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Sustainable weed management practices in direct seeded rice a review

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Abstract

The weed-rice ecological relationship 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, *Limncharis flava* (L.) Buch. *Commelina benghalensis*, *Ipomoea aquatic*, *Cyperus iria* and *Fimbristylis miliacea*.

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

Introduction

Rice (*Oryza sativa* L.) is the leading cereal of the world (Ashraf *et al.*, 2006) [5], and more than half of the human race depend on rice for their daily sustenance (Chauhan and Johnson, 2011) [45]. It is the primary source of income and employment for more than 100 million households in Asia and Africa (FAO, 2004a) [57]. 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) [67], which led to the co-evolution of agro-ecosystems and weed management (Ghersa *et al.*, 1994) [68]. Weeds are the greatest yield-limiting constraint to rice (WARDA, 1996) [161]. The risk of yield loss from weeds in direct- seeded rice is greater than transplanted rice (Rao *et al.*, 2007) [120]. Ramzan (2003) [141] 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) [22]. In tropic, average rice yield losses from weeds is 35% (Oerke and Dehne, 2004) [132], while in direct seeded aerobic rice, yield penalty is as high as 50-91% (Rao *et al.*, 2007) [120]. Sunil *et al.* (2010) [154] 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. 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. However, different weed control options are available for rice. Physical control are eco-friendly but tedious and labor-intensive (Roder and Keobulapha, 1997) [145]. Other problems include delayed weeding due to unavailability of labor damage to the rice seedlings and mistaken removal of rice seedlings. Biological control by using different bio-agents (Smith, 1992) [152] and mycoherbicides (Thi *et al.*, 1999) [157] are practiced in irrigated lowland

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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) ^[119, 91, 2].

A single weed control approach may not be able to keep weeds below the threshold level of economic damage, and may result 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) ^[40]. Besides, farmers are now becoming increasingly interested in more inclusive weed management strategy to reduce herbicide dependence (Blackshaw *et al.*, 2005) ^[28]. 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).

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) ^[105, 1]. 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) ^[16]. On the other hand broadleaved *Monochoria vaginalis* became dominant when propanil, benthocarb, 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) ^[13]. For example, in Malaysia, *Echinochloa crus-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) ^[9]. 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) ^[13]. Weed succession is also affected by seasonal changes. Chin, (2001) ^[46] 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) ^[49, 13]. Examples from Malaysia and the Philippines showed 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.

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) ^[120]. 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) ^[10] 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) ^[19]. 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) ^[11]. 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) ^[19]. 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) ^[83] or even 100% (Mishra and Singh, 2007; Jayadeva *et al.*, 2011) ^[121, 95]. 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) ^[132]. In Bangladesh, rice yield losses due to weeds were estimated at 70-80% in Aus rice (early summer), 30-40% in transplanted *Aman* rice (late summer) and 22-36% in *Boro* rice (winter rice) (BRRI, 2006) ^[36].

Yield reduction due to weeds is more critical in direct seeded rice than in transplanted rice (Karim *et al.*, 2004) ^[102]. In dry seeded aerobic rice, relative yield loss caused by weeds is as high as 50-91% (Rao *et al.*, 2007) ^[120], while in transplanted rice, yield loss has been estimated to be only 13% (Azmi, 1992) ^[8].

Weed management options in rice

Weed prevention

Prevention, the most basic of all weed control methods, restricts introduction and spread of weeds (Buhler, 2002) ^[38]. Preventive measures include using weed-free seeds, maintaining clean fields, borders, and irrigation canals, and cleaning farm equipments (De Datta and Baltazar, 1996) ^[49]. 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) ^[38]. Weeds can easily adapt to control practices because they have a huge capability to change their morphology (Buhler *et al.*, 2000) ^[41]. 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 crus-galli* (L.) Beauv.) and weedy rice in response to manual-weeding (Gould, 1991) ^[73]. Rice seed contaminated with weeds is one of the major causes of weed infestation, especially in direct seeded rice. Mai *et al.* (1998) ^[117] 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.

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) ^[143]; 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) ^[143]. In Vietnam, 85% farmers practice hand weeding in direct seeded rice (Mai *et al.* 1998) ^[117]. 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) ^[158, 144]. 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 and damage to the rice seedlings.

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) ^[152], 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 *Cyperus iria* (Pane and Fagi, 1992) ^[136]. Weed control by mycoherbicides are now being studied to reduce herbicide dependency. The most promising fungi for biocontrol of barnyardgrass are *Exserohilum monoceris* and *Cochliobolus lunatas*. *Setosphaeria* sp. *Cf. rostrata* were also found to effectively control *Leptochloa chinensis* without causing any damage to rice plant (Thi *et al.*, 1999) ^[157]. 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) ^[149, 2]. 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) ^[109, 116, 135, 45, 2]. 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) ^[125, 137]. Among the post emergence herbicides, ethoxysulfuron, cyhalofop-butyl, prtilachlor, 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) ^[118, 151, 116, 100]. 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 1.

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) ^[155]. 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) ^[131, 74].

Table 1: Chemical control of weeds in rice system.

Application Time (Days after sowing)	Activity/Herbicide	Remarks
1-4	Pretilachlor@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	Pretilachlor/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 <i>Leptochloa chinensis</i>
14-21	Molinate (Ordram) + 2,4 -D@3.0 + 0.5 kg a.i./ha	Early post emergence herbicide for <i>Echinicholola</i> 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 <i>E. crusgalli</i> and <i>L. chinensis</i> 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 Propanil (Striker) @2-4 kg a.i./ha followed by 2,4-D @ 1 kg a.i./ha Quinclorac (Facet) + Bensulfuron (Londax) @0.25+ 0.03 kg a.i./ha Bensulfuron-methyl (Londax) @0.3-.05 kg a.i./ha Molinate (Ordram) + Bensulfuron (Londax) @ 3.0 + 0.03 kg a.i./ha	Effective against <i>E. crusgalli</i> , <i>L. chinensis</i> , <i>C. iria</i> , <i>F. miliacea</i> and <i>C. difformis</i> under saturated condition Early post emergence herbicide for grassy weeds, effective under dry and saturated conditions Quinclorac is effective against <i>Echinochloa</i> spp. Bensulfuron combination gives wider spectrum of weed control Effective against almost all annual and perennial broadleaved weeds and some sedges during pre-emergence and early post emergence under wet/standing water conditions. Wide spectrum of weed control under standing water conditions.
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(Source: Azmi, 2012) ^[15]

