15 to 20%, but in severe cases the yield loss may exceed 50% (Hasanuzzaman et al., 2009) or even 100% (Mishra and Singh, 2007; Jayadeva et al., 2011). Kuan et al. (1990) reported that rice yield loss due to weeds ranged from 5 to 72%. Yield loss depends on several factors like weed species, degree of infestation, rice ecosystem, growing season, rice cultivar, management practices and so on. Weeds are estimated to cause rice yield losses of 35% in the tropics (Oerke and Dehne, 2004). In Bangladesh, rice yield losses due to weeds were estimated at 70-80% in *Au*s rice (early summer), 30-40% in transplanted *Aman* rice (late summer) and 22-36% in *Boro* rice (winter rice) (BRRI, 2006).

In Malaysia, the estimated average rice yield loss is between 10 to 35%, and yield losses by grasses, broad-leaved weeds and sedges are 41, 28 and 10%, respectively (Azmi, 1992). In China, rice yield reduction caused by weeds is 10-20% (Zhang, 2005), while in India, yield losses due to weeds ranged from 32-83% (Savary et al., 1997).

Yield reduction due to weeds is more critical in direct seeded rice than in transplanted rice (Karim et al., 2004). In dry seeded aerobic rice, relative yield loss caused by weeds is as high as 50-91% (Rao et al., 2007), while in transplanted rice, yield loss has been estimated to be only 13% (Azmi, 1992). Among the rice ecosystems, yield losses are the highest in aerobic rice (Balasubramanian and Hill, 2002). Season-long weed competition in direct seeded aerobic rice may cause yield reduction up to 80% (Sunil et al., 2010). In extreme cases, weed infestation may cause complete failure of aerobic rice (Jayadeva et al., 2011). Thus direct seeded aerobic rice is highly vulnerable to weeds compared with other rice ecosystems (Anwar et al., 2011).

Weed management options in rice

Weed prevention

Prevention, the most basic of all weed control methods, restricts introduction and spread of weeds (Buhler, 2002). Preventive measures include using weed-free seeds, maintaining clean fields, borders, and irrigation canals, and cleaning farm equipments (De Datta and Baltazar, 1996). The success of prevention is not warranted unless it is implemented through community actions by enforcement of laws and regulations. However, prevention has been de-emphasized in recent years, because of the availability of different effective and inexpensive control tools like herbicides. But preventive weed management program is still applicable against herbicide-resistant weed biotypes and difficult-to-control weeds (Buhler, 2002). Weeds can easily adapt to control practices because they have a huge capability to change their morphology (Buhler et al., 2000). Two most remarkable examples are the development of "common vetch" (*Vicia sativa* L.) seeds that mimicked lentil (*Lens culinaris* Moench) seeds in response to winnowing, and development of rice (*Oryza sativa* L.) like appearance by barnyardgrass (*Echinochloa cruss-galli* (L.) Beauv.) and weedy rice in response to manual-weeding (Gould, 1991). Rice seed contaminated with weeds is one of the major causes of weed infestation, especially in direct seeded rice. Mai et al. (1998) reported on average 466 weed seeds/kg rice seeds including 314 weedy rice seeds in Vietnam, which is forty-seven-fold higher than permitted national purity level. It is evident from the small grain crops that use of certified seed could significantly contribute to weed management (Cousens and Mortimer, 1995).

Physical control

Physical control is done manually or mechanically. Crops show varying sensitivity to disturbance, and monocotyledons like cereals are less sensitive than dicotyledons (Rasmussen and Accard, 1995); therefore, mechanical weeding is feasible in rice. Harrowing has been found effective in direct seeded rice, especially when the crop plants are larger than weeds to escape damage (Rasmussen and Accard, 1995). In Vietnam, 85% farmers practice hand weeding in direct seeded rice (Mai et al., 1998). Hand weeding is very easy and environment-friendly but tedious and highly labor intensive, and; thus. is not an economically viable option for the farmers. It has been estimated that 150 to 200-labor-day/ha are required to keep rice crop free of weeds (Trung et al., 1995; Roder, 2001) Moreover, morphological similarity between grassy weeds and rice seedlings makes hand weeding difficult at early stages of growth. The other problems with manual weeding include quite often weeding is delayed or even cancelled due to unavailability and/or high wages of labor (Johnson, 1996), and damage to the rice seedlings (Moody and Cordova, 1985).

