Competitive ability of cultivated rice against weedy rice biotypes - A review

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ABSTRACT

Weedy rice has been identified as a threat to rice production worldwide. Its phenotypic and genotypic diversity and its potential to compete against rice in all development stages from germination to maturity have resulted in a loss of rice yield and grain quality, which is remarkably high in direct-seeded rice cultivation. Weedy rice dormancy varies, it has a higher germination rate, and tolerates deeper germination depth compared to rice cultivars. Interactions of weedy rice with cultivars often reflect early vigor, more tillering, nutrient utilization ability for shoot development with respect to rice cultivars even though the latter also show an improvement in shoot development under competition. An exponential relationship has been reported between cultivated rice loss and weedy rice density: this is true for all rice cultivars. The degree of loss is dependent on the competitive ability of the rice cultivar being studied, and each weedy rice biotype also interacts differently. Hence, the need for a comprehensive study of the biology of various weedy rice variants. Difficulties arise in the management of weedy rice due to its physiological, anatomical, and morphological similarities to cultivated rice. The manipulation of the environment to improve cultivated rice production and suppress the emergence of weedy rice variants is important in the management of weedy rice, as well as other cultural practices and use of pesticides. The development of herbicide-resistant rice cultivars is necessary to totally eliminate the weedy rice variants. This review provides information on the competitive ability of weedy rice against rice cultivars; this information is essential to create management options to control weedy rice.

Key words: Competitive ability, *Oryza*, rice, weedy rice.

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INTRODUCTION

The dietary consumption of rice by the world population is the highest compared to all other foods. Rice is an important cereal crop for most of the world population (Chauhan, 2013), and it is the staple food in Asian, Pacific, Latin American, Caribbean, North African, and sub-Saharan countries. Trends in regional rice production are presented in Figure 1 where the increasing trend of global rice production is very general but not increasing satisfactorily. This is due to climate change, increasing depth of underground water levels, labor scarcity, and the shortage of energy and land to produce higher yields (Singh et al., 2013). To cope with water shortage and reduction in wetlands, rice farmers shift from puddle transplanting to direct-seeded rice (DSR) where seeds are easily planted (Farooq et al., 2011). With all of these benefits, one of the major threats to rice production is the practice of DSR, which stimulates weedy rice evolution.

Weedy rice is a threat to rice production because it competes with cultivated rice, and it is diverse and difficult to control, which leads to yield loss (Chauhan, 2013). Weedy rice, however, has emerged as a serious threat to rice production in some countries (Malaysia, Sri Lanka, Thailand, Vietnam, Philippines, and the USA) where DSR systems are common (Singh et al., 2013). According to Ziska et al. (2015), weedy rice infestation has spread across the globe and is now a problem, particularly in America, the Caribbean, South Asia, and Southeast Asia. There are many reports about weedy rice infestation worldwide although the percentage of the infested area varies (Table 1). The highest weedy rice infestation (80%) has been reported in Cuba (Sales et al., 2011; Baek and Chung, 2012) followed by 40% to 75% in Europe (Ferrero, 2003). A yield loss of 74% in DSR has also been reported in Malaysia (Azmi and Karim, 2008). Weedy rice densities of 35 to 40 plants m^{-2} can reduce yields of tall rice cultivars by 60% and short cultivars by 90%, indicating losses greater than grass weeds (Ziska et al., 2015). Sales et al. (2011) studied the threshold density of weedy rice to be 1 to 3 plants m^{-2} while the corresponding density of barnyard grass (*Echinochloa crus-galli* [L.] P. Beauv.) is 5 to 10 plants m^{-2}.

The occurrence of weedy rice has been reported globally in rice fields while its origin is believed to be in Southeast Asia where rice originated. Wild and weedy rice varieties are a phylogenetic group under the genus *Oryza* because they share some of the features of the two cultivated species *Oryza sativa* L. and *O. glaberrima* Steud. (Baek and Chung, 2012). Weedy rice is often, but not exclusively, associated with a red pericarp and can be referred to as wild rice, red rice, padi angin, windy rice, air rice, varinellu, wild

REVIEW

Figure 1. Trends in rice production in different regions of the world (FAOSTAT, 2014).

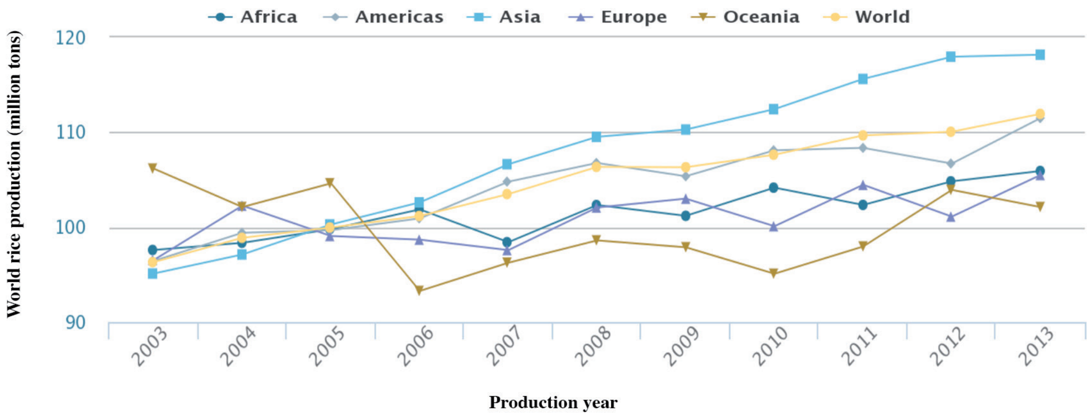


Table 1. Weedy rice infestation across the world.

