

Chapter 13

Weedy rice (*Oryza* spp.)

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Introduction

Rice is a crop of paramount importance for global food and nutritional security as rice is a staple cereal for more than half of the world population, the majority of whom are in rapidly growing low-income countries (Maclean et al., 2013). Worldwide, rice is annually grown on 167 million hectares with a production of 782 million tons (MT) of paddy, out of which 90% of rice is grown (146 million hectares) and produced (705 MT paddy) in Asia (FAOSTAT, 2018; Table 13.1). Rice contributes to a major share of total calorie and protein intake (Table 13.1). It is projected that an additional 63 MT of milled rice would be needed by 2030 to meet the global rice demand of the rising world population which is expected to be ~8.5 billion (RICE, 2016). In the future, this additional rice has to be produced with lower water, labor, and agrochemicals while buffering the risks of climate change to ensure global food security and environmental sustainability. Closing the existing rice yield gaps caused by weed competition is one approach to achieve this target as actual global yield losses in rice due to weeds is about 10% (Oerke, 2005).

Worldwide, rice is cultivated primarily by two methods—puddled transplanted rice (PTR) and direct-seeded rice (DSR). In PTR, rice seedlings are first grown in a nursery, and then seedlings are uprooted and transplanted into puddled soil (wet tillage) in the main field. In DSR, rice seeds are sown directly in the main field and it eliminates the process of nursery raising, seedling uprooting, and transplanting. DSR is further divided into three

TABLE 13.1 Area, production, productivity, share of rice in total calorie and protein intake worldwide and Asia.

Region	Area (million ha)	Production (million tons)	Productivity (t/ha)	Rice calorie intake (% of total/day) ^a	Rice protein intake (% of total/day) ^a
World	167	782	4.68	19.0	12.7
Asia	146	705	4.83	28.6	19.3
South Asia	62	251	4.02	28.8	21.9
Southeast Asia	50	221	4.42	46.5	35.8
Eastern Asia	33	231	6.97	26.3	15.5

FAOSTAT. 2018. FAOSTAT Database. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO). Retrieved July 30, 2020, from <http://www.fao.org/faostat/en/#home>.

^aBased on 2011 data.

types: (1) dry-DSR (dry ungerminated seeds are sown in nonpuddled soil), (2) wet-DSR (pregerminated seeds are sown on puddled soil), and (3) water-seeding [pregerminated seeds are sown in standing water on either puddled (in Asia) or nonpuddled soil (in the United States and Australia)] (Kumar and Ladha, 2011; Rao et al., 2017). PTR is a predominant method in Asian and African countries, whereas rice is grown by DSR methods in the United States, Australia, and Europe.

Recently, farmers in Asia are shifting from PTR to DSR in response to the major drivers of rural change in the region, especially rising labor, water scarcity, and cost of cultivation as DSR saves on labor, water, and cost of cultivation and hence increases farmers' net income (Kumar and Ladha, 2011; Rao et al., 2017). DSR has also emerged as an option to reduce greenhouse gas emissions (Chakraborty et al., 2017; Kumar and Ladha, 2011). Because of these drivers of agricultural change and benefits, DSR is now practiced widely in many Asian countries including Malaysia, Sri Lanka, Vietnam, Thailand, Cambodia, and the Philippines, and many other countries including China and India are going through this transition from PTR to DSR. In the future, more area is expected to shift from PTR to DSR as these drivers become stronger.

Weedy rice (*Oryza* spp.), also known as red rice in the United States, has emerged as one of the major global threats to rice production in DSR-based

systems (Ziska et al., 2015). In countries where DSR is the dominant crop establishment method (e.g., the United States, Brazil) or where transplanting is widely replaced with DSR (e.g., Malaysia, Sri Lanka, Thailand, Vietnam), weedy rice has emerged as dominant weed species and a threat to the sustainability of rice production (Ziska et al., 2015). With the increasing shift from PTR to DSR in several other countries in Asia and Africa, the global problem of weedy rice is expected to be exacerbated further in the future.

Weedy rice grows unintentionally and competes vigorously with cultivated rice and is similar (morphologically, genetically, and phenologically) to cultivated rice and often (not always) a red pericarp. These factors make weedy rice highly competitive and difficult-to-control weed in rice. It has been reported that weedy rice can cause severe yield losses ranging from 15%–100% (Kumar and Ladha, 2011). In addition to yield losses, weedy rice infestation reduces the grain quality leading to a reduced value of rice at harvest, and therefore, ultimately reduces farmers' net income (Ottis et al., 2005).

There are limited in-crop control options for weedy rice because of its close similarity to cultivated rice. Even hand-weeding is challenging at an early stage because it is difficult to differentiate weedy rice seedlings from rice seedlings. Also, success in selective control (in-crop) of weedy rice with herbicides has not been achieved because rice and weedy rice respond similarly to herbicides (Chauhan, 2012a). So far, selective in-crop weedy rice control has been achieved with herbicide-tolerant (HT) rice varieties only (Burgos et al., 2008). It is, therefore, important to develop and deploy integrated options to manage weedy rice which are based on a strong foundation of knowledge of biology and ecology of weedy rice.

The purpose of this chapter is to synthesize up-to-date knowledge of weedy rice on (1) its origin and dispersal; (2) biology and ecology; and (3) management so that researchers, extensionists, and farmers can utilize this information to minimize the risks associated with weedy rice in their region.