Biological control

Biological weed control by using different herbivorous bio-agents like fish, tadpoles, shrimps ducks and pigs are used to control weeds in irrigated lowland rice in a few countries (Smith, 1992), but these cannot be used in aerobic rice, where there is no standing water. In Indonesia, rice-fish (common carp and grass carp) farming system provided good control of sedges like *Fimbristylis miliacea* and C*yperus iria* (Pane and Fagi, 1992). Weed control by mycoherbicides are now being studied to reduce herbicide dependency. The most promising fungi for biocontrol of barnyardgrass are *Exserohilum monocerus* and *Cocholiobolus lunatas*. *Setosphaeria sp. Cf. rostrata* were also found to effectively control *Leptochloa chinensis* without causing any damage to rice plant (Thi et al., 1999). However, scope of using mycoherbicides is also limited in controlling weeds in direct seeded aerobic rice because such fungal pathogen requires flooded conditions.

Chemical control

For the last few decades, herbicides have been tremendous contributor to agriculture. In large scale rice farming, herbicide based weed management has become the smartest and most viable option due to scarcity and high wages of labor (Singh et al., 2006; Anwar et al., 2012a). Despite some undesirable side-effects no viable alternative is presently available to shift the chemical dependence for weed management in rice. Many researchers working on weed management in direct seeded rice opined that herbicide may be considered to be a viable alternative/supplement to hand weeding (Kumar et al., 2008; Mahajan et al., 2009; Pacanoski and Glatkova, 2009; Chauhan and Johnson, 2011; Anwar et al., 2012a). Application of different pre-emergence herbicides including thiobencarb, pendimethalin, butachlor, oxadiazon and nitrofen has been found to control weed satisfactorily in direct seeded rice (Moorthy and Manna, 1993; Pellerin and Webster, 2004). Among the post emergence herbicides, ethoxysulfuron, cyhalofop-butyl, pritilachlor, chlorimuron, metsulfuron, bispyribac sodium and penoxsulam effectively controlled weeds in direct seeded rice (Mann et al., 2007; Singh et al., 2008; Mahajan et al., 2009; Juraimi et al., 2010). A list of commonly used herbicides in direct seeded rice field with their active ingredients, application time and target weed groups has been presented in Table 2.

The efficacy of herbicide is evident, but ever mounting civic concern over the real or perceived impact of herbicides on public health and environment (Phuong et al., 2005) along with the risk of developing resistant weed biotypes (Heap, 2006), phytotoxicity (Begum et al., 2008a) and declination in soil microbial population (Ayansina and Osa, 2006) has renewed the interest to limit the use of herbicides. Since the first resistant weed biotype (*Commelina diffusa*) was found in the USA in 1957, 304 resistant biotypes of 182 weed species have been found in 58 countries (Heap, 2006). In Malaysia, incidences of weed resistance to sulfonylurea, phenoxy and molinate compounds have been reported by many researchers (Watanabe et al., 1997; Baki and Azmi, 2001). Therefore, it is a must to use herbicide judiciously (Anwar et al., 2012a). Herbicides in mixture or year to year sequence of products having different modes of action might contribute to sustainable weed management (Valvarde et al., 2000). Application of wider spectrum of chemicals could help delay the development of herbicide resistance in weed community (De Datta and Baltazar, 1996; Anwar et al., 2012a).