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) ^[71]. 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) ^[64, 44, 80, 168, 169]. Differences in weed suppressive ability among rice genotypes have been recorded up to 75% (Garrity *et al.*, 1992) ^[66]. Competitive rice cultivar effectively suppressed the infestation of *Echinochloa* spp. and helped reduce herbicide dependency (Gibson *et al.*, 2001) ^[70]. Allelopathic rice cultivars can contribute to weed suppression (Olofsdotter, 2001) ^[134].

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) ^[14]. 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) ^[20, 17]. 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) ^[104, 120, 1]. 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) ^[76]. Higher seeding rate favors rice more than weeds and increases yield under weedy conditions (Phuong *et al.*, 2005) ^[139]. It is evident that *Echinochloa crus-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) ^[87]. 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) ^[77, 1]. Under aerobic soil conditions, higher seeding rate of 500 seeds/m² reduced weed growth and increased crop yield compared to a lower seeding rate of 300 seeds/m² (Zhao *et al.* 2007) ^[171]. Anwar *et al.* (2011) ^[1] opined that direct seeding with 300 rice seeds/m² 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) ^[139]. Boyd *et al.* (2009) ^[35] also reported that planting uniformity shows a positive impact on the competitive ability of a crop.

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) ^[117]. 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) ^[62]. Noldin (2000) ^[130] 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) ^[24, 60, 3]. The traits closely associated with weed competitiveness of rice include early height growth rate, early crop biomass (Ni *et al.*, 2000) ^[128] and early vigor (Zhao *et al.*, 2006b) ^[169], 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) ^[22] results in sparse and patchy stands, which encourages weed growth (Guillermo *et al.*, 2009) ^[76] and

reduces the competitive ability of rice against weeds (Boyd *et al.*, 2009) [35]. 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) [3]. Due to seed priming, rice seedlings could compete more successfully with weeds (Harris *et al.*, 2002) [82].

Crop rotation

Crop rotation is often considered to be a vital tool of weed management (Liebman and Gallandt, 1997) [110]. By its nature, crop rotation disrupts regeneration niches of weed species and prevents the buildup of adapted weed species (Buhler, 2002) [38]. Weeds respond to crop rotation, which affects weed demography and subsequent population dynamics (Liebman and Gallandt, 1997) [110]. Rotating rice with mungbean was effective for weedy rice control because volunteer rice seedlings failed to survive in mungbean (Watanabe *et al.*, 1998) [163]. Rotation combinations of 25 crops reduced weed density compared to monoculture inclusion of forage crop, in crop rotation offers diverse mechanisms to suppress weeds through competition, grazing and mowing moreover, planting competitive/aggressive cultivar/crop in rotation could help suppress weeds.

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) [23]. Crop weed interaction takes a different form with intercropping than in monocropping (Buhler, 2002) [38]. Since resource accessibility is the key to weed occurrence, intercropping provides a unique opportunity for weed management through increased resource utilization (Buhler, 2002) [38]. Intercropping can reduce both weed density and biomass to a great extent due to decreased light transmission through the canopy (Baumann *et al.*, 2000) [25]. Intercropping with *Sesbania* for 30 days were found effective in controlling weeds in direct seeded rice (Singh *et al.*, 2007b) [148].

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) [39]. 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) [38]. On the other hand, zero tillage favors weed infestation (Hach, 1999) [78]. Conservation tillage has been criticized particularly in relation to lower yields and perennial weed problems which results in an increase in herbicide application. 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.

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) [86]. In wet-seeded rice, early flooding at 4 DAS can reduce weed infestation, particularly barnyard grass densities water depth influence on the efficacy of herbicide has been reported 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 and may contribute to long-term weed management (Blackshaw *et al.*). Fertilizer management should be aimed at maximizing nutrient uptake by crop and minimizing nutrient availability to weeds. 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.*). 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. However, review on fertilizer management and crop-weed interaction has generated conflicting conclusion (Dhima and Eleftherohorinos, 2001; Blackshaw *et al.*, 2004) [50, 29, 30]. 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) [29, 30]. 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) [38].

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) [94]. 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) [169]. Strong WSA will not guarantee high yield of a low yielding variety under weedy conditions (Zhao *et al.*, 2006c) [170]. 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) [70, 169]. 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 which can be accomplished by providing most excellent environment for crop growth and adopting cultural practices that reduce weed pressure (Buhler, 2002) [38]. Narrow spacing, higher seeding rate, proper fertilizer and water management are the practices capable of shifting competitive equilibrium in favor of crop over weeds. Enhanced crop competitiveness can also reduce the reproductive capacity of weeds (Buhler, 2002) [38]. Developing competitive cultivar to reduce weed pressure as well as increase yield has been a major research thrust and

there are good examples of farmers using competitive cultivar alone or integrating with other weed control tactics like precise herbicide application.

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 (Olofsson *et al.*, 2001, Dilday *et al.*)^[134, 52]. Several accessions of rice germplasm in the field were found to decrease the growth of ducksalad (*Heteranthera limosa* (Sw.) wild.), 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.

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)^[153] 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)^[13]. 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)^[37] 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)^[41]. Integration of diverse technologies is essential for weed management because weed communities are highly responsive to management practices and environmental conditions. A theoretical model of IWM has been suggested by Noda.

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. Various agronomic tools have been evaluated for their potentiality in managing weeds (Liebman *et al.*, 2001)^[112]. But, all the agronomic tools may not work perfectly with every crop or weed species. 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)^[28]. Adoption of IWM approach for sustainable rice production has been advocated by many researchers (Azmi and Baki, 2002; Jayadeva *et al.*, 2011)^[13, 95].