Country	Infestation (%)	References
Europe	40-75	Ferrero, 2003
Italy	70	Vidotto and Ferrero, 2005
Malaysia	74	Chauhan, 2013
USA (Arkansas)	60	Sales et al., 2011; Burgos et al., 2011
Brazil	40	Fogliatto et al., 2011; Baek and Chung, 2012
Senegal	55	Fogliatto et al., 2011; Baek and Chung, 2012
Cuba	80	Fogliatto et al., 2011; Baek and Chung, 2012
Costa Rica	60	Fogliatto et al., 2011; Baek and Chung, 2012

rice, and so forth. While weedy rice is often classified as *O. sativa*, other *Oryza* species, such as *O. rufipogon* Griff., *O. barthii* A. Chev., *O. nivara* S.D. Sharma & Shastry, and *O. longistaminata* A. Chev. & Roehr., have also been proposed as weedy rice sources (Ziska et al., 2015). Different varieties behave differently with rice cultivars.

In Malaysia, red rice was first detected in Tajung Karang rice fields in 1988 (Wahab and Suhaimi, 1991), and economic loss in the area was high (Azmi and Karim, 2008). A similar loss in cultivated rice due to a weedy rice variant infestation has been reported in India (Abraham and Jose, 2014), and this caused some farmers to abandon rice cultivation in the area. The extent of losses resulting from weedy rice infestation means it is able to compete with rice, and this needs to be understood to control it effectively.

The shift to direct seeding provides an additional advantage on weedy rice because it is well adapted to different environments and is more stress-tolerant than rice; this causes the problem to be more severe (Azmi and Karim, 2008). There is no flooding at the time of crop emergence in direct seeding, so that weedy rice and cultivated rice emerge simultaneously and the two cannot be differentiated. More so, emerging rice seedlings are less competitive with weeds (Rao et al., 2007). Therefore, one of the major threats of current DSR production is weedy rice.

Weedy rice management has largely depended on the use of traditional methods that are related to the toxicity and residual effect of herbicides, resistance to weed species, and finally to environmental safety issues. Effective N management aims to increase the ability of rice to compete with weedy rice variants. Proper water management can also help in weedy rice management since flooding suppresses seedling emergence and biomass and crop plant density. Thus, understanding the competitive ability of different weedy rice biotypes against cultivated rice in response to added N, density, and moisture could play a major role in strategies to manage weedy rice.

Origin, distribution, and biotypes of weedy rice

The phylogenetic origin of the weedy rice forms is closely related to that of cultivated rice. Many weedy rice plants share most of the features of the two cultivated species, that is, Asian rice (*O. sativa*) and African rice (*O. glaberrima*). Wild species, such as *O. nivara*, *O. rufipogon,* and *O. longistaminata,* share the same genome 'AA' as cultivated rice and can easily be crossed with the cultivated *O. sativa* and *O. glaberrima* species. The wild *O. barthii* species (*O. breviligulata*) is considered to be the progenitor of African rice. In the distant past, different types of weedy rice were generated primarily through natural crossing between wild and cultivated rice species in areas where they grew (or still grow) sympatrically (Saha et al., 2014). The main sources of weedy rice are contaminated seed stocks. Several "delivery systems", other than seed stocks, have been involved in the spread of weedy rice. Harvesting equipment is a significant source of contamination of rice seed lots and rice fields with weedy rice seeds (Saha et al., 2014). Weedy rice seeds also spread within fields and to other fields by mud adhering to the hooves and legs of animals, the wheels of carts, trucks and similar vehicles, and in the movement of rice straw (Azmi and Karim, 2008). Because the spikelets (grains) of many of the weedy rice phenotypes are pubescent and some have long, hispid awns, seeds can be spread by adhering to the fur of domestic and wild animals and even to the clothing of field workers. Weedy rice plant biotypes are diverse and characterized by early maturity and grain shattering with long periods of dormancy; some have awns while others do not. Weedy rice is also phenotypically diverse and there are variations in rice husk and pericarp color. Husk color ranges from straw-whitish to brown to black while the pericarp color is brown/red and white. Zainudin et al. (2010) identified 36 weedy rice morphotypes based on plant erectness, culm height, days until maturity, and panicle types. Panicles are compact, open, or intermediate. Different weedy rice biotypes vary in growth and development, such as height and tiller production. On the other hand, genetic analysis of quantitative trait loci (QTL) of common regions among weed groups (Ziska et al., 2015) suggest that weedy rice groups diverged from their cultivated ancestors in their evolutionary history, one from another, and the lack of QTL overlapping. For the remaining traits, despite a close evolutionary relationship, it is suggested that weedy rice groups have adapted to the same agricultural environment through different genetic mechanisms. Each weedy rice variant is therefore genetically isolated. Singh et al. (2013) reported 10 different accessions of red rice in India and their genomic differences. Their infestation in rice fields and cultivated land varies at different locations (Table 2). Thurber et al. (2014) recently conducted an SSR marker-based experiment about varying flowering behavior among weedy rice and cultivated rice silent variations; they reported divergence in flowering time between two distinct weedy rice groups, so that straw-hull weeds tend to flower earlier and black hull, awned weeds tend to flower later than cultivated rice (*indica*, *aus*, and tropical *japonica*). These differences are consistent with weed *Hd1* alleles. At both loci, weeds share haplotypes with their cultivated progenitors despite significantly different flowering times. For the first time, Subudhi et al. (2014) discovered QTL mapping on seed-shattering loci of two rice cultivars and a weedy rice accession in the southern United States. They revealed 3 to 5 QTLs that controlled seed shattering with 38% to 45% of total phenotypic variation between weedy rice and cultivated rice. Two QTLs on chromosomes 4 and 10 were consistent in both populations. Both cultivars and weedy rice contributed alleles for increased seed shattering. The major QTL *qSH4* and a minor QTL *qSH3* were validated in near-isogenic lines with the former conferring a significantly higher degree of seed shattering than the latter.