Cultural control

Weeds persist by adapting to cultural practices, and every cultural practice influences the competitive ability of both the crop and weed resulting complex interactions (Swanton and Weise, 1991). Cultural approaches play significant role to determine the competitiveness of a crop with weeds for above ground and below ground resources and hence might influence weed management (O' Donovan et al., 2001; Grichar et al., 2004).

Table 2. Chemical control of weeds in rice system.

Application Time (Days after sowing)	Activity/Herbicide	Remarks
1-4	Pretilachor@0.5 kg a.i./ha (Sofit)	Pre-emergence herbicide, broad spectrum of weed control
5-7	Benthiocarb/Propanil @6 L product/ha (Satunil)	Early post emergence herbicide, broad spectrum of weed control under saturated conditions
4-7	Fentrazamide/Propanil @60-70 g product/10L water (Lecsplo)	Early post emergence herbicide, effective against mostly grasses and some sedges, broadleaved weeds
6-8	Pretilachor/Propanil@ 100 ml product/10Lwater (Lufit)	Early post emergence herbicide, broad spectrum of weed control
10-14	Bispyribac sodium 20-40 g a.i./ha (Niminee)	contact herbicide for early post emergence application, broad spectrum of weed control except *Leptocholoa chinensis*
14-21	Molinate (Ordram) + 2,4 -D@3.0 + 0.5 kg a.i./ha	Early post emergence herbicide for *Echinicholoa* spp., wide spectrum of weed control
10-14	Cyhalofop-butyl@100 g a. i. /ha (Clincher) + Sulfonyl urea herbicides (Bensulfuron, Pyrazosulfuron, Cinosulfuron or Oxysulfuron)	Effective against *E. crusgalli* and *L. chinensis* until four leaf stage. Tank mixed with Sulfonyl urea gives wide spectrum of weed control
6-10	Penoxsulam (Rainbow) + Cyhalofop-butyl (Clincher) @12.5 g a.i +62.5 g a.i./ha	Effective against *E. crusgalli*, *L. chinensis, C. iria, F. miliacea and C. difformis* under saturated condition
	Propanil (Striker) @2-4 kg a.i./ha followed by 2,4-D @ 1 kg a.i./ha	Early post emergence herbicide for grassy weeds, effective under dry and saturated conditions
	Quinclorac (Facet) + Bensulfuron (Londax) @0.25+ 0.03 kg a.i./ha	Quinclorac is effective against *Echinocholoa* spp. Bensulfuron combination gives wider spectrum of weed control
	Bensulfuron-methyl (Londax) @0.3-.05 kg a.i./ha	Effective against almost all annual and perennial broadleabed weeds and some sedges during pre-emergence and early post emergedge under wet/standing water conditions
	Molinate (Ordram) + Bensulfuron (Londax) @ 3.0 + 0.03 kg a.i./ha	Wide spectrum of weed control under standing water conditions

(Source: Azmi, 2012)

Weed-competitive cultivar

Rice cultivar with strong weed competitiveness is deemed to be a low-cost safe tool for weed management (Gibson and Fischer, 2004). Extensive variation in weed competitiveness among rice genotypes have been documented (Fischer et al., 2001; Caton et al., 2003; Haefele et al., 2004; Zhao et al., 2006a, b). Differences in weed suppressive ability among rice genotypes have been recorded up to 75% (Garrity et al., 1992). Competitive rice cultivar effectively suppressed the infestation of *Echinochloa spp.* and helped reduce herbicide dependency (Gibson et al., 2001). Allelopathic rice cultivars can contribute to weed suppression (Olofsdotter, 2001).

Many potential allelopathic rice cultivars have been reported to inhibit weed growth significantly (Lin et al., 2000). Weed competitiveness of rice is often associated with traits like early plant height (Caton et al., 2003), tillering ability (Fischer et al., 1997), early crop biomass (Ni et al., 2000), early vigor (Zhao et al., 2006a), leaf area index (Dingkuhn et al., 1999), specific leaf area (Audebert et al., 1999), root characteristics (Fofana and Rauber, 2000) and allelopathy (Dilday et al., 1994). In general, cultivars with high tillering ability, high early growth rate, high leaf area index and specific leaf area, long leaves and droopy plant type are more weed suppressive, but at the same time conflicting findings have also been reported.