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; Dogan *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)^[93]. 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)^[93, 81, 4]. 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)^[165]. Begum *et al.* (2008b)^[27] 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.

The critical periods of weed competition in direct seeded rice under saturated and flooded conditions were studied by Juraimi *et al.* (2009a, b)^[98, 99] 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)^[18] reported that based on the predicted Gompertz 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.

References

- Anwar MP, Juraimi AS, Puteh A, Selamat A, Man A, Hakim MA *et al.* Seeding method and rate influence on weed suppression in aerobic rice. *Afr J Biotechnol.* 2011; 10(68):15259-15271
- Anwar MP, Juraimi AS, Puteh A, Man A, Rahman MM. Efficacy, phytotoxicity and economics of different herbicides in aerobic rice. *Acta Agric Scand.* 2012a; 62:604-615
- Anwar MP, Juraimi AS, Puteh A, Selamat A, Rahman MM, Samedani M *et al.* Seed priming influences weed competitiveness and productivity of aerobic rice. *Acta Agric Scand.* 2012b; 62:499-509
- Anwar MP, Juraimi AS, Samedani B, Puteh A, Man A. Critical period of weed control in aerobic rice. *Sci World J.* 2012c, 2012
- Ashraf MM, Awan TH, Manzoor M, Ahmad M, Safdar ME. Screening of herbicides for weed management in transplanted rice. *J Anim Plant Sci.* 2006; 16:92
- Audebert A, Dingkuhn M, Jones MP, Johnson DE. Physiological mechanisms for vegetative vigor of interspecific upland rice-implications for weed competitiveness. Paper presented at the International Symposium on World Food Security, Kyoto, Japan. 1999
- Ayansina ADV, Osa BA. Effect of two commonly used herbicides on soil microflora at two different concentrations. *Afr J Biotechnol.* 2006; 5(2):129-132
- Azmi M. Competitive ability of barnyard grass in direct seeded rice. *Teknologi Padi.* 1992; 8:19-25.
- Azmi M, Baki BB, Mashhor M. Weed communities in principal rice growing areas in Peninsular Malaysia. *MARDI Report No.165,* 1993, 15
- Azmi M, Baki BB. The succession of noxious weeds in tropical Asian rice fields with emphasis on Malaysian rice ecosystem. *Proc. 15th Asian Pacific Weed Science society Conference,* Tsukuba, Japan, 1995, 51-67
- Azmi M, Abdullah MZ. A manual for the identification and control of padi angin (weedy rice) in Malaysia. *Serdang (Malaysia): MARDI Publication,* 1998, 18
- Azmi M, Fujji Y, Abdullah MZ. Study on allelopathic effect of selected Malaysian rice varietals and rice field weed species. *J Tropic Agric Food Sci.* 1998; 28:39-54
- Azmi M, Baki BB. Impact of continuous direct seeding rice culture on weed species diversity in the Malaysian rice ecosystem. In *Proceedings of the regional symposium on environment and natural resources.* 10-11 April, 2002. Hotel Renaissance, Kuala Lumpur, Malaysia. 2002; 1:61-67
- Azmi M, Johnson DE. Crop establishment options for lowland irrigated rice in relation to weed infestation and grain yield. *J Tropic Agric Food Sci.* 2006; 37(1):111-117.
- Azmi M. Weed succession and management technologies in rice. Presented Research inaugural lecture, 17 May, 2012, MARDI, Serdang, Malaysia, 2012, 21
- Azmi M, Baki BB. Weed flora landscapes and innovative management in direct seeded culture. Paper presented at 2nd International Congress, New Delhi, India, 2006.
- Azmi M, Muhammad H. Water seeding an to control weedy rice (occasional paper) *MARDI,* Serdang, Malaysia, 2006, 17
- Azmi M, Juraimi AS, Mohammad Najib MY. Critical period of weedy rice control in direct seeded rice. *J Tropic Agric Food Sci.* 2007; 35(2):319-332
- Azmi M, Rezaul MR. Weedy rice- biology, Ecology and management, 2008, 56
- Azmi M, Muhammad H, Mishlamah AB, Mohad Rafee U. *Manual technology kawalan padi angin MARDI,* Serdang, 2004, 34
- Baki BB, Azmi M. *Echinochloa* aggregates in Malaysia- Ecology and management. Paper presented at FAO international Workshop on the ecology and management of *Echinochloa* spp. Beijing, China, 2001, 11
- Balasubramanian V, Hill JE. Direct seeding of rice in Asia: Emerging issues and strategic research needs for the 21st century. pp. 15-39. In *Direct Seeding: Research strategies and opportunities.* Pandey et al Eds. *IRRI,* Los Banos, Philippines, 2002.
- Barker TC, Francis CR. *Agronomy of multiple cropping systems.* In *Multiple Cropping Systems.* Francis, C.A. Ed. New York: Macmillan, 1986, 161-182
- Basra SMA, Farooq M, Tabassum R. Physiological and biochemical aspects of seed vigor enhancement treatments in fine rice (*Oryza sativa* L.). *Seed Sci Technol.* 2005; 33:623-628
- Baumann DT, Kropff MJ, Bastiaans L. Intercropping leeks to suppress weeds. *Weed Res.* 2000; 40:359-374
- Begum M, Juraimi AS, Omar SRS, Rajan A, Azmi M. Effect of herbicides for the control of *Fimbristylis miliacea* (L.) Vahl. in Rice. *Agron.* 2008a; 7(3):251-257
- Begum M, Juraimi AS, Rajan A, Omar SRS, Azmi, M. Critical period competition between *Fimbristylis miliacea* (L.) Vahl and rice (MR220). *Plant Prot Quar.* 2008b; 23(4):153-157
- Blackshaw RE, Moyer JR, Harker KN, Clayton GW. Integration of agronomic practices and herbicides for sustainable weed management in a zero-till barley field pea rotation. *Weed Technol.* 2005; 19:190-196
- Blackshaw RE, Semach G, Li X, O' Donovan JT, Harker KN. Tillage, fertilizer and glyphosphate timing effects on foxtail barley management in wheat. *Can J Plant Sci.* 2004; 80:655-660
- Blackshaw RE, Molnar LJ, Janzen HH. Nitrogen fertilizer timing and application method affect weed growth and competition with spring wheat. *Weed Sci.* 2004; 52: 614-622
- Boerboom C. Timing postemergence herbicides in corn and soybeans. *University of Wisconsin, Weed Science Website,* 2002. Retrieved June 14, 2008 from http://128.104.239.6/uw_weeds/extension/articles/timpost herb.htm
- Bond JA, Walker TW, Bollich PK, Koger CH, Gerard P. Seeding rates for stale seedbed rice production in the midsouthern United States. *Agron J.* 2005; 97:1560-1563
- Bouman BAM. Examining the water-shortage problem in rice systems: water saving irrigation technologies. In *Proceedings of the international Rice Research Conference.* Mew TW, Brar DS, Peng S, Dawe D, Hardy B. Eds. Beijing, China, 16-19. 2002, 519-535