Weedy rice accessions from Asian countries are said to have higher N use efficiency to produce shoot biomass than cultivated rice (Chauhan and Johnson, 2011). The response of weedy rice to rising CO_2 levels is also stronger than that of cultivated rice, which makes weedy rice more competitive (Ziska et al., 2015). This suggests that weedy rice could become a serious weed problem in the future because environmental and climate change might selectively favor weedy rice. Strategies to optimize rice production, such as fertilizer application, will also improve weedy rice; therefore, understanding rice N consumption under weedy rice competition is crucial.

Table 2. Infestation of weedy rice in rice fields and cultivated rice farms.

Range of weedy rice infestation			
Rice field	Cultivated field	Region	Source
5%-60%	11.32%-44.28%	India	Varshney and Tiwari, 2008
-	32.22-154.94 panicles m^{-2}	Malaysia	Mansor et al., 2012
1.3%-4%	-	Java, Indonesia	Delouche et al., 2007

Weedy rice biology and competition with cultivated rice

Dormancy and germination. Weedy rice exhibits a high competitive ability against cultivated rice and causes severe yield loss that is dependent on density, population, and rice cultivar. As for seed dormancy, weedy rice exhibits primary dormancy with respect to cultivated rice. This was tested by Xia et al. (2011) in their study where mature seeds were collected from individuals of each weedy rice population and rice cultivars and these were directly planted. The germination fractions measured after planting were almost 100% in cultivars at 28 °C. The means of germinated seed among the weedy rice variant populations ranged from 8.9% to 86.8%, which indicates weak to strong primary dormancy. Most of the populations that showed weak dormancy were those collected from a temperate area. The variation in seed dormancy between tropical and temperate weedy rice could be attributed to their evolutionary divergence. Furthermore, research showed that secondary dormancy did not occur in both weedy rice and rice cultivars; weedy rice seeds have the ability to survive at low temperatures in winter and afterward re-establish their population. This attribute is said to be ecotype dependent and influenced by other factors, such as burial depth, soil type, climate, moisture, cultivation practices, magnitude of seed production, and dormancy level (Noldin et al., 2006), even though the lower limit temperature for weedy rice germination was the same as for rice (10 °C). Seed dormancy longevity had the advantage of early colonization of rice fields by the weedy rice variant. The practice of inducing germination before applying fertilizer and subsequent rice planting results in variable dormancy and other factors, such as soil depth, could hinder the complete elimination of the weedy rice variant.

Germination of the weedy rice variant is faster and root development is earlier than in the cultivated rice varieties. This trend was observed by incubating weedy and cultivated rice at temperatures of 25 or 30 °C for 1 wk (Xia et al., 2011). Hence, weedy rice is well adapted to extreme temperatures. Additionally, it can emerge from greater depths than cultivated rice (Noldin et al., 2006). All these attributes account for the ability of weedy rice to compete well with rice cultivars.

Weak dormancy results in uniform germination during planting (Xia et al., 2011) and high variability in the weedy rice variant germination reflects the extent of variation in dormancy. The germination capacity of weedy rice tends to decline with increasing soil depth from 5 to 10 cm; however, weedy rice ceases to emerge below a 4-cm soil depth under flooding conditions (4 to 5 cm) (Ziska et al., 2015). Thus, flooding depth is an opportunity to control weedy rice in early growth stages. This characteristic could differ for some weedy rice variants because of different germination behaviors as observed by Suh and Ha (1993) for Korean weedy rice where weedy rice emergence up to 100% was observed at a 9-cm water depth.

