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Weedy Rice: An Emerging Threat for Direct-seeded Rice Production Systems in India

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Abstract

Rice is an important cereal crop in India for food security. Conventional practices for rice production (puddled transplanting) are labour-, water-, and energy-intensive. All of these resources are becoming increasingly scarce and expensive, thus making puddled transplanting less profitable. Moreover, this practice deteriorates soil physical properties and causes adverse effects on the productivity of succeeding upland crops. All these factors are forcing farmers to shift from puddled transplanted to direct-seeded rice (DSR) in irrigated or favourable rainfed rice-growing areas. Weedy rice, however, has emerged as a serious threat to rice production in countries (Malaysia, Sri Lanka, Thailand, Vietnam, the Philippines, and the United States) where DSR systems are common. Based on experiences in these countries, it is predicted that weedy rice is likely to emerge as a major threat in DSR production systems in India.

Weedy rice is highly competitive and difficult to control in rice and can result in complete crop loss if not contained. Therefore, there is a need to develop ecologically based integrated management strategies in advance to deal with the likely problem of weedy rice in DSR, suited to Indian conditions for the long-term sustainability of DSR production systems. In this article, we discuss the origin of weedy rice, its biology and dispersal mechanisms, its association with DSR, and integrated weed management strategies, with the ultimate goal of increasing awareness of the threat posed by this species and stimulating research interest to develop effective and economical management strategies.

Keywords: Weedy rice; Direct seeding of rice; Integrated weed management; Biology

Introduction

Rice (*Oryza sativa L.*) is the staple food for more than half of the world population. Asia accounts for 90% of the world's total rice area and production. In India, rice is grown on approximately 45 million ha annually with a production of 104 million tons. India's rice demand is estimated to rise to 122 million tons in 2020, which is equivalent to an overall increase of 22% in the next 10 years. But, the current evidence shows declining factor productivity and a plateau in rice yields due to fatigued natural resources, declining water table, increasing labour scarcity and energy shortage, escalating fuel prices, and changing climatic conditions. Therefore, yield gains have to be achieved by using less water, labour, land, and energy.

In India, rice is most commonly grown by transplanting rice seedlings into puddled soil (wet-tillage). Both transplanting and puddling, however, require a large amount of water, labour, and energy. All these resources are becoming increasingly scarce, making rice production more expensive and less profitable. Therefore, interest has increased in shifting from puddled transplanted rice to direct-seeded rice (DSR). DSR is more rapidly and easily planted, is less labour intensive, consumes less water, matures 7 to 10 d earlier, and has fewer methane emissions [1,2]. Despite these benefits, one of the major threats associated with the introduction of DSR is the evolution of weedy rice, one of the most difficult-to-control weed species of rice in the world [3,4].

In countries (e.g., Malaysia, Sri Lanka, Thailand, Vietnam, and the United States.) where direct-seeding is the dominant rice establishment method, weedy rice has emerged as a dominant weed species and major threat to rice production. A study in Malaysia reported that weedy rice can cause a yield loss of 60% under moderate infestation (15-20 panicles of weedy rice m^{-2}), 80% under high infestation (21-30 panicles of weedy rice m-2), and 100% under heavy infestation [5]. In India, weedy rice is prevalent in parts of the rice production areas in rainfed upland rice ecosystems of eastern Uttar Pradesh, Bihar, Odisha, Manipur, West Bengal, and the hilly tracts of the northeast, where DSR has been practiced for a long time. But, the threat will be much greater in irrigated rice systems, where DSR is being adopted by farmers on a large scale in view of the current challenges. Therefore, effective management strategies are needed to counter the weedy rice threat in the irrigated and favourable rainfed rice production environments of India.

The overall goal of this article is to create awareness of the weedy rice threat and stimulate research interest to develop effective and economical management strategies to counter this threat in the DSR production systems of India. The manuscript emphasizes the origin, characterization, biology and ecology, and dispersal mechanisms of weedy rice; its association with DSR; and integrated management strategies suitable for this species under Indian conditions.