34. Bouman BAM, Tuong TP. Field water management to save water and increase its productivity in irrigated lowland rice. *Agric Water Manag.* 2000; 1615:1-20
35. Boyd NS, Brennan EB, Smith RF, Yokota R. Effect of seeding rate and planting arrangement on rye cover crop and weed growth. *Agron J.* 2009; 101:47-51
36. BRRI (Bangladesh Rice Research Institute). Bangladesh Rice Knowledge Bank. Bangladesh Rice Research Institute, 2006. <http://riceknowledgebank.brri.org>. Accessed on January, 2010
37. Buchanan GA. Management of the weed pests of cotton (*Gossypium hirsutum*). In Proceedings of the U.S.-U.S.S.R. Symposium: The integrated control of the arthropod, disease and weed pests of cotton, grain sorghum and deciduous fruit, Lubbock, TX, 1976, 168-184
38. Buhler DD. Challenges and opportunities for integrated weed management. *Weed Sci.* 2002; 50:273-280
39. Buhler DD, Gunsolus JL. Effect of date of preplant tillage and planting on weed populations and mechanical weed control in soybean (*Glycine max*). *Weed Sci.* 1996; 44:373-379
40. Buhler DD, Hartzler RG, Forcella F. Implications of weed seed bank dynamics to weed management. *Weed Sci.* 1997; 45:329-336
41. Buhler DD, Liebman M, Obrycki JJ. Theoretical and practical challenges to an IPM approach to weed management. *Weed Sci.* 2000; 48:274-280
42. Cadriana J, Herms CP, Doohan DJ. Crop rotation and tillage system effects on weed seed banks. *Weed Sci.* 2002; 50(4):448-460
43. Castin EM, Moody K. Effect of different seeding rates, moisture regimes, and weed control treatments on weed growth and yield of wet-seeded rice. In Proceedings of the 12th Asian-Pacific Weed Science Society Conference. Seoul, Korea, 1989, 337-343
44. Caton BP, Cope AE, Mortimer M. Growth traits of diverse rice cultivars under severe competition: implications for screening for competitiveness. *Field Crops Res.* 2003; 83:157-172
45. Chauhan, BS, Johnson DE. Growth response of direct seeded rice to oxadiazon and bispyribac-sodium in aerobic and saturated soils. *Weed Sci.* 2011; 59:119-122
46. Chin DV. Biology and management of barnyardgrass, red sprangletop and weedy rice. *Weed Biol Manag.* 2001; 1:37-41
47. Clark LJ, Whalley WR, Ellis-Jones J, Dent K, Rowse HR, Finch-Savage WE *et al.* On farm seed priming in maize: a physiological evaluation. Seventh Eastern and Southern Africa Regional Maize Conference, 2001, 268-273
48. Cousens R, Mortimer AM. Weed population dynamics. Cambridge University Press, Cambridge, 1995, 332
49. De Datta SK, Baltazar AM. Weed control technology as a component of rice production systems. In Weed management in rice. Auld, B.A. and Kim, K.U. Eds. FAO Plant Production and Protection Paper 139, Rome, Italy, 1996, 27-52
50. Dhima KV, Eleftherohorinos IG. Influence of nitrogen on competition between winter cereals and sterile oat. *Weed Sci.* 2001; 49:77-82
51. Di Tomaso JM. Approaches for improving crop competitiveness through the manipulation of fertilization strategies. *Weed Sci.* 1995; 43:491-497
52. Dilday RH, Lin J, Yan W. Identification of allelopathy in the USDA-ARS rice germoplasm collection. *Aust J Exp Agric.* 1994; 34:901-910
53. Dingkuhn M, Johnson DE, Sow A, Audebert AY. Relationship between upland rice canopy characteristics and weed competitiveness. *Field Crops Res.* 1999; 61:79-95
54. Doğan MN, Ünay A, Boz Ö, Albay F. Determination of optimum weed control timing in maize. *Turk J Agric For.* 2004; 28: 349-354
55. Du LV, Tuong TP. Enhancing the performance of dry-seeded rice: effects of seed priming, seedling rate, and time of seeding. In direct seeding: research strategies and opportunities. Pandey, S., Mortimer, M., Wade, L., Tuong, T.P., Lopes, K. and Hardy, B. Eds. International Rice Research Institute, Manila, Philippines, 2002, 241-256
56. Ebana K, Yan W, Dilday RH, Namai H, Okuno K. Variation in the allelopathy effect of rice with water soluble extracts. *Agron J.* 2001, 93:12-16
57. FAO (Food and Agriculture Organization of the United Nations). Rice and us, 2004a. <http://www.fao.org/rice2004/en/aboutrice.htm>. Accessed on 20 March 2011
58. FAO (Food and Agriculture Organization of the United Nations). Rice and water: a long and diversified story, 2004b. <http://www.fao.org/rice2004/en/f-sheet/factsheet1.htm>. Accessed on 12 July 2011
59. FAO (Food and Agriculture Organization of the United Nations). FAO database 2007 for rice area. FAO, Rome, 2007. Accessed on 7 August 2011
60. Farooq M, Basra SMA, Ahmad N. Improving the performance of transplanted rice by seed priming. *Plant Growth Regul.* 2007; 51:129-137
61. Fernando CH. Rice field ecosystems: a synthesis. In Proceedings of the 5th International Symposium of tropical Ecology. Kuala Lumpur, Malaysia, 1980, 339-342
62. Ferrero A. Weedy rice, biological features and control. FAO plant production and protection paper 120add.1. Weed management for developing countries, 2003. Retrieved from: <http://www.fao.org/DOCREP/006/Y5031E/y5031e09.htm>
63. Fischer AJ, Ramierz HV, Lozano J. Suppression of jungle rice (*Echinochloa colona* L.) Link) by irrigated rice cultivars in Latin America. *Agron J.* 1997; 89:516-521
64. Fischer AJ, Ramierz HV, Gibson KD, Pinheiro BDS. Competitiveness of semi dwarf rice cultivars against palisadegrass (*Brachiaria brizantha*) and signal grass (*Brachiaria decumeans*). *Agron J.* 2001; 93:967-973
65. Fofana B, Rauber R. Weed suppression ability of rice under low-input conditions in West Africa. *Weed Res.* 2000; 40:271-280
66. Garrity DP, Movillon M, Moody K. Differential weed suppression ability in upland rice cultivars. *Agron J.* 1992; 84:586-591
67. Ghera CM, Benech-Arnold RL, Satorre EH, Martinez-Ghera MA. Advances in weed management strategies. *Field Crops Res.* 2000; 67:95-104
68. Ghera CM, Roush ML, Radosevich SR, Cordray SM. Coevolution of agroecosystems and weed management. *Bio Sci.* 1994; 44:85-94
69. Ghiyasi M, Abbasi AM, Tajbakhsh A, Sallehzade R. Effect of osmopriming with poly ethylene glycol 8000