Appropriate crop establishment

The choice of appropriate crop establishment technique is an important step towards good agricultural practice in rice culture. Water seeding appears to provide a valuable alternative to the usual wet seeding culture and this has led to improvement of weed control besides providing good crop establishment (Azmi and Johnson, 2006). The presence of standing water (5-10 cm water depth at seeding time) during rice establishment significantly reduced grassy weeds particularly weedy rice and some sedges. The choice of crop establishment method should be used based on weedy rice population in the previous season (Azmi et al., 2004; Azmi and Muhammad 2006). Under the water seeding system grassy weeds and some sedges can be suppressed by standing water, resulting in reduced herbicide application and less environmental pollution. Furthermore, damages caused by rats and birds on pre-germinated seeds can be prevented. This method is suitable for large scale planting where irrigation water is more effectively controlled.

Seeding density

Crop seeding density can be viewed as a possible strategy to decrease weed pressure and reduce herbicide dependence (Kirkland et al., 2000; Melander et al., 2005; Anwar et al., 2011). Seeding density of a crop determines solar radiation interception, canopy coverage and biomass accumulation which have cumulative effect on its weed suppressive ability. Higher seeding rate develops canopy rapidly and consequently suppresses weeds more effectively, and in contrast, lower seeding rate results in sparse stands and encourage weed growth (Guillermo et al., 2009). Higher seeding rate favors rice more than weeds and increases yield under weedy conditions (Phuong et al., 2005). It is evident that *Echinochloa cruss-galli* and *Leptochloa chinensis* densities were reduced at higher rice seeding rates of 200 kg/ha and 100 kg/ha, respectively (Hiraoka et al., 1998). Higher seeding rate of rice, especially under aerobic soil conditions has been advocated not only for weed control but also for avoiding higher risk of poor seedling establishment associated with lower seeding rates (Guyer and Quadranti, 1985; Anwar et al., 2011). Under aerobic soil conditions, higher seeding rate of 500 seeds/m^2 reduced weed growth and increased crop yield compared to a lower seeding rate of 300 seeds/m^2 (Zhao et al. 2007). Anwar et al. (2011) opined that direct seeding with 300 rice seeds/m^2 successfully suppressed weeds under aerobic soil conditions. Influence of rice seeding method on weed growth, and row seeding in east-west direction resulted in lower yield loss under weedy condition (Phuong et al., 2005). Boyd et al. (2009) also reported that planting uniformity shows a positive impact on the competitive ability of a crop. Combination of increased crop density and more uniform plating for better weed suppression has been emphasized by many researchers (Weiner et al., 2001; Boyd et al., 2009), who concluded that row seeding allows for weeds to utilize the light between the rows, while evenly distributed crops compete better with weeds.

In contrast, Castin and Moody (1989) did not suggest higher seeding rates for rice when herbicides are available for effective weed control. As stated in several studies higher seed rate may bring about problems of mutual shading and intra-specific competition for resources, and may cause problems like lodging, insect and disease infestation and rat damage (Castin and Moody, 1989; Bond et al., 2005).

Seed quality

Direct seeding method is expected to continue in the future because of scarcity in labor supply and escalation in overall production cost. As a result, the amount of seeds required per hectare of land is increased by several folds. Certified seeds produced through transplanting method, which is the recommended practice for seed production. Rice seeds contaminated with weedy rice seeds are important contributory factors to weedy rice infestation in the rice fields (Mai et al., 1998). The spread of weedy rice to uninfected fields has occurred in Europe and Southeast Asian countries by the distribution of rice seeds contaminated with weedy rice seeds to the farmers (Ferrero. 2003). Noldin (2000) stated that in Brazil, planting fields free of weedy rice with rice seeds contaminated by only 2 seeds/kg may result in a soil infestation of 10 kg weedy rice seeds/ha after only three seasons.