What is Weedy Rice and what is its Origin?

Broadly, weedy rice can be defined as a weedy population of

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genus *Oryza* that (1) is similar to cultivated rice but has greater seed dormancy and longevity, high susceptibility to seed shattering, and red pigmentation of pericarp; (2) grows unintentionally and vigorously in and around cultivated rice; (3) is very diverse phenotypically and genotypically; (4) is highly competitive and difficult to control; and (5) reduces farmers' income by reducing grain yield, quality, and profit [3,5,6]. Wild rice is the species of genus *Oryza*, including the progenitors of the two cultivated rice species that grow in largely undisturbed areas. However, some wild rice species, particularly those of the *O. sativa* (AA) complex (i.e., *O. rufipogon*, *O. barthii* and *O. longistaminata*) and three species of the *O. officinalis* complex (i.e., *O. punctata*, *O. latifolia* and *O. officinalis*), have become invasive and these are very troublesome weeds in rice and other cropped areas.

The literature reveals three major hypotheses of weedy rice evolution/origin (Figure 1). Hypothesis 1: through a continual process of gene flow between cultivated rice and its reproductively compatible wild populations, which leads to natural hybridization [7,8]. Hypothesis 2: through a process of "de-domestication" of cultivated rice to weedy rice [8,9]. Hypothesis 3: through direct adaptation of wild rice to continuous habitat disturbance, along with domestication of crop species [8,10].

Dispersal of Weedy Rice

Weedy rice spreads rapidly from infested fields to new non-infested areas. Knowledge of the sources responsible for the dispersal of weedy rice can help in preventing its spread to non-infested areas. The major dispersal mechanisms of weedy rice are summarized in Figure 2. The use of contaminated weedy rice seeds is the most important source of its spread to new areas [6]. The use of weedy rice–contaminated agricultural equipment/machinery also plays a vital role in its dispersal. It is therefore important to use weedy rice–free certified seeds and machinery should be cleaned before moving it to new areas to prevent weedy rice spread. In addition, weedy rice can be dispersed from one field to another through irrigation channels or irrigation water, heavy winds or storms, and flooding.

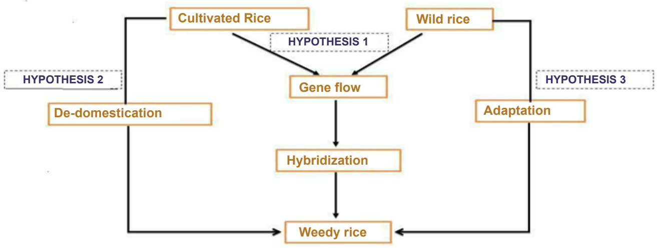

Figure 1: Three hypotheses for the origin of weedy rice [8].

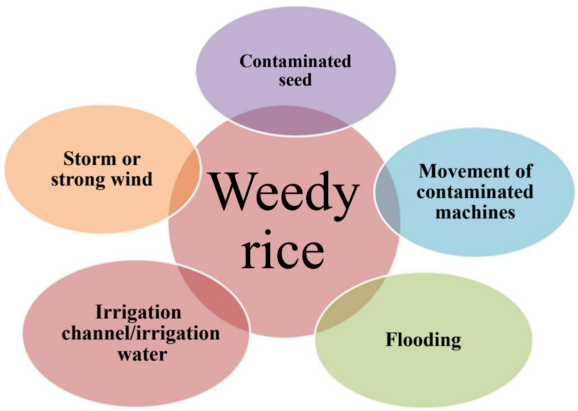

Figure 2: Sources of weedy rice spread or movement from infested areas to new areas.