- (PEG8000) on germination and seedling growth of wheat (*Triticum aestivum* L.) seeds under salt stress. *Res J Biol Sci.* 2008; 3(9):1249-1251
70. Gibson KD, Hil JE, Foin TC, Caton BP, Fischer AJ. Water seeded rice cultivars differ in ability to interfere with water grass. *Agron J.* 2001; 93:326-332
 71. Gibson KD, Fischer AJ. Competitiveness of rice cultivars as a tool for crop-based weed management. In *Weed Biology and Management*. Inderjit Ed. Kulwer Academic Publishers, the Netherlands, 2004, 517-537
 72. Gill GS, Holmes JE. Efficacy of cultural control methods for combating herbicide-resistant *Lolium rigidum*. *Pesti. Sci.* 1997; 51:352-358
 73. Gould F. The evolutionary potential of crop pests. *Am Sci.* 1991; 79:496-507
 74. Grichar WJ, Bessler BA, Brewer KD. Effect of row spacing and herbicide dose on weed control and grain sorghum yield. *Crop Protec.* 2004; 23:263-267
 75. Grundy AC, Froud-Williams RJ. The control of weeds in cereals using an integrated approach. *Applied Biol.* 1997; 50:367-374
 76. Guillermo DA, Pedersen P, Hartzler RG. Soybean seeding rate effects on weed management. *Weed Technol.* 2009; 23:17-22
 77. Guyer R, Quadranti M. Effect of seed rate and nitrogen level on the yield of direct wet-seeded rice. In *Proceedings of the 10th Asian-Pacific Weed Science Society Conference*. Chiangmai, Thailand, 1985, 304-311
 78. Hach CV. Study on some weed control methods in wet seeded rice in Mekong delta. Ph. D. thesis. Vietnam Institute of Agricultural Science and Technology, Hanoi, 1999, 183.
 79. Hach CV, Chin DV, Dien TV, Luat NV. Study the effect of water depths and herbicides on weeds and grain yield of rice. In *Scientific Proceedings of the Vietnam Institute of Agricultural Science and Technology*. 1997; 5:20-21
 80. Haefele SM, Johnson DE, Bodj DM, Wopereis MCS, Miezian KM. Field screening of diverse rice genotypes for weed competitiveness in irrigated lowland ecosystems. *Field Crops Res.* 2004; 88:39-56
 81. Hall MR, Swanton CJ, Anderson GW. The critical period of weed control in grain corn (*Zea mays*) *Weed Sci.* 1992; 40:441-447
 82. Harris D, Tripathi RS, Joshi A. On-farm seed priming to improve crop establishment and yield in dry direct-seeded rice, In *Proceedings of the International workshop on Direct Seeding in Asian Rice systems: Strategic Research Issues and Opportunities*. Pandey, S., Mortimer, M., Wade, L., Tuong, T.P., Lopes, K. and Hardy, B. Eds. 25-28 January 2000. Bangkok, Thailand, 2002, 383
 83. Hasanuzzaman M, Ali MH, Akther M, Alam KF. Evaluation of pre-emergence herbicide and hand weeding on the weed control efficiency and performance of transplanted Aus rice. *Am Eurasian J Agron.* 2009; 2(3):138-143
 84. Hassan SM, Rao AN, Bastawisi AO, Draz AE. Weed management using allelopathic rice varieties in Egypt. *Proceedings of International Workshop on Constraints, Opportunities and Innovations for Wet-Seeded Rice*, Bangkok, Thailand, 31 May–3 June 1994; International Rice Research Institute: Los Banos, Phillipines, 1998, 257-269
 85. Heap I. *The International Survey of Herbicide Resistant Weeds*, 2006. Available at: <http://www.weedscience.com>
 86. Hill JE, Mortimer AM, Namuco OS, Janiya JD. Water and weed management in direct seeded rice: Are we ahead in the right decision? In *Proceeding of the International Rice Research Conference*, 31 March-3 April, 2000, International Rice Research institute, Los banos, Philippines, 2001, 491-510
 87. Hiraoka H, Tan PS, Khuong TQ, Huan NT. On seeding rate in wet seeded culture in alluvial soil of the Mekong delta. Paper presented at the workshop on rice technology in Central Vietnam, Qui Nhon, Vietnam, 1998
 88. Ho NK. Integrated weed management in Malaysia: some aspects of the Muda irrigated scheme's approach and experience. Paper presented at a Workshop on Appropriate Weed Control in Southeast Asia, Kuala Lumpur, Malaysia, 1994.
 89. Ho NK, Asna BO, Azman A, Rabirah A. Herbicide usage and associated incidences of poisoning in the Muda area, Malaysia: a case study. In *Proceedings of the third Tropical Weed Science Conference*, Kuala Lumpur, Malaysia. Malaysian Plant Protection Society, Kuala Lumpur, Malaysia, 1990, 321-333
 90. Holm LG, Plucknett DL, Panth JV, Herberger JP. *The world's worst weeds*. Honolulu, Haw (USA): University Press of Hawaii, 1977, 609
 91. Hussain S, Ramzan M, Akhter M, Aslam M. Weed management in direct seeded rice. *J Anim Plant Sci.* 2008; 18(2-3):86-88
 92. IRRI (International Rice Research Institute). Main weeds of rice in Asia, 2003. <http://www.knowledgebank.irri.org>. Accessed on 5 July 2011
 93. Isik D, Mennan H, Bukun B, Oz A, Ngouajio M. The critical period for weed control in corn in Turkey. *Weed Technol.* 2006; 20:867-872
 94. Jannink JL, Orf JH, Jordan NR, Shaw RG. Index selection for weed suppressive ability in soybean. *Crop Sci.* 2000; 40:1087-1094
 95. Jayadeva HM, Bhairappanavar ST, Hugar AY, Rangaswamy BR, Mallikarjun GB, Malleshappa C *et al.* Integrated Weed management in Aerobic Rice (*Oryza sativa* L.). *Agric Sci Digest.* 2011; 31(1):58-61
 96. Jensen PK. Effect of light environment during soil disturbance on germination and emergence pattern of weeds. *Ann Applied Biol.* 1995; 127:561-571
 97. Johnson DE. Weed management in small holder rice production in the tropics, 1996. Available at <http://ipmworld.umn.edu/chapters/johnson.htm>. Accessed on 7 August 2009.
 98. Juraimi AS, Begum M, Sherif AM, Rajan A. Effects of sowing date and nut sedge removal time on plant growth and yield of tef [*Eragrostis tef* (Zucc.) Trotter]. *Afr J Biotechnol.* 2009b; 8(22):6162-6167
 99. Juraimi AS, Najib MYM, Begum M, Anuar AR, Man A, Puteh A *et al.* Critical period of weed competition in direct seeded rice under saturated and flooded conditions. *Pertanika J Trop Agric Sci.* 2009a; 32(2):305-316
 100. Juraimi AS, Begum M, Yusuf MNM, Man A. Efficacy of herbicides on the control weeds and productivity of direct seeded rice under minimal water conditions. *Plant Protec Quat.* 2010; 25(1):19-25
 101. Juraimi AS, Saiful AHM, Uddin MK, Anuar AR, Azmi M. Diversity of weed communities under different water regimes in bertam irrigated direct seeded rice field. *Aust J Crop Sci.* 2011; 5(5):595-604