Weedy rice: its origin and dispersal

Origin of weedy rice

Hypotheses for the origins of weedy rice have traditionally considered four potential models: (1) descent from wild rice populations that have invaded agricultural habitats; (2) emergence from crop-wild hybrids; (3) emergence from intervarietal hybridization within domesticated rice; and (4) direct descent from rice varieties or landraces through dedomestication (feralization). In the last two decades, the availability of high-quality rice reference genomes, together with increasingly cost-effective sequencing and genotyping technologies, has enabled multiple genetic studies of weedy rice populations around the world (Li and Olsen, 2020; Qiu et al., 2020). This accumulated research has

made it clear that with few exceptions (described below), the vast majority of weedy rice strains are descended primarily from domesticated ancestors (model #4). These studies have also definitively established that weedy rice has evolved multiple times independently from different crop varieties and that strains that have convergently evolved shared weediness traits such as seed shattering and dormancy.

Another important insight from these recent population genetic studies is that the dynamics of weedy rice evolution differ markedly between world regions within and outside the distribution range of common wild rice (*Oryza rufipogon* Griffiths). In regions of tropical Asia where the wild progenitor species occurs, gene flow between wild, cultivated, and weedy rice appears to add a level of genetic complexity that is absent from weedy rice outside the geographical range of the wild species (Neik et al., 2019). For this reason, following sections first examine weedy rice origins and evolution in areas outside the range of common wild rice, and then consider weedy rice evolution within areas of overlap (Fig. 13.1).

Regions without *O. rufipogon*

Most weedy rice population genetic and evolutionary studies have been conducted in regions where there is no common wild rice present. These include the United States, Brazil, Colombia, Italy, Spain, northern China, Japan, Taiwan, and South Korea. Among these countries, the occurrence and spread of weedy rice in the United States has been particularly well documented. Both neutral marker [e.g., simple sequence repeat (SSR), single nucleotide polymorphism (SNP); Li et al., 2017; Reagon et al., 2010] and candidate

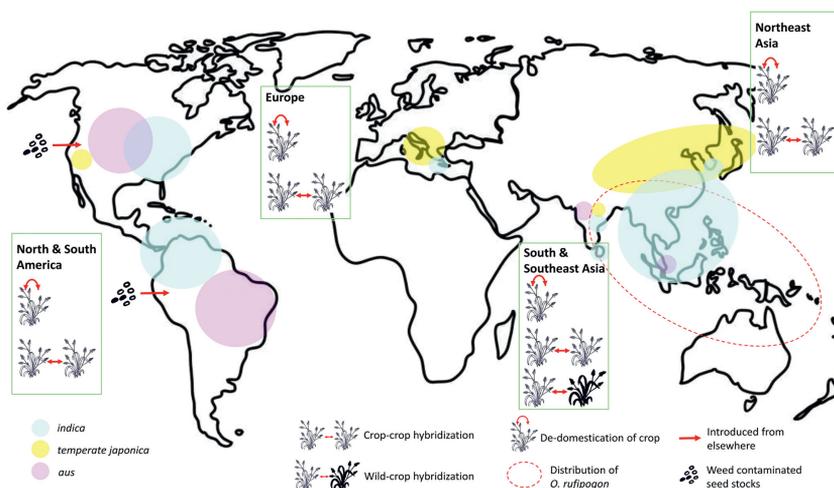


FIGURE 13.1 Global occurrence and ancestry of weedy rice.

gene analyses [e.g., *sh4*, conferring shattering (Thurber et al., 2010); *Bh4*, controlling hull color (Vigueira et al., 2013); *Rc*, conferring pericarp color and seed dormancy, (Gross et al., 2010)] revealed that the US weedy rice strains are genetically closest to cultivated rice grown in Asia. Specifically, the two major southern US weedy rice morphotypes, referred to as strawhull awnless (SH) and blackhull awned (BHA) weeds, are genetically most similar to domesticated *indica* and *aus* varieties, respectively. Given that neither *indica* nor *aus* rice has been commercially cultivated in the United States, it is likely that these weeds were accidentally introduced through contaminated seed stocks (Reagon et al., 2010). Studies using SSR and genome-wide SNP datasets further substantiate the dedomestication model for the US weedy rice. A recent study using SNPs derived from whole-genome resequencing indicated that SH weeds diverged from *indica* rice much later than BHA strains from *aus* varieties (Li et al., 2017). Similar to weedy rice morphotypes in the southern United States, Californian strawhull awned (SHA) weedy rice, which is genetically related to temperate *japonica* rice planted in California, appears to have been introduced from outside the United States (Kanapeckas et al., 2016).

Using morphological and genetic markers including SSRs and genome-wide SNPs, similar dedomestication results have been inferred for weedy rice populations studied in Latin America (Federici et al., 2001; Hoyos et al., 2020; Qiu et al., 2020), northern China (Cao et al., 2007; Qiu et al., 2017; Qiu et al., 2020), Italy (Grimm et al., 2013), South Korea (Kim et al., 2016; Vigueira et al., 2019), and Japan (Akasaka et al., 2009; Kawasaki et al., 2009; Qiu et al., 2020). In Central and South America, the presence of the reproductively compatible (AA genome) wild rice species, *O. glumaepatula* Steud., has led to speculation that this native wild species might be contributing to the evolution of local weedy strains (Hoyos et al., 2020; Qiu et al., 2020). However, morphological, genetic, and genomic studies (Arrieta-Espinoza et al., 2005; Qiu et al., 2020) do not support this hypothesis.