Biology of Weedy Rice

Emergence of weedy rice

Weedy rice emerges faster than cultivated rice and develops vigorous root systems; thus, it is highly competitive with cultivated rice for nutrients, light, water, and other plant growth resources. Its emergence depends on soil texture, soil moisture, seed burial depth, tillage methods, and soil temperature [11,12]. Emergence of weedy rice decreases with increases in seed depth in both moist and flooded soil conditions. In a study from Italy, maximum emergence of weedy rice was from 0-5 cm and then it declined with increases in depth and ceased at 10 cm [13]. However, under flooded conditions (water depth 4-5 cm), no emergence was recorded from seeds placed in soil below 4 cm depth [13].

Suh and Ha [14] from Korea reported that cultivated rice is more sensitive than weedy rice to water depth at emergence. They found that cultivated rice emergence declined drastically at a water depth of 5 cm and dropped to zero at 9-cm water depth but weedy rice emergence was 60-100% at 9-cm water depth. Higher emergence of weedy rice was observed in no-tillage compared with rotary tillage or ploughing+rotary tillage [14]. Another study reported 2.5% and 7.2% emergence of the total seed bank (0-10-cm depth) in the soil in ploughed and minimum-tilled plots, respectively [15]. This response was observed because of the deep burial of weedy rice seeds by tillage, especially in the ploughing treatment, and thus low emergence from seeds buried deep in the soil.

Seed dormancy

Weedy rice seeds are often associated with dormancy [16]. The duration of dormancy varies with ecotype and storage conditions and can range from a few months to a few years [17,18]. Environmental conditions during seed development and storage conditions (moisture and temperature) can affect the duration of dormancy [19]. A previous study observed that the loss of dormancy in weedy rice was rapid at 6-14% moisture content and very low at moisture content <5% and >18% [19].

Longevity

The longevity of weedy rice seeds in the soil varies with ecotype and other factors such as burial depth, soil moisture, and seed dormancy [20]. A study conducted at two locations in Texas, USA, found that weedy rice seed longevity increased with increases in burial depth [21]. The study found that seeds buried at 5 cm or kept at the soil surface had almost no viability after one year but, when buried at 12 and 25 cm, seeds remained viable longer than two years. Two ecotypes from the southern U.S. maintained >20% viability after 10 years of burial at 17 cm in Arkansas [20].

These results suggest that deep ploughing/tillage enhances the longevity of weedy rice seeds in the soil. Therefore, rice producers should avoid deep tillage practices after the rice harvest in weedy rice–infested areas because deep tillage places seeds deeper in the soil where the environment is less suitable for germination and seeds can remain viable longer. A study in Vietnam evaluated the effects of soil moisture (moist soil versus submerged conditions) on weedy rice longevity in the soil and found that the reduction in viability was faster under moist conditions than in submerged conditions [22]. After 4 months of burial, for example, 57% of the weedy rice seeds remained viable under submerged conditions as opposed to 27% under moist conditions.

Seed shattering characteristics

Heavy and early seed shattering is a major reason for the dispersal and distribution of weedy rice. Seed shattering behaviour is biotype-specific and varies from a few days to a few weeks [5]. A study from Vietnam reported that seed shattering time and percentage are not correlated and seed shattering in weedy rice varies from 20% to 95% in different seasons and biotypes [23].

Flowering

Flowering in weedy rice is dependent on day length, plant age, and biotype. The flowering period range of weedy rice (8-93 days) is usually longer than that of cultivated rice (7-22 days) and floret opening is also longer by 1 hour, which leads to cross-pollination in some weedy rice biotypes [24,25]. Early flowering and taller plants of weedy rice may lead to a prolonged reproductive phase.

Weedy/wild rice Species in India

Weedy rice's origin in India is as old as the cultivation of rice since it occupies a special position in the Vedas from ancient times. Many weedy and wild relatives of rice are present in the rice-growing areas of India (Table 1) as India is considered the centre of origin of cultivated rice. Weedy rice has been classified into two groups corresponding to *indica* and *japonica* cultivars; each of these groups was further classified into resembling either cultivated rice or a wild type. Some workers grouped Indian weedy rice into *indica* type, meaning that these weedy rice biotypes may have originated by natural hybridization between cultivated rice (*indica* type) and wild rice [26].