102. Karim SMR, Man AB, Sahid IB. Weed problems and their management in rice fields of Malaysia: An overview. *Weed Biol. Manag.* 2004; 4:177-186
103. Khush GA. Origin, dispersal, cultivation and variation of rice. *Plant Mol Biol.* 1997; 35:25-34
104. Kirkland KJ, Holm FA, Stevenson FC. Appropriate crop seeding rate when herbicide rate is reduced. *Weed Technol.* 2000; 14:692-698
105. Kosaka Y, Takeda S, Sithirajvongsa S, Xaydala K. Plant diversity in paddy fields in relation to agricultural practices in Savannakhet Province, Laos. *Economic Bot.* 2006; 60(1):49-61
106. Koskinen WC, McWhorter CG. Weed control in conservation tillage. *J Soil Water Conser.* 1986; 41:365-370
107. Kropff MJ, Van Laar HH. Modelling crop-weed interactions. CAB international, Wallingford, UK, 1993.
108. Kuan CY, Ann LS, Ismail AA, Leng T, Fee CG, Hashim K *et al.* Crop loss by weeds in Malaysia. In Proceedings of the third Tropical Weed Science Conference, Kuala Lumpur, Malaysia. 4-6 December 1990. Malaysian Plant Protection Society, Kuala Lumpur, Malaysia, 1990, 1-21.
109. Kumar V, Bellinder RR, Brainard DC, Malik RK, Gupta RK. Risk of herbicide-resistant rice in India: A review. *Crop Protec.* 2008; 27:320-329
110. Liebman M, Gallandt ER. Many little hammers: ecological management of crop-weed interactions. In *Ecology in Agriculture*. Jack-son, L.E. Ed. San Diego, CA: Academic Press, 1997, 291-343
111. Liebman M, Ohno T. Crop rotation and legume residue effects on weed emergence and growth: applications for weed management. In *Integrated Weed and Soil Management*. Hatfield, J.L., Buhler, D.D and Stewart, B.A. Eds. Chelsea, MI: Ann Arbor Press, 1998, 181-221
112. Liebman M, Mohler CL, Staver CP. Ecological management of agricultural weeds. Cambridge University Press, Cambridge, 2001, 532
113. Lin XQ, Zhu DF, Chen HZ, Cheng SH, Uphoff N. Effect of plant density and nitrogen fertilizer rates on grain yield and nitrogen uptake of hybrid rice (*Oryza sativa* L.). *J Agric Biotechnol Sustain Develop.* 2009; 1(2):44-53
114. Lin WX, Kim KU, Shin DH. Rice allelopathic potential and its modes of action on barnyard grass. *Allelopathy J.* 2000; 792:215-224
115. Maclean JL, Dawe DC, Hardy B, Hettel GP. *Rice Almanac*. Los Baños (Philippines): International Rice Research Institute, Bouaké (Cote d'Ivoire): West Africa Rice Development Association, Cali (Colombia): International Center for Tropical Agriculture, Rome (Italy): Food and Agriculture Organization, 2002, 253.
116. Mahajan G, Chauhan BS, Johnson DE. Weed management in aerobic rice in northwestern indo-gangetic plains. *J Crop Improv.* 2009; 23:366-382
117. Mai V, Chien HV, Suong VTT, Thiet LV. Survey and analysis of farmers' seed contamination by weed and weedy rice seeds in South Vietnam. Paper presented at the International Symposium on Wild and Weedy Rices in Agroecosystems. Ho chi Minh City, Vietnam, 1998.
118. Mann RA, Ahmad S, Hassan G, Baloch MS. Weed management in direct seeded rice crop. *Pak J Weed Sci. Res.* 2007; 13(3-4):219-226
119. Marwat KB, Saeed M, Gul B, Hussain Z. Performance of different herbicides in wheat (*Triticum aestivum* L.) under rainfed conditions of Kohat, *Pak J Weed Sci Res.* 2006; 12(3):163-168
