Weedy rice: an emerging threat to rice cultivation and options for its management

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Weedy rice, evolved largely by natural hybridization between wild and cultivated rice, is an emerging threat to rice cultivation as it affects crop production, harvest quality and thereby farmers' income. With diverse biotypes, this conspecific weed has already infested large rice-growing areas across the globe and with no selective herbicide available for its control varied cultural practices are being used to manage it. These include use of clean machinery, certified seeds, stale seed-bed technique, land preparation, crop rotation, use of purple coloured cultivars and many more. However, an integrated approach is essential to manage weedy rice as the problem is yet to aggravate with changing climatic conditions.

Keywords: Infestation, management strategies, weedy rice.

RICE is seen to exhibit weedy traits and is competing with cultivated paddy in the farmers' field. With an increase in labour costs and water scarcity in many Asian countries, transplantation of rice is being replaced with direct seeding. This weedy rice, which otherwise used to be suppressed at early stages of growth due to waterlogged conditions now emerges with the rice crop[1] and competes for space, air and nutrition. As no selective herbicide (Box 1) is available to control weedy rice, it seems to be flourishing.

Important traits of weedy rice

The conspecific weedy rice (*Oryza sativa* f. *spontanea*, Poaceae) is a biosimilar of AA genome complex (Box 2) rice and shares traits with both cultivated (high fecundity, enhanced growth) and wild types (asynchronous maturity, early shattering, dormancy, coloured pericarp) of rice. Most types of weedy rice possess a red pericarp though some have white pericarp[2] with presence or absence of awns. Numerous phenotypes are available in weedy rice (Figure 1). Ninety-five accessions across eight states of India analysed for hull and pericarp colour revealed immense variation in hull colour ranging from straw, wheatish, brown to black. Majority had brown/red pericarp (88 accessions) while few had a white pericarp (seven accessions, unpublished data). Weedy rice has competitive advantage over cultivated rice as it grows taller and faster, tillers profusely and competes with cultivated rice for nutrients, light and space. It flowers much earlier than cultivated rice and produces grains that shatter easily, thus enhancing the weed seed bank. Burgos *et al.*[3] report that red rice may take up to 60% of applied fertilizer nitrogen and has high nitrogen use efficiency (Box 2) for biomass production than cultivated rice.

The genesis

Conspecific weeds like weedy rice are morphologically and ecologically different from cultivated and wild counterpart species. Studies indicate that in most cases hybridization between cultivated and wild species facilitates weed evolution, though they may evolve through genetic variation from either wild or cultivated species too. Mutations may also lead to evolution of conspecific weeds. Numerous studies indicate weedy rice to largely be the result of hybridization between cultivated and wild rice[4–10], while sporadic studies support de-domestication of rice[11] or genetic mutation[12] as a cause for rice to evolve as weeds. There is also the possibility of evolution of weedy rice during development and production of hybrid rice. Rice, as such, is a self-pollinated crop capable of fertilizing its ovary with its own pollen. But for developing hybrid rice a sterile parent is required that cannot pollinate its ovule and is known as a cytoplasmic male sterile (CMS) line. The sources of male-sterility-inducing cytoplasm for developing better CMS lines are poor. At present, about 85% of the CMS lines used in commercial production still belong to the wild abortive (WA) type. This donor is grown next to the pollen parent to produce hybrids by cross-pollination done manually. There are great chances of the wild female CMS parent being pollinated by other cultivars naturally and may be a potential reason for the evolution of weedy rice and its

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Box 1. Explanation of certain terms used in the text.

Selective herbicides: These are herbicides formulated to control specific weeds or a category of weeds. The formulation may be toxic to some plant species but less toxic to others.

Oxyflourfen: This is a diphenyl-ether herbicide used for broad spectrum pre- and post-emergent control of annual broadleaf and grassy weeds. It is manufactured by Dow AgroSciences and Makhteshim-Agan under the tradenames Goal and Galigan.

Glyphosate: This is a broad-spectrum systemic herbicide used to kill weeds, especially annual broadleaf weeds and grasses. It is absorbed through plant leaves and soft stem tissue. From where it is transported throughout the plant, where it acts on enzyme of the shikimic acid pathway. This pathway exists in higher plants and microorganisms, but not in animals. Plants treated with glyphosate slowly die over a period of days or weeks, and because the chemical is transported throughout the plant, no part survives.

Wick applicator: A herbicide wick applicator helps target weeds without the need for broadcast or spraying. The wick is submerged in herbicide and used to kill weeds by making contact with their plant parts.