Knowledge of wild and weedy relatives of rice present in India and their possibility of hybridization with cultivated rice can be useful in devising management strategies for weedy rice, especially in the era when herbicide-resistant rice cultivars have been developed. *O. sativa* is the cultivated rice grown in India. Wild rice species, including *O. nivara* and *O. rufipogon* present in India, share the same genome (AA) as cultivated rice; therefore, they can easily cross with cultivated rice (Table 1). Other wild species such as *O. malampuzhaensis* (BBCC), *O. eichingeri* (BBCC), *O. granulata* (GG), *O. meyeriana* (GG), *O. indandamanica* (GG), and *O. ridleyi* (HHJJ) are also present in India but are unlikely to cross with cultivated species because of a different genome than cultivated rice [27].

In India, the major weedy rice species found in cultivated rice areas is *O. sativa f. spontanea*. The Western Ghats regions of southern India are rich in the biodiversity of many wild and weedy species and Bhoothathankettu, Parambikulam, and Kuralai forest reserves along with the Western Ghats in Kerala have been identified for *in situ* conservation of wild species [28,29]. These wild and weedy species are present in the eastern part of India (eastern Uttar Pradesh, Bihar, Odisha, Manipur, and West Bengal) and southern India (Karnataka, Kerala, etc.). However, in some northwestern parts of India (e.g., Punjab and Haryana), weedy or wild rice species are not present.

Species	Genome	Weediness
Oryza sativa	AA	Cultivated
O. rufipogon	AA	Weed
O. nivara	AA	Weed
O. sativa f. spontanea	AA	Weed
O. eichingeri	BBCC	Weed
O. malampuzhaensis	BBCC	Weed
O. officinalis	CC or BBCC	Weed
O. granulata	GG	Weed
O. meyeriana	GG	Weed
O. indandamanica	GG	Weed
O. ridleyi	HHJJ	Weed

Table 1: Major *Oryza* species found in India with their genomes and nature of weediness [40,41].

Management of Weedy Rice

Weedy rice is very difficult to control with a single method and an integrated weed management (IWM) strategy is needed for its effective control in DSR systems [3,30]. IWM consists of preventive, cultural, chemical, mechanical, and biotechnological approaches. Here, we review published studies that have identified effective weedy rice control techniques and can be integrated to manage weedy rice in DSR systems under Indian conditions.

Preventive methods

Prevention is one of the most important steps that can be implemented immediately to minimize the infestation of weedy rice in DSR fields. Preventive methods include the following: A. Use of weedy rice–free seeds: It is one of the best preventive measures to control weedy rice. The use of self-saved rice seeds is considered one of the major causes of the spread of weedy rice to new areas [6]. Therefore, seed replacement and the selection of pure, good-quality certified seed is the best method to prevent the introduction or dissemination of weedy rice in new areas. B. Use of clean agricultural implements: As described above, too, agricultural implements can disperse weedy rice seeds from one area to another and proper cleaning of harvesting/sowing equipment prior to its use in new areas can prevent the spread of weedy rice seeds. C. Increasing awareness for farmers: There is a need to increase awareness for farmers about the risk imposed by weedy rice. Closer watch on the species in new areas is needed to avoid its invasion, and such plants should be rogued out upon their initial appearance in the field.