120. Melander B, Rasmussen IA, Barberi P. Integrating physical and cultural methods of weed control-examples from Euro Res. *Weed Sci.* 2005; 53:369-381
121. Mishra JS, Singh VP. Integrated weed management in zero till direct seeded rice-wheat cropping system. *Ind J Agron.* 2007; 52:198-203
122. Moody K. Weed control in upland rice with emphasis on grassy weeds. In *Tropical grass weeds* Baker, F.W.G. and Terry, P.J. Eds. CAB Intl., Wallingford, UK, 1991, 164-178
123. Moody K, Cordova VG. *Wet-seeded Rice*. In *Women in rice farming*. International Rice Research Institute, Los Baños, Philippines, 1985, 467-480
124. Moonen AC, Barberi P. Size and composition of the weed seed bank after 7 years of different cover crop-maize management systems. *Weed Res.* 2004; 44:163-177
125. Moorthy BTS, Manna GB. Studies on weed control in direct seeded upland rainfed rice. *Ind J Agric Res.* 1993; 27:175-180
126. Moss SR. Strategies for the prevention and control of herbicide resistance in annual grass weeds. In Proceedings of the international symposium on weed and crop resistance to herbicides, Corboda, Spain, 1995, 13-6.
127. Najib MYM, Juraimi AS, Anua AR, Azmi M, Shamsuddin Z. Critical period of weed competition in direct-seeded rice under minimal water condition. *Agriculture Congress*, 2006, 65-66
128. Ni H, Moody K, Robles RP, Paller EC, Lales JS. *Oryza sativa* plant traits conferring competitive ability against weeds. *Weed Sci.* 2000; 48:200-204
129. Noda K. Integrated weed control in rice. In *Integrated control of weeds*. Frayer, J.D. and Matsunaka, S. Eds. Tokyo (Japan): University of Tokyo Press, 1977, 17-46
130. Noldin JA. Red rice status and management in the Americas. *Proc of wild and weedy rice in rice ecosystem in Asia- A review* (Baki., B.B., Chin D.V. and Mortimer, M., eds.). Loss Baños, IRRI, 2000, 21-24.
131. O' Donovan JT, Harker KN, Clayton GW, Newman JC, Robinson D, Hall LM *et al.* Barley seeding rate influence the effects of variable herbicide rates. *Weed Sci.* 2001; 49:746-754
132. Oerke EC, Dehne HW. Safeguarding production- Losses in major crops and the role of crop protection. *Crop Prod.* 2004; 23(4):275-285
133. Olofsdotter M, Valverde BE, Madsen KH. Herbicide resistant rice (*Oryza sativa* L.): global implications for weedy rice and weed management. *Ann Applied Biol.* 2000; 137:279-295.
134. Olofsdotter M. Rice- a step toward to use all elopathy. *Agron J.* 2001; 93(1):3-8
135. Pacanoski Z, Glatkova G. The use of herbicides for weed control in direct wet seeded rice in rice production region in the Republic of Macedonia. *Plant Protec Sci.* 2009; 45(3):113-118
136. Pane H, Fagi AM. Integrated weed control to minimize herbicide application in lowland rice. In *International Rice Research Conference*, IRRI, Los Baños, Philippines, 1992, 23.
137. Pellerin KJ, Webster EP. Imazethapyr at different rates and times in drill and water seeded imidazolinone-tolerant rice. *Weed Technol.* 2004; 18:223-227
138. Pester TA, Burnside OC, Orf JH. Increasing crop competitiveness to weeds through crop breeding. *J Crop Prod.* 1999; 2:31-58