In China, population genetic analyses have revealed that most crop- and wild-like weedy rice strains are genetically closer to local *japonica* cultivars than to *indica* or common wild rice, suggesting a role for *japonica* dedomestication in their origin (Cao et al., 2007; Sun et al., 2013; Qiu et al., 2017). Using whole-genome resequencing, similar observations of dedomestication in China were recently reported (Qiu et al., 2020), with weedy rice accessions showing the highest kinship with co-occurring cultivars or varieties from nearby regions. Genome scans further indicate that selection on genomic regions that were not targets of selection during domestication may have facilitated feralization of cultivated rice and conferred weedy adaptations in present-day weedy rice strains.

Whole-genome sequence analysis of South Korean weedy rice has suggested a crop–weed hybridization mechanism where local landraces were found to have crossed with co-occurring modern rice cultivars (He et al., 2017).

In contrast, weedy rice strains in Bhutan were found to have originated from natural hybridization between local *indica* and *japonica* cultivars (Ishikawa et al., 2005). A recent population genomic study of Latin American weedy populations revealed that approximately 54% of the 95 weedy rice genomes examined comprise *aus-indica* admixed genotypes, suggesting that many Latin American weedy rice strains originated through recent hybridization of local weedy rice populations. Similarly, an *indica-japonica* hybridization origin has been reported for weedy rice in eastern China, where *indica* cultivars were recently replaced by *japonica* rice (Qiu et al., 2014).

Regions with *O. rufipogon*

As the wild progenitor of Asian rice, common wild rice has played an important role in contributing to modern rice breeding (Morishima et al., 1984; Oka, 1988). It is distributed over tropical and subtropical countries from western India through Southeast Asia and southern China. In South and Southeast Asia, where co-occurrence of cultivated and common wild rice is common, genetic diversity of weedy rice populations is influenced by contemporary introgression from proximal wild populations (Pusadee et al., 2012; Song et al., 2014; Wedger et al., 2019).

In Malaysia, for example, SSRs and genome-wide SNPs were used to demonstrate hybridization between the common wild rice and cultivated or weedy rice (Song et al., 2014; Neik et al., 2019; Vigueira et al., 2019). Specifically, Malaysian common wild rice is most likely the major contributor to the evolution of brown-striped-like and BHA-like weedy rice that are abundant in parts of Peninsular Malaysia. As a complement to the neutral marker studies, findings of heterozygous copies of candidate genes (e.g., *sh4*, *Bh4*, *Rc*, *An-1*) in Malaysian weedy rice samples suggest recent introgression into weed strains from both common wild rice and modern elite cultivars (Song et al., 2014; Cui et al., 2016; Neik et al., 2019).

Such intercrossing and hybridization between rice crops and local *O. rufipogon* were also found in Thailand (Pusadee et al., 2012). Natural gene flow occurring in fields has contributed to the wild-like adaptive traits of weedy rice types (e.g., easy seed shattering, presence of awns, open panicles), which promote their invasiveness in rice planting areas (Niruntrayakul et al., 2009; Wedger et al., 2019). Intercrosses among wild, weedy, and cultivated rice, although occurring at low rates (<1%), would assist the migration of alleles from wild rice to cultivars, or vice versa (Cao et al., 2006; Chen et al., 2004; Gealy et al., 2003).

In South Asia, wild-like weedy rice genomic analyses based on genome-wide SNP data demonstrate a major wild rice ancestry contribution (Huang et al., 2017). Although this weedy rice evolution suggests adaptive introgression from local common wild rice populations, weedy rice samples collected

from Bangladesh, Myanmar, India, Nepal, Pakistan, and Sri Lanka show a heterogeneous genetic makeup, suggesting that cultivated varieties (*aus* and *indica*) also play a major role in the evolution of the weedy rice (Qiu et al., 2020). Such crop-to-crop and crop-to-weed allelic introgression in weedy rice populations was also found in Malaysia (Neik et al., 2019; Song et al., 2014), Thailand (Pusadee et al., 2012), southern China (Qiu et al., 2020), and Taiwan (Wu et al., 2020), indicating that continuous introgression from rice cultivars can contribute to the adaptive and crop mimicry nature of weedy rice.

Dispersal of weedy rice

Knowledge of weedy rice dispersal mechanisms in DSR systems can help to prevent its spread and in identifying management strategies based on dispersal prevention. The use of contaminated rice seeds is one of the most important dispersal mechanisms for weedy rice (Singh et al., 2013; Rao et al., 2017). This mechanism plays an even more vital role in regions where farmers use their saved seeds instead of certified seeds, and where farmers use high seeding rates in DSR systems (Rao et al., 2017). Another important mechanism of weedy rice dispersal reported is through farm machinery/equipment movement within a field and from one field to another without cleaning (Singh et al., 2013; Gao et al., 2018). Widespread occurrence of weedy rice in several countries (e.g., Malaysia, Vietnam, China, and Cambodia) in Southeast Asia is linked with the increased use of combine harvester on a rental basis (Vaughan et al., 1995). Other possible dispersal mechanisms of weedy rice reported include irrigation channels or irrigation water, heavy winds or storms, and flooding.