Cultural methods

A. Stale seedbed technique: In this method, the field is irrigated and left unsown for two to three weeks to allow weedy rice seeds to germinate and then emerged weedy rice seedlings are killed by either a non-selective herbicide (paraquat or glyphosate) or by shallow tillage prior to rice sowing [1,3]. The duration of the stale seedbed must be long enough to allow the weedy rice seedlings to grow up to the 2- to 3-leaf stage and must not delay the sowing of the main crop. This technique not only reduces the weedy rice population in the crop but also decreases the weedy rice seed bank in the soil [6]. The rice seed should be sown with minimum disturbance to avoid bringing new seeds buried at deeper depth to the upper germination zone of the soil and also to avoid exposure of weedy rice seeds to light and other stimuli that encourage germination and emergence of weedy rice.

B. Tillage: Tillage plays an important role in controlling weedy rice populations in DSR. Weedy rice seeds emerge from shallow soil depths; therefore, weed seeds present in the upper soil layer can be buried deep by deep ploughing. Under zero-till conditions, weedy rice seeds present in upper soil layers can be depleted before rice crop sowing by employing the stale seedbed technique. Residue should be retained on the soil surface as mulch under zero-till conditions can help in reducing weedy rice recruitment.

C. Selection of rice cultivars: Selecting cultivars with vigorous initial growth plays an important role in suppressing weedy rice. In Malaysia, cultivars having tall stature, more tillering capacity, more vegetative growth in the initial crop growth phase, and early maturity reduced the weedy rice population [31]. Coloured-stem cultivars are effective in identifying weedy rice at an early stage and thus in its management. In eastern and southern India, coloured-leaf (purple) rice cultivars help in differentiating cultivated rice from weedy rice. Similarly, farmers in Himachal Pradesh adopted purple-leaf rice cultivars in weedy rice–infested fields [32].

D. Line sowing: Line sowing of cultivated rice instead of broadcasting facilitates the identification and removal of weedy rice seedlings that emerge between rows as inter-cultivation operations are easier in row-seeded crops. In a recent study in farmers' fields in Sri Lanka, a row-seeded rice crop had fewer weedy rice plants than the broadcast culture (Chauhan et al., unpublished data).

E. Seed rate: Weedy rice growth and seed production can be suppressed by rapid closure of the crop canopy through many cultural practices, including high seeding rate and narrow spacing. In Malaysia, for example, a study reported an increase in rice grain yield with an increase in the seeding rate from 20 to 80 kg ha^{-1} in DSR fields infested with weedy rice [33].

F. Water management: Good water management is another alternative for weedy rice control. Flooding fields at the appropriate time and depth can help in suppressing weedy rice emergence and growth. In Vietnam, a water depth of more than 5 cm was found to suppress the germination and emergence of weedy rice [34]. Early flood establishment after crop establishment can help suppress weedy rice. In a recent study in the Philippines, a flooding depth of 2 cm reduced seedling growth of four weedy rice biotypes by >85% [11].

G. Water seeding: Rice plants require oxygen, moisture, and optimum temperature for germination and one of these missing may cause a reduction in rice germination. In the water-seeding technique, pre-germinated rice seeds are shown on well-levelled flat soils having minimum residue with clear standing water by the broadcasting method to decrease the weedy rice population [35]. Seedling broadcasting is also an innovative technology adopted in some DSR-growing countries, such as Vietnam, China, and Sri Lanka, for controlling weedy rice where 12-15-day-old seedlings are broadcast on 5-7 cm of standing water and this layer of water controls the emergence of weedy rice [35].

H. Shifting from direct seeding to transplanted culture: Transplanting is an established and efficient method for controlling weedy rice. Alternating transplanting (preferably, mechanical transplanting) with DSR after 3-4 years of DSR can minimize the problem of weedy rice and help in reducing the weedy rice seed bank in the soil. Transplanting also helps to improve competitiveness against weedy rice germination, establishment, and growth.

I. Hand weeding/roguing: Roguing is another important, effective, and viable option for minimizing the infestation of weedy rice and other weeds in DSR. Although it is a very tedious, time-consuming, and slow process, it can give farmers high profit. Roguing is effective only if it is done before the seed shattering of the weedy rice plants.