Seed priming

Beneficial effects of seed priming include increased germination rate, synchronized germination and faster emergence of seedlings (Basra et al., 2005; Farooq et al., 2007; Anwar et al., 2012b). The traits closely associated with weed competitiveness of rice include early height growth rate, early crop biomass (Ni et al., 2000) and early vigor (Zhao et al., 2006b), which can be obtained through higher and faster germination of primed seeds. Therefore, seed priming is supposed to play a significant role in weed suppression. Besides, poor germination under aerobic soil condition (Balasubramanian and Hill, 2002) results in sparse and patchy stands, which encourages weed growth (Guillermo et al., 2009) and reduces the competitive ability of rice against weeds (Boyd et al., 2009). Higher and synchronized emergence of primed seeds can ensure vigorous crop stand with rapid canopy development giving rice plants a preliminary advantage over weeds (Anwar et al., 2012b). Due to seed priming, rice seedlings could compete more successfully with weeds (Harris et al., 2002). A robust seedling stand obtained from primed seeds enhanced rice competitiveness against weeds and improved tolerance to environmental stress (Clark et al., 2001; Du and Tuong, 2002; Ghiyasi et al. 2008). Anwar et al. (2012b) observed a positive influence of seed priming on the weed competitiveness of rice variety AERON1 under direct seeded condition. On the other hand, no significant effect of seed priming on weed suppression in aerobic rice was observed by Zhao et al. (2007).

Crop rotation

Crop rotation is often considered to be a vital tool of weed management (Liebman and Gallandt, 1997). By its nature, crop rotation disrupts regeneration niches of weed species and prevents the buildup of adapted weed species (Buhler, 2002). Weeds respond to crop rotation, which affects weed demography and subsequent population dynamics (Liebman and Gallandt, 1997). Rotating rice with mungbean was effective for weedy rice control because volunteer rice seedlings failed to survive in mungbean (Watanabe et al., 1998). Rotation combinations of 25 crops reduced weed density compared to monoculture (Liebman and Ohno, 1998). Inclusion of forage crop, in crop rotation offers diverse mechanisms to suppress weeds through competition, grazing and mowing (Gill and Holmes, 1997). Moreover, planting competitive/aggressive cultivar/crop in rotation could help suppress weeds (Swanton and Weise, 1991).

Intercrop and cover crop

Intercropping, simultaneous culture of two or more crops on the same land produces greater yield as compared to monoculture of any of the component crops (Barker and Francis, 1986). Crop weed interaction takes a different form with intercropping than in monocropping (Buhler, 2002). Since resource accessibility is the key to weed occurrence, intercropping provides a unique opportunity for weed management through increased resource utilization (Buhler, 2002). Intercropping can reduce both weed density and biomass to a great extent due to decreased light transmission through the canopy (Baumann et al., 2000). Intercropping with *Sesbania* for 30 days were found effective in controlling weeds in direct seeded rice (Singh et al., 2007b).

Cover crop may appear as a standing crop or as stubble after crop harvest (Swanton and Weise, 1991). Cover crops are included in the cropping system to conserve soil fertility, moisture and to activate soil nutrient dynamics (Melander et al., 2005). Another objective is to replace unmanageable weed population with a manageable crop (Teasdale, 1998). Moreover, incorporation of cover crop into the soil may add allelochemicals to the soil to prevent germination and establishment of weeds (Buhler, 2002). A 25% reduction in weed seed bank density and 22% reduction in weed biomass 7 years after introduction of rye cover crop in corn were observed (Moonen and Barberi, 2004). Although promising uses of cover crops, especially allelopathic cover crops in rice ecosystem is still in its infancy.