Biology and ecology of weedy rice

Knowledge of ecology and biology of weedy rice can help in designing weedy rice control tactics. Understanding of factors affecting seed dormancy, seed shattering, seed longevity, seed mortality, and emergence and growth of seedlings would help in identifying weak points for weedy rice management. These have been discussed below:

Seed dormancy

Seed dormancy is an adaptive trait contributing to its success to adapt and survive in rice ecosystems. A large variation in seed dormancy of weedy has been reported with no dormancy (Xia et al., 2011) to few days to several years depending on the biotype and seed storage conditions after its harvest (Vidotto and Ferrero, 2000; Tseng et al., 2013). This variation in dormancy in weedy rice is attributed to genetic factors [> 10 interacting quantitative

trait loci (QTL) reported to regulate dormancy] and environmental factors [weather conditions during seed development and storage conditions (moisture and temperature)] (Ziska et al., 2015; Leopold et al., 1988). Leopold et al. (1988) reported that weedy rice lost dormancy faster at 6%–14% moisture content but dormancy loss was very low when the moisture content was < 5% or >18% (Leopold et al., 1988). This information can be exploited for weedy rice management by using tillage intelligently to bring grain moisture in the range of 6%–14% and then using stale seedbed. Dormancy-breaking chemicals have been found effective in breaking weedy rice dormancy in laboratory experiments (Cohn, 2002); however, factors that contribute to the release of weedy rice dormancy under field conditions are not yet fully characterized (Ziska et al., 2015). Therefore there is a need for more research to identify dormancy-breaking factors under field conditions, so that weedy rice seedbank can be minimized using techniques like stale seedbed. Generally, light is not required for the germination of weedy rice but some photoblastic weedy rice biotypes from Korea have been reported, whose germination will be increased with exposure to light (Chung and Paek, 2003)

Seed longevity

In weedy rice, seed longevity is associated with seed dormancy and presence of red pericarp (Xia et al., 2011). The longevity of weedy rice in the soil is influenced by dormancy, seed burial depth, soil moisture, and varied with biotypes (Noldin, 2000). It has been reported that the longevity of weedy rice increased with an increase in seed burial depth (Noldin et al., 2006). For example, at Beaumont, Texas, when weedy rice biotypes were buried at 5-cm depth, all biotypes lost viability within 5 months except three biotypes whose viability was <1%. However, when weedy rice seeds were buried at 25 cm, seeds of nine biotypes remained viable (ranged from <1% to 12%) even after 2 years. Seeds of cultivated rice did not survive longer than 5 months irrespective of burial depth. In Sri Lanka also, it was found that weedy rice seeds can remain viable for up to 2 years and higher viability when buried deeper (30 cm) than at shallow depth (15 cm), whereas cultivated rice lost viability within 16 weeks of burial (Ratnasekera, 2015). A study conducted in Vietnam found that weedy rice seed viability declined faster under moist conditions than under submerged conditions (Chin et al., 2000). They found 52% and 27% of seeds remained viable after 4 months under submerged and moist conditions, respectively. Under room conditions, *indica*-type weedy rice from Korea had longer seed viability than *japonica*-type weedy rice. However, overwinter survival of weedy rice seeds in the field was observed higher in *japonica*-type weedy rice than *indica*-type weedy rice (50% germination vs 10%) (Kyoung et al., 1999). The country-specific knowledge and factors influencing weedy rice seed longevity would help in

the development of ecological-based weed management including designing crop rotation duration.

Seed decay/mortality

Understanding factors influencing weedy rice seed decay in the soil can have important implications for management targeting weed seedbank of weedy rice. However, information on factors affecting the decay of weedy rice in DSR systems is meager. Soil moisture has been probably best documented for its influence on weedy rice seed decay. For example, winter flooding in Italy between rice crops reduced the viability of weedy rice seeds on the soil surface by >95% compared to a reduction by 26%–76% when the field is left dry (Fogliatto et al., 2010). The study concluded that the reduction in viability was partly due to seed decay of nongerminated seeds under low-temperature conditions and flooding. However, another study conducted in Korea by Baek and Chung (2012) also observed that winter flooding reduced the germination of weedy rice but the effect was not as dramatic as reported by Fogliatto et al. (2010). They observed that >60% weedy rice seeds could overwinter under flooded conditions, whereas in dry conditions, about 90% weedy rice seeds could overwinter.

Seed shattering

Seed shattering trait is one of the seed dispersal mechanisms for weedy rice (Ziska et al., 2015). Early shattering in weedy rice may also prevent drying of seeds and loss of seed dormancy as high moisture content confers greater levels of dormancy (Leopold et al., 1988). A large variation in the time and degree of seed shattering has been reported in weedy rice biotypes. Across the US rice belt, on average, seed shattering in weedy rice starts 15 days after anthesis (Noldin et al., 1999). In Vietnam, the onset of the shattering starts from 7 to 15 days after flowering, and the degree of shattering ranged from 20% to 94% (Chin et al., 2000). In Sri Lanka also, the extent of seed shattering is quite variable among biotypes (Ratnasekera, 2015). These results suggest that roughing should not be delayed after anthesis and should be done maximum at anthesis to avoid seed shattering.