Studies on the effect of the stress tolerance level of weedy rice and rice cultivars have been reported. Uddin et al. (2015) recorded higher germination (100%) in awned and compact weedy rice at salinity up to 16 dS m^{-1}. A lower germination percentage was observed in ‘MR219’ and ‘TQR-8’ (50% to 60%) although weedy rice showed 100% germination; mean germination time (MGT) was higher in all weedy rice biotypes compared to cultivated rice. In the same study, the mean germination index and seedling vigor index were higher for awned, compact, and open biotypes of weedy rice, and they were generally more salt-tolerant compared to cultivated rice ‘MR219’, ‘MR269’, and ‘TQR-8’. In another study by Hakim et al. (2010), germination of rice ‘IR20’, ‘BR29’, ‘BR40’, ‘Pokkali’, ‘MR33’, ‘MR68’, ‘MR84’, ‘MR52’, ‘MR212’, ‘MR219’, ‘MR220’, and ‘MR232’ have been reported to occur at 20 dS m^{-1} salinity, and germination percentages were found to be inversely related to the salinity level. Uddin et al. (2015) used maximum salinity of 16 dS m^{-1} and the upper limit of salinity tolerance of weedy biotypes was therefore not reported. Based on the work by Hakim et al. (2010), it can be observed that tolerance of rice varieties to salinity stress also varies. At the 4 dS m^{-1} salinity level, observed germination was > 90% for ‘MR52’, ‘MR 211’, ‘MR219’, ‘MR232’, ‘BR40’, and the salt-tolerant control ‘Pokkali’. While ‘IR20’, ‘MR33’, ‘MR68’, and ‘MR84’ germinated at rates of 80% to 90%, the lowest germination percentage (< 70%) was recorded for ‘MR220’ and ‘BR29’. Therefore, under salinity stress, weedy rice variants have a higher ability to germinate compared to most rice cultivars (Table 3).

Early life stage. Early vigor, higher tillering ability, and plant height have been reported for weedy rice. For 36 weedy rice morphotypes identified by Zainudin et al. (2010) in Malaysia, the principal component analysis (PCA) of morphological traits showed that most weedy rice variants were grouped in a different axis and had a higher tiller number, longer panicle length, culm height, and leaf length compared to cultivated rice. The early emergence of weedy rice allows prompt establishment and higher competitive ability against cultivated rice. Weedy rice exhibited early germination from a deeper soil depth compared to rice cultivars, and this varies among biotypes. Individual weedy rice plants and biotypes avoid harsh environmental conditions, as well as weed control measures, because of the differences in the emergence period. In Arkansas, the optimum planting period of rice is in mid-April; it was reported that greater differences in the initiation of emergence were observed in the optimum rice planting period than in late April and mid-May planting, which are the late planting periods (Burgos et al., 2011). Therefore, at the early planting date, the effect of weedy rice biotypes on rice cultivars is higher than at late planting dates.

Some populations of weedy rice biotypes were reported to survive after early POST herbicide application due to late emergence or resistance to herbicides compared to rice cultivars (Burgos et al., 2008). The differences in competitive ability of weedy rice biotypes and yield loss in rice fields, especially when the rice field is infested by weedy rice biotypes with higher competitive potential, suggest the need for an intensive weedy rice management approach. Weedy rice control is easy when the rice field is infested by one biotype as compared to a situation where different weedy rice biotypes are present in the field, which makes weedy rice control and management more difficult. Weed management could be cheaper if predominant weedy rice biotypes in an area were identified and management strategies performed to control them. Improving cultivar traits can help overcome the seedling vigor advantage under competition with weedy rice variants.

Growth and development. Starting at seedling emergence, weedy rice significantly affects cultivated rice plant growth (Chauhan, 2013). Several growth parameters of cultivated rice, such as tiller number, plant height, leaf area index, leaf number, and shoot dry mass can be affected by the presence of weedy rice (Ottis et al., 2005) more than in intra-varietal competition in which weedy rice acted as the dominant competitor (Ottis et al., 2005).

The growth of weedy rice can vary among different variants and this affects cultivated rice growth and yield differently. In addition, different rice cultivars can also respond differently to weedy rice variants. In a study in the United States, rice ‘Kaybonnet’ was found to be less competitive than ‘PI 312777’ against weedy rice biotypes (Estorninos et al., 2005). Ratnasekera et al. (2013) evaluated the interactions of weedy rice with improved rice (At 362) under transplanting and direct seeding conditions where the general performance of weedy rice was higher with or without competition. The direct-seeded plot (DSP) significantly contributed to poor performance of rice iinteracting with weedy rice. The highest plant height and tiller number (90.08 ± 12.32 cm and 3.70 ± 1.42, respectively) were found in transplanted weedy rice variants with no competition while the lowest plant height (55.88 cm) and tiller number (2.08) were observed in improved rice in

Table 3. Comparison of germination rates of different weedy rice variants.