Tillage

The importance of thorough land preparation to minimize weed pressure is well recognized. Tillage can affect weed community through the changes in weed seed distribution in the soil. Primary tillage can reduce annual weed populations, especially when planting is delayed to allow weed seeds to emerge before final tillage (Buhler and Gunsolus, 1996). While shallow tillage before crop emergence and post plant tillage after crop establishment help remove annual weeds and inhibit the growth of perennial weeds (Buhler, 2002). On the other hand, zero tillage favors weed infestation (Hach, 1999). Conservation tillage has been criticized particularly in relation to lower yields and perennial weed problems which results in an increase in herbicide application (Koskinen and McWhorter, 1986). In contrast, presence of crop residue in conventional tillage increases weed suppression and tillage in darkness can delay and reduce the emergence of certain weed species (Jensen, 1995).

Water management

Water is the "best herbicide". Every weed species has an optimum soil moisture level, below or above which its growth is hampered, and therefore time, depth and duration of flooding could play an important role in suppressing weeds. The importance of water management for controlling weeds in rice is well-known but water management is yet to achieve its full potential (Hill et al., 2001). In wet-seeded rice, early flooding at 4 DAS can reduce weed infestation, particularly barnyardgrass densities (Hach, 1999). Water depth influence on the efficacy of herbicide has been reported by Hach et al. (1997) who found that increased water depth enhanced the efficiency of early post emergence application of pyrazosulfuron-ethyl but not butachlor and thiobencarb.

Fertilizer management

Manipulation of crop fertilization is a promising approach to reduce weed infestation (Di Tomaso, 1995), and may contribute to long-term weed management (Blackshaw et al., 2004). Fertilizer management should be aimed at maximizing nutrient uptake by crop and minimizing nutrient availability to weeds (Di Tomaso, 1995). Since most of the annual weeds germinate from the top few millimeters of the soil, fertilizers broadcast on the top soil would give the weeds equal chance to utilize nutrient together with the crop (Melander et al., 2005). Nitrogen fertilizer has been reported to break weed seed dormancy and influence weed densities. Many weed species consume high amount of N and; thus, reduces N availability for crops. Several researchers observed that weeds became less competitive when N was applied at early growth stages of crop compared with later application, and weeds are found to be more responsive to added N than that of crop (Blackshaw et al., 2000). However, review on fertilizer management and crop-weed interaction has generated conflicting conclusion (Dhima and Eleftherohorinos, 2001; Blackshaw et al., 2004). It is not always recognized that fertilizer management can affect crop-weed competitiveness, and results may be crop and weed specific (Blackshaw et al., 2004). Fertilizer management can definitely alter the competitive balance between crops and weeds, but methods to incorporate it into integrated weed management are yet to be developed (Buhler, 2002).

Increased crop competitiveness

Weed competitiveness (WC) of a crop comprises two components: weed suppressive ability (WSA) - the ability to lessen weed growth through competition, and weed tolerance (WT) - the capability of maintaining potential yields in the presence of weeds (Jannink et al., 2000). The WSA should be emphasized more than WT for long term weed management. However, the roles of WSA, WT and yield potential to influence yield under weedy conditions are generally ambiguous (Zhao et al., 2006b). Strong WSA will not guarantee high yield of a low yielding variety under weedy conditions (Zhao et al., 2006c). Therefore, high yield potential and strong WSA need to be pooled to ensure economically acceptable yields. Nonetheless, tradeoff between yield potential and WC was reported in the past, recent findings confirm the compatibility between them (Gibson et al., 2001; Zhao et al., 2006b). Crop and weeds compete for below ground resources like water and nutrients, and above ground resources like light. Enhancing the ability of crop to compete with weeds is a smart tool of weed management (Pester et al., 1999), which can be accomplished by providing most excellent environment for crop growth and adopting cultural practices that reduce weed pressure (Buhler, 2002). Narrow spacing, higher seeding rate, proper fertilizer and water management are the practices capable of shifting competitive equilibrium in favor of crop over weeds (Buhler and Gunsolus, 1996). Enhanced crop competitiveness can also reduce the reproductive capacity of weeds (Buhler, 2002). Developing competitive cultivar to reduce weed pressure as well as increase yield has been a major research thrust (Kropff and Van Laar, 1993), and there are good examples of farmers using competitive cultivar alone or integrating with other weed control tactics like precise herbicide application (Moss, 1995).