Emergence and early growth

Weedy rice emergence generally declines with an increase in seed burial depth under both moist as well as flooded conditions. Weedy rice could sprout from soil up to 8 cm of flooding depth (Chauhan, 2012b) and had 50% or even higher emergence rate at 10 cm of flooding depth (Ghosh et al., 2017a,b). The emergence rate of weedy rice seedlings was 92%–45% in 0–5 cm saturated soil layers (Vidotto and Ferrero, 2000). Although the

emergence rate gradually decreased with the increase in soil depth (Zhang et al., 2019), it could still emerge when the soil depth reached 10 cm under saturated conditions (Vidotto and Ferrero, 2000). Weedy rice has early growth survival strategies for persisting in the field. The seedling growth vigor is attributed to stronger photosynthetic ability in leaves than cultivated rice at early seedling stages (Dai et al., 2017). Early tillering and early maturity are the two important traits associated with weedy rice competitiveness against the commercial variety (Estorninos et al., 2002). Shivrain et al. (2009) reported 12 biotypes of weedy rice produced 226–462 tillers/m², whereas the cultivar of inbred rice produced 250 tillers/m² at 1:19 (weedy rice:cultivated rice) ratio. Early maturity is a key survival strategy that allows weedy rice to escape from harvesting, which has been reported in many countries including India, China, Costa Rica, and Malaysia (Zhao et al., 2018). The early maturity in weedy rice is attributed to the combination of early flowering and shorter grain-filling stages due to faster grain filling (7–21 days) than cultivated rice (Zhao et al., 2018).

Diversity in weedy rice

Weedy rice is rich in morphological polymorphism and phenotypic plasticity (Andres et al., 2015). In Malaysia, different weedy rice biotypes were reported: (1) taller, shorter, and similar height as the cultivated rice (Fig. 13.2); (2) erect, horizontal, and descending flag leaves (Fig. 13.3); (3) open and closed panicles (Fig. 13.3); (4) easy shattering and nonshattering seeds (Fig. 13.4); and (5) awned and awnless seeds (Fig. 13.4) (Dilipkumar et al., 2020). The morphology, karyotype, and genetic diversity of weedy rice in different regions of the world have been extensively studied (Suh et al., 1997). Tang and Morishima (1997) classified 24 weedy rice populations from China, Japan, and South Korea into wild-like rice type and cultivated-like rice type according to the seed shattering, dormancy, and 1000 grain weight. The classification criteria of phenol reaction, potassium chlorate resistance, lemma hair length, and the isozyme analysis of 11 loci further demonstrates various classification of *indica*-like, *indica*-like autotype, and *japonica*-like autotype (Tang and Morishima, 1997). According to



FIGURE 13.2 Weedy rice height taller (A), shorter (B), and similar (C) as cultivated rice (Dilipkumar et al., 2020).

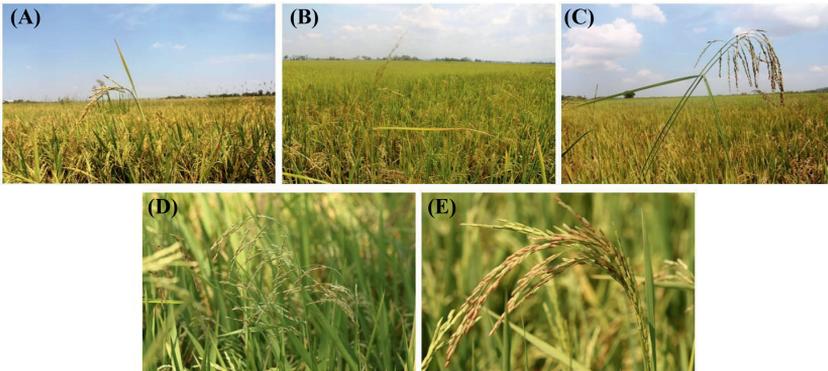


FIGURE 13.3 Weedy rice with erect (A), horizontal (B), and descending flag leaves (C), open (D), and closed (E) panicles (Dilipkumar et al., 2020).



FIGURE 13.4 Weedy rice seeds with easy shattering (A), nonshattering (B) characteristics, awned (C), and awnless (D) seeds (Dilipkumar et al., 2020).

the color of awns and glumes, weedy rice in the United States can be divided into two categories: yellow awn rice husk and awn black husk (Noldin et al., 1999), with the former accounting for the majority (Shivrain et al., 2010a,b). Their morphological differences may originate from different Asian cultivated rice varieties (Londo and Schaal, 2007). In conclusion, global weedy

rice may be roughly divided into four types (Suh et al., 1997): (1) wild-type weedy rice: similar to wild rice, such as easy shattering, long awn, black or purple glume, and red pericarp; (2) cultivated-type weedy rice: similar characteristics with cultivated rice, such as weak shattering, awnless or short awn, yellow or brown glume, and white pericarp; (3) *japonica* weedy rice: shorter grain length, less tillers, shorter plant height, and seed setting; and (4) *indica* weedy rice: longer grain length, more tillers, higher plant height, larger seed setting, but slightly smaller 1000 grain weight. Phenotypic diversity in weedy rice is reflection of underlying genetic variability and just phenotypic diversity information is not enough but intervention at the molecular level to understand genetic diversity is critical in devising management strategy (Rathore et al., 2016)

Management of weedy rice

Greater morphological and genetic diversity and close similarity of weedy rice to cultivated rice make it difficult to obtain the best control of weedy rice with any single method. Therefore to manage weedy rice in DSR systems effectively and sustainably, an integrated approach based on the combination of preventive, cultural, mechanical, chemical, and biotechnological methods is required (Fig. 13.5).