139. Phuong LT, Denich M, Vlek PLG, Balasubramanian V. Suppressing weeds in direct seeded lowland rice: effects of methods and rates of seeding. *J Agron Crop Sci.* 2005; 191:185-194
140. Radosevich SR, Holt J, Ghersa CM. *Weed ecology: Implications for management.* Wiley, New York, 1997.
141. Ramzan M. Evaluation of various planting methods in rice-wheat cropping systems, Punjab, Pakistan. *Rice Crop Report 2003-2004.* 2003, 4-5
142. Rao AN, Johnson DE, Sivaprasad B, Ladha JK, Mortimer AM. Weed management in direct seeded rice. *Adv Agron.* 2007; 93:153-255
143. Rasmussen J, Accard J. Weed control in organic farming systems. In *Ecology and Integrated Farming Systems.* Glen, D.M., Greaves, M.P. and Anderson, H.M. Eds. Chichester, U.K. Wiley, 1995, 49-67
144. Roder W. Slash-and-burn rice systems in the hills of northern Lao PDR. In *Description, challenges, and Opportunities,* IRRI, Los Banos, Philippines, 2001, 201
145. Roder W, Keobulapha B. Weeds in slash-and-burn rice fields in northern Laos. *Weed Res.* 1997; 37:111-119
146. Savary S, Srivastava RK, Singh HM, Elazegui FA. A characterization of rice pests and quantification of yield losses in the rice-wheat system of India. *Crop Protec.* 1997; 16(4):387-398
147. Shibayama H. Experience with rice herbicides in Japan. In *Herbicides in Asian rice: transitions in weed management.* Naylor, R. Ed. Palo Alto (California): Institute for International Studies, Stanford University, and Manila (Philippines): International Rice Research Institute, 1996, 243-254
148. Singh P, Singh P, Singh R, Singh KN. Efficacy of new herbicides in transplanted rice under temperate conditions of Kashmir. *Ind J Weed Sci.* 2007b ; 39(3&4):167-171
149. Singh S, Bhushan L, Ladha JK, Gupta RK, Rao AN, Sivaprasad B *et al.* Weed management in dry seeded rice cultivated on furrow irrigated raised bed planting system. *Crop Protec.* 2006; 25:487-495
150. Singh S, Ladha JK, Gupta RK, Bhushan L, Rao AN, Sivaprasad B *et al.* Evaluation of mulching, intercropping with *Sesbania* and herbicide use for weed management in dry-seeded rice. *Crop Protec.* 2007a; 26(4):518-524
151. Singh S, Ladha JK, Gupta RK, Bhushan L, Rao AN. Weed management in aerobic rice systems under varying establishment methods. *Crop Protec.* 2008; 27:660-671
152. Smith Jr RJ. Biological controls as components of integrated weed management for rice in the U.S. In *Proceedings of the International Symposium on Biological Control and Integrated Management of Paddy and Aquatic Weeds in Asia.* Sukuba, Japan, 1992, 335-351.
153. Spliid NH, Koeppe B. Occurrence of pesticides in Danish shallow ground water. *Chemosp.* 1998; 37:1307-1316
154. Sunil CM, Shekara BG, Kalyanmurthy KN, Shankaralingappa BC. Growth and yield of aerobic rice as influenced by integrated weed management practices. *Ind J Weed Sci.* 2010; 42(3&4):180-183
155. Swanton CJ, Weise SF. Integrated weed management: the rationale and approach. *Weed Technol.* 1991; 5:657-663
156. Teasdale JR. Cover crops, smother plants, and weed management. In *Integrated Weed and Soil Management.* Hatfield, J.L., Buhler, D.D. and Stewart, B.A. Eds. Chelsea, MI: Ann Arbor Press, 1998, 247-270
157. Thi HL, Man LH, Chin DV, Auld BA, Hetherington SD. Research on some fungi to control barnyard grass and red sprangletop in rice. In *Proceedings of the 17th Asian-Pacific Weed Science Society conference,* Bangkok, Thailand, 1999, 562-566
158. Trung HM, Tan NT, Cung HA. Present status and prospect of weed control in rice in Vietnam. In *Proceeding of the 5th Asian-Pacific Weed Science Society Conference,* Tsukuba, Japan, 1995, 601-606
159. Valverde BE, Riches CR, Caseley JC. Prevention and management of herbicide resistant weeds in rice: Experiences from Central America with *Echinochloa colona.* Tropical Agricultural Centre for Research and Higher Education (CATIE), Camera de Insumes Agropecuarios. Son Jose (Costa Rica), 2000.
160. Wang, HQ, Bouman BAM, Zhao DL, Wang C, Moya PF. Aerobic rice in northern China: Opportunities and challenges. In *Water-Wise Rice Production.* Bouman, B. A.M., Hengsdijk, H., Hardy, B., Bindraban, P.S., Tuong, T.P. and Ladha, J.K. Eds. *Proceedings of a Thematic Workshop on Water-Wise Rice Production,* 8-11 April 2002 at IRRI Headquarters in Los Banos, Philippines, 2002.
161. WARDA (West Africa Rice Development Association) Annual Report for 1995. West Africa Rice Development Association, Bouake, Cote d'Ivoire, 1996.
162. Watanabe H, Azmi M, Md Zuki I. Emergence of major weeds and their population change in wet-seeded rice fields in the Muda area, Peninsular Malaysia. In *Proceedings of the 16th Asian Pacific Weed Science Society,* 1997, 246-250
163. Watanabe H, Vaughan DA, Tomaka N. Weedy rice complexes: case study from Malaysia, Vietnam and Suriname. Paper presented at the International Symposium on Wild and Weedy Rices in Agroecosystems, 10-11 August 1998, Ho Chi Minh City, Vietnam, 1998.
164. Weiner J, Griepentrog HW, Kristensen L. Suppression of weeds by spring wheat increases with crop density and spatial uniformity. *J Applied Ecol.* 2001; 38:784-790
165. Williams II, Martin M. Planting date influences critical period of weed control in sweet corn. *Weed Sci.* 2006; 54:928-933
166. Wyse DL. Future of weed science research. *Weed Technol.* 1992; 6:162-165
167. Zhang ZP. Weed management on rice, wheat, soybeans and cotton in China. In *Proceedings of the 20th Asian Pacific Weed Science Society Conference,* 2005, 601-605
168. Zhao DL, Atlin GN, Bastiaans L, Spiertz JHJ. Developing selection protocols for weed competitiveness in aerobic rice. *Field Crops Res.* 2006a ; 97:272-285
169. Zhao DL, Atlin GN, Bastiaans, L, Spiertz JHJ. Cultivar weeds competitiveness in aerobic rice: heritability, correlated traits, and the potential for indirect selection in weed-free environments. *Crop Sci.* 2006b; 46:372-380
170. Zhao DL, Atlin GN, Bastiaans L, Spiertz JHJ. Comparing rice germplasm groups for growth, grain yield and weed suppressive ability under aerobic soil conditions. *Weed Res.* 2006c; 46:444-452
171. Zhao DL, Bastiaans L, Atlin GN, Spiertz JHJ. Interaction of genotype \times management on vegetative growth and weed suppression of aerobic rice. *Field Crops Res.* 2007; 100:327-340