Allelopathy approach

Allelopathy, the direct or indirect effect of one particular plant on another through the production of chemical compounds that are released in to the root environment, may provide an alternative weed control strategy. This approach may lead to less dependence on the use of herbicides in rice production. Rice plants with allelopathic effects on weeds can lessen production costs because the need for herbicide application and/or hand weeding is reduced. Thus, using rice cultivars having allelopathic properties could benefit farmers, consumers as well as the environment. Allelopathic plants in a crop rotation or as part of an intercropping system may provide a non-herbicide mechanism for weed control.

Laboratory and field experiments have shown that rice allelopathy can suppress both monocot and dicot weeds (Olofsdotter et al., 2001, Hassan, et al, 1998; Dilday et al., 1994). Several accessions of rice germplasm in the field were found to decrease the growth of ducksalad (Heteranthera limosa (Sw.) wild.) (Dilday et al. 1994), which is a major weed in the southern United States and caused a 21% reduction in the yields of direct-seeded rice. In field experiments, some rice cultivars produced a weed free radius of 10 to 15 cm around an individual plant while others were densely surrounded by ducksalad. Rice cultivars with allelopathic effects to barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] have been screened by assessment in the field and laboratory conditions. Ebana et al. (2001) studied the allelopathic effect of rice on lettuce (*Lactuca sativa* L.) and ducksalad with water-soluble extracts. Extracts from the leaves of rice seedlings at the six-leaf stage inhibited the growth of ducksalad and lettuce, and a close relationship existed between the inhibitory effect and the two test plants

Integrated weed management

Until 1940s, weed control was accomplished through physical, cultural and biological means. Since the introduction of herbicides in late 1940s, their amazing performance led to the belief that herbicide would solve the weed problem forever. But, after over 50 years of extensive use of herbicides, it is now clear that sole reliance on herbicide is a losing strategy. Herbicides are often blamed for environmental pollution (Spliid and Koeppen, 1998) and impoverishment of the natural flora and fauna and therefore, over reliance on herbicides may bring unwarranted environmental decay and shift in weed species dominance (Azmi and Baki, 2002). This demands resurgence of physical, cultural and biological weed management, combined with judicious application of herbicides- known as integrated weed management (IWM). The IWM was first introduced and defined by Buchanan (1976) as “the application of many kinds of technology in a mutually supportive manner. It involves the selection, integration, and implementation of effective weed control means with due consideration of economics, environmental, and sociological consequences. The IWM better utilizes resources and offers a wider range of management options (Buhler et al., 2000). Integration of diverse technologies is essential for weed management because weed communities are highly responsive to management practices and environmental conditions (Buhler et al., 1997). A theoretical model of IWM has been suggested by Noda, (1977).

None of the control measures in single can provide acceptable levels of weed control, and therefore, if various components are integrated in a logical sequence, considerable advances in weed management can be accomplished (Swanton and Weise, 1991). Various agronomic tools have been evaluated for their potentiality in managing weeds (Liebman et al., 2001). But, all the agronomic tools may not work perfectly with every crop or weed species (Blackshaw et al., 2005). Integration of higher seed rate and spring-applied fertilizer in conjunction with limited herbicide use managed weeds efficiently and maintained high yields (Blackshaw et al., 2005). Adoption of IWM approach for sustainable rice production has been advocated by many researchers (Azmi and Baki, 2002; Sunil et al., 2010; Jayadeva et al., 2011).