Imidazolinone herbicides: Imidazolinones are a class of widely used herbicides in legumes and cereals. They kill plants (weeds) by inhibiting acetohydroxyacid synthase, the first common enzyme in the biosynthesis of the branched-chain amino acids. The imidazolinones were discovered in the 1970s by American Cyanamid Company. The first commercial herbicides were developed in the 1980s and reached their peak in the 1990s. These herbicides continue to provide effective weed management for farmers throughout the world.

Acetolactate synthase (ALS) inhibitor herbicides: Herbicides that inhibit acetolactate synthase (ALS), the enzyme common to the biosynthesis of the branch-chain amino acids (valine, leucine and isoleucine), affect many species of higher plants as well as bacteria, fungi, yeast and algae. ALS is the primary target site of action for at least four structurally distinct classes of herbicide, including the sulfonylureas, the imidazolinones, the triazolopyrimidine sulfonamides and the pyrimidinylsalicylates (pyrimidinyl carboxy herbicides). The extremely good weed control activity achieved with these herbicides indicates that ALS is an effective target site for herbicidal action.

biotypes. Cultivated rice can also cross pollinate, but the average outcrossing rates are as low as 5%. In wild rice outcrossing rates[13] can go up to 100%. Also, though it was thought that interspecific hybridization in rice without human interference is not possible, scientific reports indicate otherwise[14]. Microsatellite markers (Box 2) and morphological characteristics used to explore genetic diversity and possible origin of weedy rice in Taizhou city, Jiangsu Province, China, with wild rice, hybrid rice and cultivated rice revealed low diversity amongst weedy rice populations and suggested weedy rice to originate from segregating populations of hybrid rice that hybridized naturally with cultivated rice[4]. Studies on the origin of weedy rice from Bhutan suggest that they were generated by natural hybridization between cultivated and wild rice[12]. Weedy biosimilars from Lianing in North East China are genetically diverse and probably originated by intervarietal hybridization and mutation[5]. Outcrossing of weedy rice with nearby cultivars allows introgression of different alleles into the population leading to high genetic diversity[8]. Diversity assessed amongst weedy rice populations from two different provinces of China revealed low diversity amongst them. Cluster analysis and PCA suggested close relationship with locally grown cultivars than with other cultivated rice and wild rice[11]. The close genetic background and high morpho-physiological resemblance between weedy rice and cultivated rice in Okayama Prefucture, Japan, suggest that here weedy rice originates from cultivated rice as an off-type caused by genetic mutation along with development of a strong shattering habit[15]. Molecular variability in weedy rice accessions from Haryana revealed weedy rice to be closer to cultivated rice, but cluster analysis based on agronomic parameters did not reveal similar results[7]. Morpho physiological diversity assessment of weedy rice accessions from Central India based on cluster analysis reveal that at 80% variability the weedy biosimilars clustered into three groups, wherein few accessions grouped with cultivated rice while those in the other group clustered with *Oryza rufipogon* and few cultivated rice[16]. Four weedy rice biosimilars formed an independent cluster. This suggests that the roots of origin of weedy rice vary. And hence, a single route of evolution of weedy rice cannot be concluded and its genesis may vary with geographical location.

Extent of infestation

Weedy red rice was first documented in USA as early as 1846 and has continued to affect the rice production areas[17]. The problem has now invaded India with an infestation of 5–60% across different states, with 11.32–44.28% in cultivators' fields[18]. Figure 2 shows a paddy field in Kharif 2012 of Jabalpur district, Madhya Pradesh infested with weedy rice where labours are engaged in hand weeding to remove the same. In 2009, agronomists from West Bengal

Box 2. Explanation of certain terms used in the text.

Conspecific weeds: These are weeds belonging to the same species.

AA genome complex: Rice belongs to the genus *Oryza* which has been grouped into five species complex namely *sativa*, *officinalis*, *meyeriana, ridleyi* and unclassified. The *sativa* complex has the AA genome of the nine distinct genomes available in *Oryza* (A, B, C, D, E, F, G, H and J). Weedy rice has the AA genome.

N use efficiency: Nitrogen is essentially required by plants for growth and development. They obtain nitrogen from the soil, which may be a poor source. Farmers replenish this deficit by adding fertilizers to gain better crop and yield. Due to the substantial yield increases resulting from fertilization, farmers have steadily increased the amount of fertilizer added per unit of land area. Nitrogen use efficiency is a term used to indicate the ratio between the amount of fertilizer N removed from the field by the crop and the amount of fertilizer N applied.