Agroecotypes	Variety	Range of germination capacity (%)	Source
Arkansas weedy rice	Blackhull, strawhull, and brownhull	34-84	Burgos et al., 2011
Italian weedy rice	Awnless, awned, and one mucronate	20-80	Fogliatto et al., 2011
Korean weedy rice	-	60-100	Suh and Ha, 1993
Malaysian weedy rice	SP, KP, Besut, and Perlis and KADA strains	19-86	Puteh et al., 2010

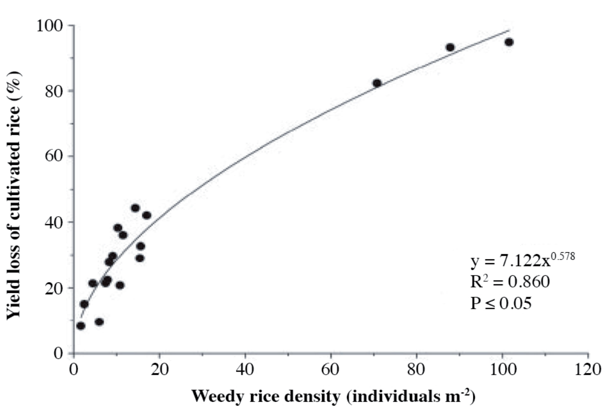
DSP interacting with weeds. Shivrain et al. (2009) reported that 12 ecotypes of weedy rice produced 226 to 462 tillers m^{-2} while the cultivar of inbred rice produced 250 tillers m^{-2} in a competition of 1/19 weedy vs. rice. The effects of weed density on rice growth, higher tillering capacity, and shoot development potential of weedy rice generally decreases grain yield in rice production.

Yields. In a research study conducted in Arkansas by Burgos et al. (2011), the yield of the semi-dwarf rice 'Lemort' begins to be affected by weed rice at a density of 2 plants m^{-2}. To obtain an optimal yield of cultivated rice, the nearly total or total elimination of weed rice variants is essential. Chauhan (2013) reported that, 5 and 20 weedy rice plants m^{-2} caused a yield loss of 40% and 60%, respectively, in 'Oryzical'. In the same study, a 40-d competition of rice with weedy rice variants at emergence resulted in 50% yield loss at a density of 24 weedy rice plants m^{-2}; a longer period of competition resulted in 80% yield loss. This implies that both weedy rice density and duration of competition play a vital role in yield loss.

Ratnasekera et al. (2013) described the different degrees of rice yield loss related to cultivars, agronomic practice, and interference of approximately 32 weedy rice panicles m^{-2} with 64% rice yield loss, 12% more root biomass production, and an increase of sterile spikelets in cultivated rice. Noldin et al. (2006) found that weedy rice at 4, 16, 25, and 300 plants m^{-2} caused 20%, 43%, 58%, and 91% yield loss of rice 'Mars'. Cultivated rice yield loss was also reported between 100 and 755 kg ha^{-1} for every weedy rice plant m^{-1} in a study conducted in the United States by Ottis et al. (2005). Burgos et al. (2011) reported that every individual weedy rice variant is responsible for a mean decrease of 270 kg ha^{-1} in cultivated rice yield with 20 weedy rice plants m^{-2} in a rice field. Therefore, rice yield was drastically reduced when weedy rice density increased in the rice field. A relationship of weedy rice density vs. rice yield modeled by Zhang et al. (2014) is presented in Figure 2.

Effects of added nitrogen. Nitrogen is an important nutrient in the production of rice and other crops because it plays a vital role in photosynthesis and crop yield capacity. It is a major component in many biological compounds and is a constituent of chlorophyll (Rao et al., 2007), secondary metabolites, and co-factor proteins (Marschner, 1995). Approximately 1% to 6% N is present in plants by weight, and it is absorbed from the soil by the plant as nitrate (NO_3^-) and ammonium (NH_4^+). When the plant has high photosynthetic activity, it grows vigorously during the vegetative stage and the dark green color of the leaves shows that N is adequately supplied. Plant density is a major factor in the competition for available N and it is inversely proportional to resources available to the plant (Rao et al., 2007).

Figure 2. Relationship between weedy rice density and yield loss in cultivated rice (Zhang et al., 2014).



Weeds can be effectively managed by incorporating different N rates to the soil to make the crop healthy and have a greater ability to compete with weeds (Khan et al., 2012). This principle has been used by researchers to investigate optimal N for rice competing against weedy variants. However, N is also used by weeds to reduce its availability to crops (Blackshaw et al., 2003). It was reported that high N rates lead to high competition of weeds in corn fields because the weed leaf area index is higher than for corn (Burgos et al., 2008). Burgos et al. (2011) stated that N availability for use by the rice cultivar is further reduced by competition with weedy rice, which has been observed to accumulate N fertilizer, transform it into biomass production, and efficiently convert it into higher biomass production.

The competitive interaction between weedy rice and cultivated rice in terms of added N was studied by Burgos et al. (2011). Weedy rice produces more biomass for every unit of absorbed N than rice cultivars, and weedy rice competitiveness against rice increases as N increases (Burgos et al., 2008). Finer and longer roots in weedy rice variants and the resulting higher root surface area would allow weedy rice to absorb more nutrients than rice cultivars (Sales et al., 2011). This advantage makes weedy rice adapt and grow better even under N-deficient conditions (Sales et al., 2011). Different weedy rice ecotypes respond differently to added N rates when grown in competition with rice cultivars (Chauhan and Johnson, 2011). It was observed that both weedy rice and cultivated rice continue to absorb nutrients without increasing growth, shoot biomass, and yield when N rates were more than 160 to 180 kg N ha^{-1} (Chauhan and Johnson, 2011). While Burgos et al. (2011) observed that weedy rice continued to use added N for biomass production up to 200 kg N ha^{-1}, added N beyond this level was not used by the rice cultivars. This can be exemplified by differences in the behavior of different weedy rice and cultivated rice when N is added.