Critical period for weed control

The critical period for weed control (CPWC) is defined as the time period in the crop growth cycle, during which weeds must be controlled to prevent unacceptable yield loss (Isik et al., 2006; Doğan et al., 2004). It is the time interval between two components of weed interference namely, the critical weed interference and critical weed-free periods. Critical weed interference period is the maximum length of time during which weeds emerging soon after crop planting can coexist with the crop without causing unacceptable yield loss. On the contrary, the critical weed-free period is the minimum length of time required for the crop to be maintained weed-free before yield loss caused by late-emerging weeds is no longer a concern (Isik et al., 2006). The timing of herbicide application based on CPWC is a key concept in an integrated weed management (IWM) program (Isik et al., 2006; Hall et al., 1992; Anwar et al., 2012c). In theory, weed competition before and after the CPWC will not reduce crop yield below acceptable levels; and therefore, negligible (Williams II and Martin, 2006). Begum et al. (2008b) studied the critical period of specific crop-weed interference in a step to develop effective and sustainable weed management. They found that the critical period to control *Fimbristylis miliacea* in direct-seeded MR220 rice falls between 14 and 28 days after sowing at 5 % yield loss. Increasing duration of *F. miliacea* reduced grain yield, rice straw biomass and number of productive tillers along with increased weed dry matter.

Anwar et al. (2012c), in their study on rice variety AERON 1, determined critical period of weed control as 7-49 days in off season and 7-53 days in main season to achieve 95% of weed-free yield, and 23-40 days in off season and 21-43 days in main season to achieve 90% of weed-free yield under direct seeded aerobic condition. Najib et al. (2006) studied the critical period of weed competition in direct-seeded MR 220 rice under minimal water condition. They observed that the critical periods of competition in a saturated condition at 5 and 10% yield losses were at 2 to 71 DAS and 5 to 52 DAS, respectively. Meanwhile, the critical periods in a flooded condition were predicted at 15 to 73 DAS and 25 to 51 DAS at 5 and 10% yield losses, respectively. A longer weed control period was suggested for saturated rice field condition than the flooded due to different pattern of weed growth with respect to dominant weed species that exist in varied water regimes.

The critical periods of weed competition in direct seeded rice under saturated and flooded conditions were studied by Juraimi et al. (2009a, b) in off-season 2005 and main season 2005/2006. Based on the 5 % level of yield loss, they reported that the critical period in the off-season was between 2 and 71 days after sowing (DAS) in saturated condition and 15 to 73 DAS in flooded condition. Meanwhile, in the main season, the critical period was between 0 and 72 DAS in the saturated condition and 2 to 98 DAS in the flooded condition. Azmi et al. (2007) reported that based on the predicted Gompetz and Logistic response curves, the CP for weedy rice control based on 5% yield loss was estimated from 16 to 53 DAS.

Conclusion

Weed management is a fundamental practice, failure of which may result in severe losses in terms of yield and economic return. Weed is a serious problem in direct seeded rice and weed management has been a huge challenge for the weed researchers and rice farmers as well. Weeds are dynamic in nature and a shift in their abundance and dominance is likely with the changes in management practices. Herbicide is the smartest and most economic tool to fight against weeds. But recurrent use of one herbicide for a long time may result in development of herbicide resistant weed biotypes. Integrated approaches are suggested for sustainable weed control in direct seeded rice, such as the use of clean certified seeds, higher seeding densities, cultivation of competitive variety, seed invigoration, stale seed bed preparation, crop rotation, water and fertilizer management along with rotation of herbicides with different mode of actions followed by manual weeding and rouging after mid stage of rice growth. Moreover, any weed management approach should be aimed at controlling weeds only during critical period of weed competition for a more cost-effective and eco-friendly weed management. A long term changes in weed flora, herbicide efficacy, resistance, residual toxicity and environmental implications of continuous use of herbicides should be properly addressed for sustainability of direct seeded rice culture.

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