J. Crop rotation: Crop rotation helps in breaking the weed seed cycle as well as facilitating the identification of weedy rice, and it leads to better control. Therefore, effective weedy rice control can be obtained by rotating the rice crop with other crops, such as soybean, mungbean, cotton, maize, etc., which allow using other herbicides and cultural practices that cannot be used in rice. The rotation of mungbean helps in decreasing the population of weedy rice due to insufficient moisture for weedy rice.

Mechanical methods

The following implements can be used for controlling weeds, including weedy rice, in DSR fields:

A. Inter-cultivation using mechanical weeders: Mechanical weeding is possible in row-seeded rice. Mechanical weeders, such as the cono-weeder and inter-cultivation implements (tractor-drawn, bullock-drawn, or manual) remove weeds from between the rows. Line sowing also reduces seed cost as a lower seed rate is used when seeds are drilled than when seeds are broadcast.

B. Chopping: Chopping is applicable for controlling weedy rice plants, which are taller than cultivated rice. The panicles are chopped from the weedy rice plants before seed setting takes place. In many countries, weedy rice panicles are cut with the help of a machete or a special knife attached to a stick. In developed countries, a combine harvester cutting device is mounted on the front of the tractor and used to cut the weedy rice panicles [15].

Chemical methods

Selective control of weedy rice with post-emergence herbicides is difficult due to its genetic, morphological, anatomical, and physiological similarity to cultivated rice. But, weedy rice can be controlled effectively with herbicides when applied before crop planting as pre-plant, that is, both before and after the emergence of weedy rice. Some success can also be achieved by using pre-emergence herbicides. The post-emergence herbicides that have been reported to be effective against emerged weedy rice as pre-plant using the stale seedbed technique are paraquat, glyphosate, glufosinate, quizalofop-ethyl, cycloxydim, dalapon-sodium, and clethodim [36,37].

Weedy rice control with these herbicides ranged from 80 to 100%. Pre-emergence herbicides, if applied after rice sowing, can cause phytotoxicity to the crop but, if applied a few days before rice sowing, can be effective for weedy rice control. Pre-emergence herbicides, such as acetochlor (1.5 kg ai ha^{-1}), metolachlor (2.5 kg ai ha^{-1}), alachlor (2.4 kg ai ha^{-1}), and dimethenamid (1.4 kg ai ha^{-1}), provided 85-92% control of weedy rice with no phytotoxicity when applied 15 days before crop sowing [36].

In another study, pretilachlor at 1.5 kg ai ha^{-1} provided >75% control of weedy rice but, to avoid rice phytotoxicity, the herbicide had to be applied at least 25 days before rice planting [15]. Very limited post-planting options are available for chemical control of weedy rice. However, weedy rice plants growing taller than cultivated rice can be controlled by treating them with foliar herbicides such as glyphosate or cycloxydim at 20 and 5% concentrations, respectively, by using a wiper/wick applicator [37].

This technology helps in reducing viable seed setting/production. Weed wipers are made up of a frame with a rope, sponge, or carpet that can absorb the herbicide solution and wipe it on the weeds without affecting the crop adversely because of the difference in the height of the crop and weed. This technology can be more useful if using short-statured rice cultivars than tall cultivars because some of the panicles of weedy rice can remain below the crop canopy of tall cultivars and therefore not be exposed to wipers.

Biotechnological approach: herbicide-resistant rice

The use of herbicide-resistant rice cultivars is another strategy advocated by researchers for selective control of weedy rice in cultivated rice [38,39]. One of the main reasons for the development of herbicide-resistant rice was to obtain effective and selective control of weedy rice in the rice crop [38]. Three major herbicide-resistant rice systems developed are imidazolinone (IMI)-resistant rice (IMI-rice), glyphosate-resistant rice, and glufosinate-resistant rice, which conveys resistance to the imidazolinone group of herbicides (imazethapyr, imazomox, imazapyr, etc.), glyphosate, and glufosinate, respectively.