De domestication: Plant domestication is the genetic modification of a wild species to create a new form of the plant altered by humans to meet their needs. For example, rice was domesticated from its wild easily shattering, less grain number type to the present less shattering, high grain number cultivated type. De-domestication is the reversal of domestication where plants tend to return to their wild attributes, either naturally or due to human interference.

Threshold density for weeds: This is largely calculated taking into consideration the economic loss it causes. Hence the population or density of weeds that causes economic loss to the crop in which it occurs is the threshold density of weeds.

Microsatellite markers: These are molecular markers that are tandem repeats of a variable number of DNA base pairs, commonly known as simple sequence repeats, and used for studies of molecular fingerprinting. Molecular markers are heritable DNA repeats which are phenotypically neutral, developmentally and evolutionary stable and hence able to reveal polymorphism between two genetically distinct organisms.

Cover crops: These cover the soil and protect it from wind and water erosion. The top growth covers the soil surface, while roots bind and stabilize the soil particles. Cover crops may be planted over a whole field for erosion protection, or they may be selectively planted in the most erosion-prone areas. They may also add to soil organic matter and reduce nutrient loss, reduce pest population, weed population and help in water management.

Hull: This is the hard protective covering around grain of crops. Rice hull or rice husk is formed of hard materials, including opaline, silica and lignin and it protects rice during growing season.

Pericarp: This is the part of a fruit formed from the wall of the ripened ovary. The rice grain beneath its hull has the fruit which has an outer cover known as the pericarp. Pigmentation is confined to the pericarp.

also detected and revealed their concerns regarding weedy rice to the State authorities[19]. Rice agricultural fields in Kerala were found to have weedy rice as a major problem. Heavy infestation in the fields of Kerala during recent years has caused a reduction in yield by 30–60% depending on severity of infestation (3–10 mature plants of weedy rice/m^2)[20]. Recently, Jharkhand recorded 24–32% infestation of weedy rice across Ranchi, Khunti and East Singhbhum areas with as estimated yield loss of 10–45%[21]. Heavy infestation of weedy rice is seen in eastern and southern India where direct seeding of rice is common, though it is yet not a problem in Haryana and Punjab where paddy is cultivated through transplanting method.

The infestation has spread across the globe and is now a problem particularly to America, the Carribean, South Asia and Southeast Asia[22]. There are many reports on weedy rice infestation although per cent area infested varies. Infestation of weedy rice has also been reported in China[11], Thailand[23,24], Sri Lanka[25], Vietnam[26–28], the Philippines and in many states of India (Table 1)[18].

An yield loss of 74% in direct seeded rice has been reported in Malaysia[29]. Weedy rice densities of 35–40 plants/m^2 can reduce yields of tall rice cultivars by 60% and short cultivars by 90%, indicating losses greater than grass weeds[30,31]. Smith[32] studied the threshold density for weedy rice to be 1–3 plants/m^2 while the corresponding density for barnyard grass (*E. crusgalli* L. P. Beauv.) is 5–10 plant/m^2.

Management strategies

Weedy rice cannot be differentiated from cultivated rice in vegetative stages and by the time panicles emerge, the damage is already done. With no specific herbicide available for weedy rice, management is possible only through land preparation, mechanical tools and other cultural practices. Use of certified seeds and maintenance of clean mechanical tools, crop rotation, use of cover crops, use of pigmented rice varieties, higher seed rate, straw burning and scientific water management are some basic methods to manage weedy rice.

Preventive measures

The use of clean rice seeds is essential to prevent spread of weedy rice. Farmers should purchase certified seeds from authorized stockists and outlets only to rule out use of spurious and contaminated seed material. Contaminated seed sources have infested clean rice-growing areas in many countries[33,34]. Also, machines and implements used for land preparation, sowing and threshing should be cleaned and supervised before use.

Land preparation

Stale seed-bed technique followed by mechanical weeding or use of herbicides also reduces the weedy rice problem. A single irrigation stimulates weed seed germination in the absence of crop and consequently seedling emergence. The emerged seeds can then be destroyed using mechanical weeding tools or by spray of herbicides. Surface application of oxyflourfen (Box 1) in 2 inches standing water after land preparation and three days before sowing effectively controls weedy rice in the initial critical period of 12–15 days[20]. Use of stale seed-bed technique is reported to reduce the number of weedy rice plants in the crop[35]. However, efficacy of the technique is dependent on the degree of dormancy of weedy rice seed bank and also the duration available between the crop already harvested and the crop to be sown[36].