Therefore, manipulating the condition of N could be effective together with improved cultural practices when weeds are not present in the field. To ensure that only cultivated rice benefits from N that is applied in the rice field, timely removal of weeds is important. A study concluded that the rice field should be kept free of weeds for the first 8 wk to obtain higher grain yields (Chauhan and Johnson, 2011).

Effects of water regimes. Water selectively controls weeds in rice production (Chauhan, 2013). Permanently flooding transplanted rice fields without weeding for 45 d after transplanting allows the growth of different compositions of weed flora as compared to saturated soil. Flooding depth, timing, and duration in conjunction with the crop establishment method governs the exact nature of weed suppression by water.

Transplanting seedlings in standing water for 10 to 15 d afterward affects the dominance hierarchy of semi-aquatic weed species, including competitive grasses (which is now dominating the aquatic weed species), compared to wet seeding of pre-germinated rice in saturated puddled soil (Chauhan, 2013).

Azmi and Karim (2008) reported seven seasons where wet seeding of rice resulted in the emergence of 21 new weed species, especially the *Echinochloa* species and weedy rice. Comparative autecological studies of seed germination, seedlings, and plant growth related to flooding regimes are involved with the selective nature of water for the survival of weed species. Moisture regimes can differ from permanently aerobic moist soils to continuously saturated aerobic soils and saturated soils, which are subjected to different water depths as a result of periodic flooding and draining because of the variation in rainfall or water management policy.

Control of weedy rice infestation in rice fields

Effective control of weedy rice would require a holistic and integrated system incorporating various cultural management strategies, such as tillage system, weed-competitive cultivars, high crop seeding rate, narrow crop-row spacing, crop residue mulching, optimum planting time, and flooding depth, in addition to herbicides and other weed control systems.

Preventive measures

The use of clean rice seeds is very important in managing weedy rice. The distribution of contaminated seeds plays an important role in spreading weedy rice from an infested field (Azmi and Karim, 2008). When a small amount of weedy rice seeds contaminate a rice field, it can cause heavy weedy rice infestation within a year, especially in a field where mono-cropping is practiced. Clean rice seeds can be produced through regular field inspection and by removing weedy rice plants when they emerge and, obviously, at or before flowering. This can be achieved if the farmers are familiar with the cultivars they plant and can differentiate them from weedy rice plants (Delouche et al., 2007), especially when using row planting. Creating awareness about weedy rice among farmers is necessary; machines used for preparing the land, sowing, harvesting, and threshing should be cleaned and free of weedy rice seeds before moving from one field to another; moreover, farmers need to make sure that field margins and irrigation canals are free from weedy rice seeds.

Stale seedbed practices can be applied to reduce the weedy rice seed bank (Chauhan, 2013). When the field is irrigated before tilling and weedy rice seedlings are allowed to germinate, this is followed by tilling the field or using non-selective herbicides to kill the weedy rice plant in the field. Delouche et al. (2007) reported that this practice has reduced the number of weedy rice plants in fields although the efficacy of this method depends on the degree of weedy rice dormancy. Tilling the land could bury weedy rice seeds below the maximum depth of their emergence, so that deep tilling of land that buries seeds below 8 cm can be used to suppress the emergence of weedy rice. It is also suggested that subsequent tilling of land should be shallow in the next few seasons to avoid bringing back the seeds to the surface of the soil. It has been reported that proper leveling of the land prior to tillage operations improves crop establishment, saves energy and water, increases nutrient use efficiency, and improves weed control (Chauhan, 2013).

Transplanting

Transplanted rice seedlings are more competitive against emerging weedy rice than DSR cultivation. It is difficult to distinguish between weedy rice and cultivated rice at early stages in a direct-seeded system because cultivated rice is broadcasted and both weedy and cultivated rice emerge at the same time. The problem of weedy rice infestation could be reduced by reintroducing rice seedling transplanting in weedy rice infested areas with a mechanized transplanting machine. When rice seedlings are transplanted, they are more competitive against the newly emerging weedy rice seedlings, and it is easy to differentiate between weedy and cultivated rice seedlings. The presence of standing water in the field during transplanting also suppresses the emergence of weedy rice (Azmi and Karim, 2008; Chauhan, 2013).

Malaysian farmers have succeeded in reducing weedy rice in their fields by transplanting rice seedlings in one or two cropping seasons after their field was infested by weedy rice using a direct-seeding system. Azmi and Karim (2008) conducted an experiment to determine the effectiveness of mechanical transplanting to control weedy rice; they found a marked decrease in weedy rice infestation after two consecutive seasons using transplanters in which the density of weedy rice panicle was reduced from 58 to 20 m^{-2}. It was reported that machine-transplanted rice seedlings in a 3-yr study reduced more than 90% weedy rice plants in Korea (Kim et al., 2000). The practice of seedling broadcasting is growing seedlings in the nursery and then throwing two or three seedlings into well-puddled soil. A flooding water depth of 5 to 10 cm is enough to suppress weedy rice emergence (Azmi and Karim, 2008).