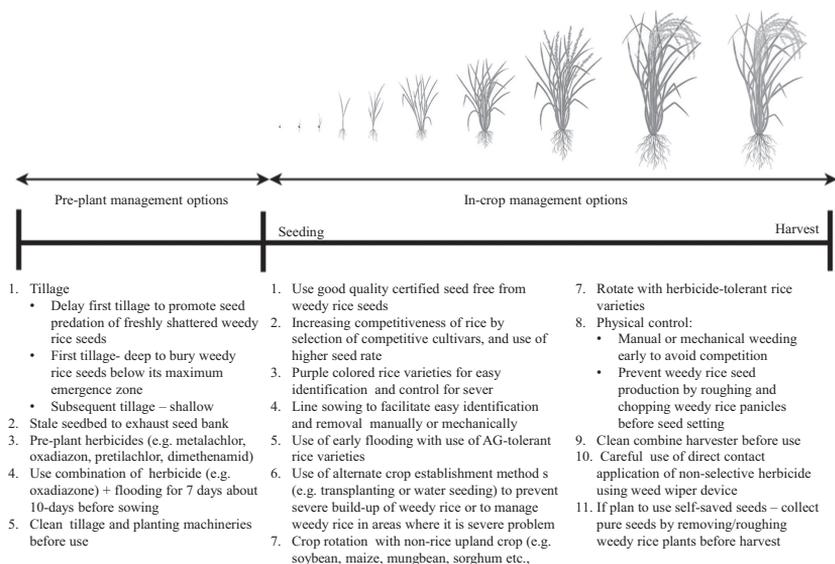


FIGURE 13.5 Integrated weed management options before sowing (preplant period) and after sowing (in-crop period) for weedy rice control.

Preventive method

As part of integrated weed management strategy, early detection and prevention are the first steps to minimize the infestation and spread of weedy rice in DSR systems. Increasing awareness of farmers, extension personnel, and researchers about the potential risks and problems imposed by weedy rice and the importance of its prevention is the first important step to develop successful strategies to combat the weed. A survey conducted by Mishra et al. (2017) revealed that about 58% of farmers in tribal areas of Madhya Pradesh, India do not know that weedy rice is a type of weed in the rice field. Monitoring for the emergence of weedy rice in a new area is important to avoid its invasion and for making timely management decisions. In DSR, the use of rice seeds contaminated with weedy rice is considered one of the main factors contributing to introduction and spread of weedy rice to new areas (Kumar and Ladha, 2011; Ziska et al., 2015). In many Asian countries where DSR is widely practiced, farmers use their own-saved seeds and the quality of farmers' own-saved seeds is often poor with weed seed contaminants including weedy rice. Noldin (2000) estimated that if paddy seed contaminated with two weedy rice seeds per kg of paddy seed is planted can produce 100 kg/ha weedy rice seeds within three seasons. The contamination level generally far exceeds this level in most of the Asian countries. For example, in Cambodia, 92% of surveyed paddy seed samples were contaminated with 524 weedy rice seeds per kg of paddy seed (Chhun et al., 2020). In Vietnam, more than one-third of surveyed paddy seed samples were found contaminated with weedy rice, and 314 weedy rice seeds were found per kg of paddy seed (Mai et al., 2000). In Thailand, up to 4000 weedy rice seeds in 1 kg of paddy seed were found (Maneechote et al., 2004). In the United States, Norsworthy et al. (2007) reported that rice seed contamination is one of the important factors of weedy rice spread in Arkansas as weedy rice seeds have been observed even in certified seeds.

Therefore it is widely accepted that the use of certified seeds free from weedy rice seeds is one of the effective strategies to prevent the introduction and spread of weedy rice in DSR. Chauhan et al. (2014) in a field study from Sri Lanka found that the use of clean rice seeds in the broadcast DSR method reduced weedy rice seed production by 29%–41% and increased rice yield compared to farmers' practice of broadcast DSR with their own-saved seeds. Besides, weedy rice also spreads rapidly within and between fields through agricultural implements (Saha et al., 2014). Machinery should be cleaned before moving it to new areas to prevent contamination. For example, combine harvesting is considered a major cause for the spread of weedy rice in several Southeast Asian countries (Vaughan et al., 1995).

Cultural and mechanical methods

Stale seedbed technique and tillage

Many studies reported that weed establishment in the forthcoming crop can be dramatically decreased if using the stale seedbed technique (Singh et al.,

2018; Kumar et al., 2013; John and Mathew, 2001). This method involves wetting the soil to stimulate weedy rice to establish well before sowing the rice and then emerged weedy rice seedlings are killed either by a nonselective herbicide (paraquat, glyphosate, or glufosinate) or by shallow tillage (Chauhan, 2012a). In Europe and South America, stale seedbed is practiced to keep weedy rice under check (Ferrero, 2003; Foloni, 1999). In Brazil, under a no-till system, stale seedbed with two cycles of irrigations with killing emerged weedy rice 15 days after irrigation was effective in reducing the weedy rice seedbank (Foloni, 1999). A successful stale seedbed method interconnected with soil tillage systems. Zheng et al. (2019) proposed to detect the distribution of weedy rice in soil seedbank before the stale seedbed method is practiced. If the distribution of seeds is mainly concentrated in the topsoil layer, induce germination and eradication methods could be applied as stated above. However, if the distribution of seeds is high in the deep soil layer, deep tillage could be performed first to bring back the seeds to the shallow soil depth before applying the stale seedbed technique.

Tillage also plays an important role in weedy rice control. Since weedy rice emergence declines with an increase in seed burial depth, higher emergence from top 0–5 cm and emergence ceases at 8–10 cm depth (Vidotto and Ferrero, 2000; Chauhan, 2012b). Therefore if the stale seedbed technique is not applied, then deep tillage can be used to bury weedy rice seeds deeper (below the maximum depth of their emergence; > 10 cm) to reduce weedy rice recruitment in the DSR crop, especially if the weed seedbank is concentrated in the topsoil layer prior to tillage (Massoni et al., 2013). Exposing newly shattered weedy rice seeds for predation by delaying first tillage after rice harvest is found an effective strategy to reduce its seedbank in Italy (Fogliatto et al., 2010).