Figure 1. Varying morphology of panicles of weedy rice. ***a***, Farmer with weedy rice having asynchronous maturity, black hull with awns. ***b***, greyish hull with awns. ***c***, black hull without awns.

Deep tillage operations could also be helpful by burying the weed seeds beyond maximum depth of their emergence[28], followed by shallow tilling in subsequent years.

Residue burning is another effective method to control weedy rice, but the emanating smoke is a big source of air pollution and hence this practice is largely banned in several countries.

Crop establishment methods

Weedy rice is a major problem in direct seeded rice. Paddy cultivation by transplantation has an upper hand as weedy rice, by and large, is unable to germinate under flooded conditions. Transplanting, either manual or under mechanical control[37] and broadcasting of pregerminated rice seeds in puddled soil conditions is also beneficial to manage weedy rice. Crop rotation is an age-old practice that helps manage weeds. Growing different crops in the same field over a few years helps reduce weed seed count. Cover crops used as green manure or dead mulch are a possible method of managing weedy rice, especially between the rows. Intercropping too can be beneficial to manage the weeds between rows. Studies suggest that increasing rice crop interference could help reduce weedy rice growth significantly[38]. And hence higher seeding rates could help suppress weedy rice in infested fields. In USA, shoot biomass and grain yield of weedy rice decreased with increase in rice seeding rate from 50 to

Figure 2. Labours engaged in (***a***) hand weeding of weedy rice in a rice field (Kharif 2012) and (***b***) armful of weedy rice.

Table 1. Weedy rice infestation across the world

Country	Infestation (%)	Reference
Europe	40–75	44
Italy	70	45
Malaysia	74	28, 29
USA (Arkansas)	60	46, 47
Brazil	40	48, 49
Senegal	55	48, 49
Cuba	80	48, 49
Costa Rica	60	48, 49

150 kg/ha. In some Asian countries farmers are using high seeding rates to suppress weeds and compensate for poor seed quality and crop establishment[36]. Line sowing using tractor-mounted seeders can ease detection of weeds as all inter-row rice would be weedy rice. And these emerging plants can be easily rouged manually or by use of chemicals. Application of glyphosate, paraquat to leaf blades of weedy rice through special wick applicators may be helpful[39]. Use of purple-coloured cultivars, e.g. P502, R575 is an effective option to gradually weed out the biosimilars within few years and deplete the weed seed bank[40].

Herbicides: Due to non-availability of selective herbicides to control weedy rice infestation in rice field, the management of weedy rice with the help of post-emergence herbicide is not possible. Use of herbicides before sowing the main crop is possible and aptly manages weedy rice in stale seed-bed technique or even during land preparation[40]. Biotechnological interventions for control include genetically modified rice plants that are tolerant to a certain group of herbicides, e.g. Clearfield (CL) rice is a mutated rice that is resistant to imidazolinone herbicides, acetolactate synthase (ALS) inhibitors. It is largely used in USA and Malaysia[41] to overcome the problem of weedy rice. Two other transgenic herbicide-resistant rice varieties have also been developed – glyphosate and glufosinate-resistant. Glyphosate inhibits the EPSP enzyme (5-enolpyruvylshikimate phosphate synthase), while glufosinate inhibits glutamine synthase enzyme[42]. An attractive option could be developing selective herbicides targeting proteins active at tillering stage present in wild and weedy rice, and absent in cultivated ones. In today's era of genomics and proteomics, this herculean task can be looked into.

As such, no single method can control weedy rice and hence an integrated approach is essential for its management.

Effect of climate change (elevated CO_2) on crop–weedy rice interaction: Recently Ziska[43] reported that higher levels of atmospheric carbon dioxide (CO_2) facilitate the flow of genes between closely related wild or weedy rice plants and domesticated rice varieties. But this gene flow is not the same in both directions. Increased temperatures due to CO_2 levels lead to double flowering in wild rice varieties. Moreover, the weedy rice may grow taller than domesticated rice. Flowering and plant height are important factors in pollen sharing and impact gene flow. Transfer of wild genetic material to domesticated rice can result in the production of seed with weedy characteristics that would be undesirable in rice production. It suggests that rising CO_2 may enhance the competition from wild weedy rice in rice production and reduce consumable rice production.

Conclusion

With a shift to direct seeding of rice and increasing infestation of weedy rice, the biosimilar has emerged as a potential threat to rice cultivation in India as well. In the context of climate regime the problem is bound to aggravate. Hence, it would not be wrong to say that weedy rice demands immediate attention from scientists in different fields to work on its biology and management strategies.

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