Seeding rate and row seeding

Weeds can be suppressed by using high seeding rates in several crops (Zhao, 2006). Grain yields of rice infested with weedy rice were reported to increase with an increasing seeding rate from 20 to 80 kg ha^{-1} in direct-seeded rice fields. Azmi and Karim (2008) also pointed out that the weedy rice problem in infested areas can be reduced by high seeding rates. However, this might not necessarily increase yield, but it can suppress weedy rice.

Chauhan and Johnson (2011) conducted a greenhouse experiment and revealed that the shoot biomass of five weedy rice accessions in competition with 60 kg 'IR82' seed ha^{-1} was 13% to 30% less than that of weedy rice plants grown alone. This study suggested that increasing rice crop interference could significantly reduce weedy rice growth. Estorninos et al. (2005) stated that the above-ground biomass and weedy rice grain yield decreased with the increase in the cultivated rice seeding rate from 50 to 150 kg ha^{-1} and, at the same time, rice yield increased with increased crop seeding rates in weedy rice infested fields. High seeding rates could improve the successful reduction of herbicide rates and perceived risks connected to the environmental effect of this chemical.

It is difficult to distinguish weedy rice from cultivated rice in DSR at the early stages until they reach flowering. At this stage, the damage has already been done. Therefore, sowing seeds in rows has its advantages over broadcasting seeds, so that weedy rice emerging between rows can be identified and immediately removed (Chauhan, 2013). In addition, manual weeding of weedy rice is easy when seeds are sown in rows. A seed drill fitted to a two- or four-wheel tractor can be used to sow seed in dry-seeded rice while a drum seeder is used in wet-seeded rice. The problem is that most farmers cannot adapt to the drum seeder because it is difficult to pull in puddled soil. There is a need to develop a seeder that can be easily pulled in puddled soil.

Highly competitive cultivars

The first requirement to develop weed management strategies is the use of weed-competitive cultivars. Early vigor and quick canopy closure are some cultivar features that are more competitive against weeds. Modern short-statured cultivars produce higher yields than local tall cultivars, which are found to be more competitive but have low yields (Chauhan, 2013). Azmi and Kairm (2008) reported that the 'IR64' rice variety matured earlier than weedy rice; when 'IR64' was harvested, weedy rice was only at the flowering stage, which helped to reduce the weedy rice seed bank.

Growing cultivars with purple-colored leaves may also help to reduce the weedy rice seed banks, especially in DSR where weedy rice emergence can be easily differentiated and the plant can be pulled out from the rice field. For example, 'P502' is being planted in the eastern parts of India to minimize weedy rice infestation (Tewari, 2008). In the state of Himachal Pradesh, India, farmers have already adapted to the practice of planting rice cultivars with purple leaves ('R585') in weedy rice infested fields (Kaushik et al., 2011). Weeding operations are carried out by farmers to remove weeds and any green leaf plants; weedy rice is therefore removed from their field.

Cultivars with purple-colored leaves can substantially minimize the weedy rice seed bank when planted in a season in double- or triple-crop rice systems. These cultivars produce low yields and farmers do not like to grow them, but it is a better option than leaving the field uncultivated due to high weedy rice infestation. Purple-stemmed cultivars with high yield potential and green foliage can also assist in getting rid of weedy rice plants. Tewari (2008) stated that farmers in eastern India are trying to adapt to growing purple-based cultivars in weedy rice infested fields, and efforts should be made in breeding to increase the yield potential of these purple-colored cultivars.

Nitrogen and water management

In the production of non-legume crops, N is the key nutrient element. It plays a vital role in photosynthetic activities and crop yield capacity because it is a component in many biological compounds (Chauhan and Johnson, 2011). Nitrogen is one of the most important inorganic macronutrients and is the limiting factor in crop productivity. It is the major constituent of secondary metabolites, co-factor proteins that affect all the plant functions at all levels (Marschner, 1995). When the plant has high photosynthetic activity, it grows vigorously during the vegetative stage and the dark green color of the leaves shows that N is adequately supplied. Photosynthesis is regulated in plants to balance the C flux through optimized N resource distribution (Khan et al., 2012). The C status modulates the effect of N supply on overall plant growth, and the development of other metabolic pathways can be affected by plant N deficiency. Plant density is a major factor in competition; it is inversely proportional to the resources available to the plant (Chauhan and Johnson, 2011).

Weeds could be effectively managed by incorporating different N rates to the soil to make the crop healthy and have a greater ability to compete with weeds (Khan et al., 2012). Apart from reducing N that is available to the crop, weeds grow intensively under increasing N levels (Blackshaw et al., 2003). It was reported that high N rates lead to high competition of weeds in corn fields because the leaf area index of the weeds is higher than that of corn (Burgos et al., 2008). It was found in a study that the influence of N on weed emergence is dependent on the weed species, seed source, and environmental conditions. In another study about the effect of N on weed emergence and weed growth parameters, it was found that N influences germination, emergence, and competitiveness of different weeds (Sweeney et al., 2008). Burgos et al. (2011) stated that N availability for use by rice cultivars is further reduced by competition with weedy rice, which has been observed to accumulate N fertilizer and efficiently transform it into biomass production. Weedy rice has physiological and morphological structures that give it more competitive advantages over rice cultivars even in adapting to poor N conditions, and it can take N to produce more biomass than rice cultivars under the same conditions.