Early flooding and role of anaerobic germination tolerant rice cultivars

Early flooding has been an effective tool for weed control in PTR as the emergence and growth of the majority of rice weeds including weedy rice is highly suppressed by flooding (Rao et al., 2017; Chauhan, 2012b). But early flooding for weed suppression in DSR has limited scope as rice is also sensitive to early flooding (anaerobic conditions) at the early emergence/crop establishment stage, and hence, can affect crop establishment negatively. Currently, in DSR systems, flooding is established only after rice emergence/establishment, and by then most of the weeds including weedy rice also emerge when flooding is not very effective. Water seeding with a higher seed rate is practiced in some areas where weedy rice is becoming a severe problem (Azmi and Johnson, 2009). In Malaysia, a 30 to 50% higher seed rate is used in the water-seeding system compared to the seed rate used in the wet-DSR system (Dilipkumar et al., 2017).

The availability of anaerobic germination (AG) tolerant rice cultivars—tolerant to anaerobic conditions/flooding during early emergence/crop establishment—would enable the use of early flooding for weed control including weedy rice without any adverse effect on crop establishment. International Rice Research Institute has identified AG-tolerant QTLs (AG1 and AG2) and introgressed these OTLs into high-yielding rice cultivars such as IR64, PSB Rc 82, and Ciherang-Sub 1 (Mondal et al., 2020). In a greenhouse study, a combination of early flooding (24–72 h after seeding) of 5-cm depth and pretilachlor + safener with AG-tolerant rice varieties suppressed 80%–90% emergence of weedy rice without affecting crop establishment (Kumar et al., 2017).

Improving rice competitiveness and purple-colored cultivars

Rice cultivar with strong weed competitiveness is another important tool for weedy rice management. In Malaysia, taller rice cultivars with higher tillering ability suppressed the weedy rice population (Azmi and Abdullah, 1998). The hybrid variety was found higher-yielding and suppressed the growth and seed production of weedy rice than inbred varieties in Arkansas, United States (Ottis et al., 2005). Similarly, Shivrain et al. (2009) also reported that hybrid varieties reduced the tillering and competitive effect of weedy rice biotypes. Practices such as the use of high seeding rates, which improve early canopy, cover shift competition in favor of crop than weeds. For example, in Malaysia, a four times higher seeding rate increased the yield of the DSR crop infested with weedy rice (Azmi et al., 2000). There is a need for more research in identifying high-yielding and weedy rice-suppressive rice cultivars. Growing cultivars with purple-colored leaves or purple-stemmed base may help to reduce the weedy rice seedbanks, where weedy rice emergence can be easily differentiated and removed from the field. Farmers in Himachal Pradesh, India have adapted to cultivate purple leaves rice cultivar “R585” in weedy rice infested fields (Kaushik et al., 2011).

Rice establishment methods

Line sowing instead of broadcasting facilitates the identification of weedy rice at an early stage that emerges between rows and can be easily removed manually or using mechanical tools like finger weeder or cono weeder (Chauhan, 2012a). A field study conducted in Sri Lanka indicated that row seeding reduced weedy rice panicle density from 39–49 panicles/m² to 15–30 panicles/m² and increased rice grain yield (Chauhan et al., 2014). Alternate rice establishment methods such as transplanting (manually or mechanically) and water seeding are proven effective establishment methods for weedy rice control. Hence, the introduction of these methods for one or two seasons if weedy rice has become a serious problem in DSR can help in keeping the weedy rice problem under check. In Malaysia, weedy rice

panicle density declined by 66% with the use of mechanical transplanted rice for two consecutive seasons compared to continuous DSR (Azmi et al., 2005). In Korea, the reduction in weedy rice panicle density was 90% with three consecutive seasons of mechanical transplanted rice (Kim et al., 2000). In Sri Lanka, rice seedling broadcast and manual transplant reduced weedy rice seed production by 71%–87% and 95%–98% as compared to broadcast DSR (Chauhan et al., 2014).

Physical methods

Manual weeding or roguing or chopping of weedy rice panicles before seed production is another effective option for minimizing weedy rice infestation in DSR. However, the chopping or roughing technique is not feasible if the field is infested with weedy rice accession with the same or shorter plant height compared to the cultivated rice. Mechanical weeding can reduce the labor requirement, but line sowing is a prerequisite for mechanical weeding.

Crop rotation

Crop rotation helps to break the weedy rice life cycle, enables the use of other herbicides to control weedy rice, and also makes it easy to identify weedy rice—all leading to better control of weedy rice. In the southern United States, the rice–soybean rotation has been the most effective and widely adopted rotation to minimize weedy rice infestation (Burgos et al., 2008). In Uruguay, Scavino et al. (2013) observed a low problem of weedy rice in DSR because of the adoption of crop rotations with pastures (Scavino et al., 2013). Andres et al. (2012) in Brazil found a 90% reduction in weedy rice when rice was rotated with 2 years of cultivation of soybean (*Glycine max* (L.) Merr.), corn (*Zea mays* L.), or sorghum (*Sorghum bicolor* (L.) Moench). Similarly, in Asia, the weedy rice problem can be drastically reduced if one rice crop, preferably dry season, in a double or triple rice cropping system is rotated with non-rice upland crops such as soybean, corn, or mungbean (Chauhan, 2013). Alternate herbicides that are effective for weedy rice control but could not be used in rice can be used in these crops. In the Philippines, glyphosate-tolerant corn is commercialized and hence by using glyphosate-tolerant corn in rotation with rice enables farmers to use glyphosate to control weeds including weedy rice.