Out of these three herbicide-resistant rice systems, IMI-rice is non-transgenic, whereas both glyphosate- and glufosinate-resistant rice are transgenic and are known as genetically modified crops. Glyphosate and glufosinate are non-selective, broad-spectrum, and post-emergence herbicides with no soil or residual activity. The imidazolinone group of herbicides is also broad-spectrum, effective at low doses, can be applied pre- and post-emergence, has soil or residual activity, and has a favourable environmental profile. IMI-rice is the only herbicide-resistant rice that has been commercialized. In Asia, IMI-rice cultivars have been released only in Malaysia.

Although herbicide-resistant rice technology offers opportunities for selective control of weedy rice, the risk of gene flow from herbicide-resistant rice to weedy rice poses a serious threat for the long-term utility of this technology [3]. Therefore, it is important to assess the potential risks imposed by this technology before its introduction in the region. The risk of gene flow from herbicide-resistant rice to weedy rice will be minimal in the northwestern Indian states of Punjab and Haryana as wild and weedy rice are not present in this region, but continuous direct seeding of rice could potentially lead to the evolution of weedy rice in this region, too. The risks of gene escape are higher in the eastern and southern Indian states where many wild and weedy relatives are present. In summary, these methods can target many phases of the weedy rice life cycle as an integrated weed management strategy for weedy rice control as summarized in Figure 3.

Conclusions and Future Research

Weedy rice will likely emerge as a major problem in rice with increases in the adoption of DSR in India owing to the rising scarcity of labour and water. Weedy rice belongs to the same genus (*Oryza*) as cultivated rice and is an important weed in DSR production areas. Its unique characteristics, such as early and heavy seed shattering, prolonged dormancy and longevity, and high competitiveness, make it a difficult-to-control, troublesome, and economically damaging weed problem. Satisfactory control of weedy rice requires an integrated approach based on the combination of preventive, cultural, mechanical, chemical, and biotechnological means rather than using only a single method for its control. However, more research in the following critical areas would help in developing effective and economical management of weedy rice in India:

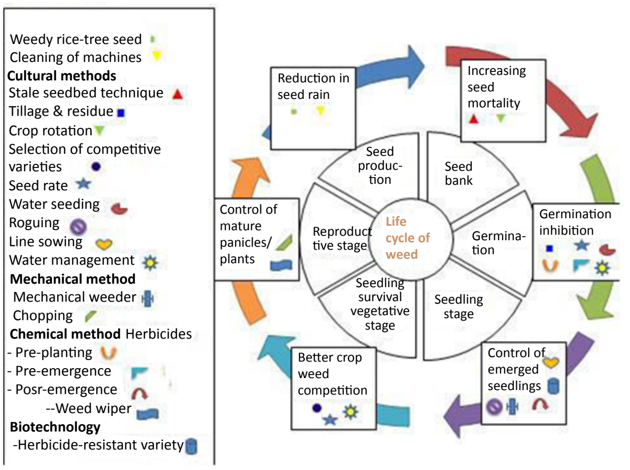

Figure 3: Life cycle and integrated control measures at different life stages of weedy rice.

Morphological and phenological characterization of weedy rice present; Understanding the biology and ecology of weedy rice biotypes/ecotypes; Identifying weak points in weedy rice life cycles to target for management.

Identifying new selective herbicides for its control; evaluating the dormancy and longevity of Indian weedy rice biotypes; Factors that can enhance germination of weedy rice for making the stale seedbed more effective.

Emergence periodicity of weedy rice under alternative tillage systems (zero tillage or unpuddled soil); Evaluating herbicide-resistant rice for its potential benefits (e.g., weedy rice control) and risks (e.g., possibility of gene transfer to weedy rice); and Developing integrated crop management that provides a competitive advantage to rice rather than to weedy rice (e.g., optimizing seed rate, selection of appropriate cultivars, fertilizer management, water management, etc).

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