Water is among the powerful selective agents for weed control in rice production. Permanently flooding transplanted rice fields without weeding for 45 d after transplanting (DAT) allows the growth of weed flora that are different from the field where the soil water is kept saturated. Flooding depth, timing, and duration in conjunction with the crop establishment method governs the exact nature of weed suppression by water. Transplanting seedlings in standing water affects the dominance hierarchy of weeds in which semi-aquatic species, including competitive grasses, replaces the aquatic dicotyledon species when it is flooded for 10 to 15 d afterward as compared to wet seeding of pre-germinated rice in saturated puddled soil. Azmi and Karim (2008) reported that wet seeding of rice for seven seasons resulted in the emergence of 21 new weed species, especially the *Echinochloa* species and forms of weedy rice. Comparative autecological studies of seed germination and seedling and plant growth as related to flooding regimes is necessary to understand the process involved in the selective nature of water for the survival of weed species. Moisture regimes can differ from permanently aerobic moist soils to continuously saturated aerobic soils and saturated soils, which are subjected to different water depths as a result of periodic flooding and draining because of the variation in rainfall or water management policy. A proper understanding and management of cultural methods, especially water regime and N application, would efficiently control weedy rice; additional investigation will also be needed to achieve the desired output. In any rice establishment system, water management plays an important role for managing weeds. Flooding is one of the important components for cultural weed management in rice and the growth of weedy rice is affected by optimal timing, duration, and flooding depth (Chauhan and Johnson, 2011; Chauhan, 2013). Weedy rice infestation could be reduced when flooding is carried out at the early stages (Chauhan and Johnson, 2011). A flooding depth of 5 cm or more was reported to suppress germination and emergence of weedy rice in Vietnam (Chin et al., 2000). In Malaysia, Azmi and Karim (2008) suggested a flooding depth of 5 to 10 cm to reduce the emergence of weedy rice. Fogliatto et al. (2011), in a study conducted in Italy, reported a greater reduction in the number of weedy rice seeds on the soil surface when winter flooding occurred between rice crops as compared to fields left dry between crops. Another study in the Philippines showed that a flooding depth of 0 to 8 cm had no or less effect on seedling emergence in four accessions of weedy rice when seeds were sown on the soil surface (Chauhan, 2013); however, when seeds were sown at a 1 cm depth in the soil, flooding decreased emergence and seedling biomass of all weedy rice accessions by more than 85% in the same study.

There is flooding during crop establishment in the wet seeding system while in the DSR system, flooding is usually carried out after crop emergence when it is too late to control weedy rice seedlings. When weedy rice emerges together with cultivated rice seedlings, the situation may be very hard to control by flooding (Chauhan, 2013). Cultivars with the potential of emerging from anaerobic soil conditions play an important role in suppressing weedy rice emergence and growth when the crop is also emerging in the DSR system (Chauhan, 2013). When there is water management, manual weeding would be easier and faster than in situations where water management is poor. In the absence of standing water, herbicides used for weed control would perform poorly (Allard et al., 2005). The availability of standing water with a small amount of propanol could be used and also be applied after crop growth. Chauhan (2013) stated that good water management and chemical weed control provide moisture conservation and reduce rice production costs because the use of herbicides should supplement good water management.

Herbicide use

Selective herbicides are not available to control weedy rice in rice fields because both weedy and cultivated rice belong to the same species and have similar anatomical and physiological traits. Therefore, pre-planting herbicide application is required. This technique is called the stale seedbed technique in which a non-selective herbicide is applied after seedling emergence of weedy rice. In Malaysia, the weedy rice seed bank was reduced by applying pretilachlor before or immediately after tillage under standing water conditions. In this situation, standing water was left in the field for 2 to 4 d before draining. Then the pre-germinated seeds of cultivated rice were planted by broadcasting. Allard et al. (2005) reported that applying pretilachlor by dripping the slightly diluted or concentrated herbicide directly into the water during the last leveling effectively controls weedy rice in Thailand.

Herbicides, such as oxadiazon and metolachlor, offer effective weedy rice control, but these herbicides should be applied at least 15 d before rice planting to avoid the phytotoxic effect on rice (Estorninos et al., 2005). In an intensive rice-based cropping system, there is a need to evaluate the possibility of using herbicides to control weedy rice in situations where the time interval between the two crops is short.

CONCLUSIONS

Geographic origin (latitude) of weedy rice biotypes, their mixture ratio under competition with the crop, and their genetic diversity are determining factors in the outcome of competition and the associated decline in the rice crop yield. Genetic improvement approaches through the development of more highly competitive and weed-suppressing rice cultivars, in addition to other weed management methods, such as chemical application, will minimize the effects of weedy rice. The management of heavily infested fields ensures that the soil seed bank is reduced through, for example, crop rotation, tillage operations, and fallowing; this would be recommended before other weedy rice control measures. Similarly, adopting different cultural practices that enhance weedy rice suppression should be encouraged.

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