In the dry season, farmers in Central Vietnam rotate rice with mungbean (*Vigna radiata* (L.) R. Wilczek) to manage weedy rice because voluntary and weedy rice seedlings struggle to thrive in mungbean due to inadequate soil moisture (Watanabe et al., 1998). Ulguim et al. (2018) recorded high weed density, mostly weedy rice with continuous rice cultivation whereas systems with crop rotation and crop diversification reduced the weedy rice infestation level with a trade-off higher infestation of perennial species.

Chemical method including herbicide-tolerant rice technology

Weedy rice management using herbicide can only be feasible before rice sowing. Any chemical control activity made after sowing the rice may give adverse effects on rice growth and yield. Metolachlor and oxadiazon, for example, effectively inhibited germination of weedy rice without affecting rice if sprayed at least 15 days before rice planting (Estorninos et al., 2005). In European rice conditions, pretilachlor or dimethenamid sprayed alone or in combination at 25 days before rice planting could obtain more than 75% of weedy rice control (Ferrero et al., 1999). In Peninsular Malaysia, application of oxadiazon at 500 g ai/ha in 5-cm standing water just after the second tillage and retained the water in the field up to 7 days before rice sowing suppressed weedy rice (Dilipkumar et al., 2020). This technique could significantly destroy the superficial weed seed bank, where the density of weedy rice could be reduced to 30%–45% in the first season and the reduction rate could be increased up to 75% in the following season. There are limited in-crop herbicide options for selective control of weedy rice other than HT-rice varieties. However, weedy rice plants which are taller than cultivated rice can be selectively controlled by carefully treating these plants with nonselective herbicides such as glyphosate/glufosinate/paraquat or cycloxdim at 15%–20% and 5% concentration, respectively using a weed wiper/wick applicator (Ferrero et al., 1999; Jose et al., 2020). Jose et al. (2020) recently developed a hand-held weed wiper device to minimize risks of herbicide dripping which can be used at 60–65 days after sowing (DAS) to selectively kill weedy rice panicles.

The introduction of HT-rice variety made selective control of weedy rice possible with the use of the herbicide. One of the successful HT-rice technologies that have been commercialized globally is Clearfield rice. Clearfield rice also known as imidazolinone (IMI)-tolerant rice was developed through mutagenesis of the acetolactate synthase locus which offers an opportunity to selectively control weedy rice with IMI herbicides (Croughan, 2003). At the beginning of introducing this technology, it provided 95%–100% weedy rice control in most cases (Burgos et al., 2008). In Malaysia, fields planted with Clearfield rice reduced the weedy rice population effectively, hence doubled the rice yield from 3.5 to 7.0 t/ha (Sudianto et al., 2013). Despite the benefit of the technology, the evolution of IMI-resistant weedy rice has been reported in some countries, including the United States, Brazil, Colombia, Costa Rica, Italy, and Malaysia (Sudianto et al., 2013; Dilipkumar et al., 2018a,b). Population genetic studies indicate that the IMI-resistant weedy rice was mainly originated from the gene from IMI-tolerant cultivars and distributed by seed migration (Song et al., 2009; Shivrain et al., 2010a,b).

Based on the survey conducted in Malaysia, most farmers cultivated Clearfield rice for more than two consecutive seasons, and some extended the planting to seven seasons. Ignorance of the stewardship guidelines such as purchasing noncertified seeds, cultivating Clearfield rice without using

IMI herbicide, or spraying the herbicide at the wrong time and at lower than recommended rate may have resulted in the escape of the resistance trait from Clearfield rice to weedy rice or wild rice (Dilipkumar et al., 2017). To help combat IMI-resistant weedy rice and complement the Clearfield technology, Badische Anilin- und SodaFabrik (BASF) recently developed another new HT-rice technology namely, Provisia rice that confers resistance to the acetyl coenzyme-A carboxylase inhibitor herbicide (Mankin et al., 2014). Considering all the experiences gained from the Clearfield rice technology, the new Provisia rice should be used wisely and carefully. The evolution of multiple-resistant weedy rice populations is possible if ignoring past experiences gained from the Clearfield rice technology. For the longevity of HR-rice technology, it is important that farmers should not continuously use these varieties and should be rotated with other HR-rice varieties with different modes of action or with conventional non-HR-rice varieties along with compliance with the stewardship program.

Conclusion

Weedy rice is the most troublesome weed of cultivated rice and it has emerged as a threat to DSR-based rice production systems. Its close similarity to the cultivated rice has complicated the implementation of the systematic weedy rice control strategy. In the absence of selective herbicides for weedy rice control in conventional rice cultivars, diversified weed management with multiple tactics prior to sowing and after sowing should be integrated for effective control such as optimization of tillage schedule, stale seedbed technique, preplant application of preemergence herbicides (e.g., pretilachor or oxadiazon) with flooding before rice sowing, use of clean seeds and machinery, a high seeding rate of rice, rotation of rice establishment methods, line sowing, roguing, and crop rotation. HT-rice could be another effective tool for weedy rice control. However, prior to the commercialization of HT-rice, it is important to assess potential risks associated with the technology, and stewardship guidelines should be developed to minimize the risk and for the long-term sustainability of the technology.

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