INTEGRATED APPROACHES FOR WEEDY RICE (*Oryza sativa* L. *spontanea*) MANAGEMENT IN VIETNAM AND BEYOND: CHALLENGES AND PROPOSED STRATEGIES

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ABSTRACT

Weedy rice is a major problem for rice cultivation in many countries, including Vietnam. Due to the complexity and multidimensional aspects of weedy rice species, weed control measures are often difficult and require persistence and care in crop management. In this manuscript, we review the status and problems of weedy rice in Vietnam and some other countries, including the strategies for controlling this weed. The main strategies for controlling weedy rice include preventing infiltration or reinfection of weedy rice, limiting and reducing the amount of weedy rice seeds, preventing germination and growth of weedy rice, and changing the rice field environment. Biotechnology and chemical herbicides are also potential solutions for managing weedy rice. However, the strategies used for controlling weedy rice must be adjusted frequently based on changes in cultivated rice varieties, cropping systems, farming practices, water availability and marketing standards for rice grains. Overall, we conclude that the effective management of weedy rice requires a multidisciplinary and integrated approach that includes the adoption of appropriate weed control measures and regular monitoring of weedy rice populations.

Keywords: *Weedy rice, rice cultivation, weed control, crop management.*

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1. INTRODUCTION

Rice is a crucial food source for over half of the world's population and is cultivated on about 153 million hectares, with 90% of production taking place in Asia. While global rice production has been increasing, it has not been significant due to several factors such as the effects of climate change, declining irrigation water resources and the scarcity of labor, energy, input costs and land to increase rice yields [1]. In Vietnam, the total rice cultivation area in 2021 was 7.24 million hectares, with an average yield of 60.6 quintals/ha and total rice production was 43.88 million tons [2].

In recent years, rice farmers have been shifting from transplanting rice to direct - seeded rice (DSR) due to the increase in production costs, shortage of labor and water supply for rice crops. DSR cultivation has certain advantages, such as being quick and easy to cultivate, requiring less labor and water, having a shorter rice life cycle, being easier to mechanize and emitting less methane. However, this cultivation method also leads to some disadvantages, such as increased presence and invasion of weeds, particularly weedy rice (*Oryza sativa* f. *spontanea*), which is a potential pest in rice production because it is closely related to cultivated rice [3]. In the North and Central regions of Vietnam, transplanted rice using in the most of the cultivating area, while in the South, especially in the Mekong Delta, the area of DSR accounts for over 90% of the rice - growing area. The use of rice varieties of unknown origin and poor quality, as well as the maintenance and development of DSR area, lead to the spreading and prospered of weedy rice in the Mekong Delta, affecting the quality, output and income of farmers, as well as Vietnam's rice exports in general.

In the other hand, DSR systems impact both dry-seeded rice and wet - seeded rice cultivation methods [4]. In dry - seeded rice, the absence of standing water during the early stages of crop establishment creates favorable conditions for weed growth, including weedy rice. Weedy rice seeds can persist in the soil seed bank for multiple years, germinating when conditions become conducive. Additionally, the reliance on herbicides in dry - seeded rice systems for weed control may inadvertently select for herbicide - resistant weedy rice biotypes, exacerbating weed management challenges and necessitating alternative approaches [5]. Conversely, wet - seeded rice experiences reduced weedy rice infestation compared to dry - seeded rice, primarily due to the shallow layer of water maintained during crop establishment. The water layer suppresses weed growth, including weedy rice, during the initial stages of cultivation. However, wet - seeded rice does not completely eliminate weedy rice infestation and under certain conditions, it may even promote the growth of aquatic weeds, including weedy rice variants adapted to flooded environments.

Water seeding, an alternative method where rice seeds are pre-germinated before being sown into flooded fields, offers unique challenges regarding weedy rice infestation. While water seeding can facilitate uniform crop establishment and early growth, it may also inadvertently introduce weedy rice seeds into flooded fields, especially if proper seed cleaning and management practices are not adhered to. Once established, weedy rice can proliferate rapidly under flooded conditions, outcompeting cultivated rice and impeding crop growth and development.

In developed countries such as the United States, Korea, Japan, as well as some developing countries such as Brazil, Malaysia, China, India, and Thailand, investment in weedy rice research has been ongoing for many years, with systematic, continuous, and scaled - up studies conducted on the collection, evaluation of phenotypes and genotypes, classification and distribution of weedy rice, as well as evaluating its spreading and harmful effects in the field, increasing the status of weedy rice seeds, and investigating measures to prevent and control weedy rice. However, in Vietnam, there are only a few small - scale research projects on weedy rice, which are fragmented, lack continuity and inheritance. Furthermore, there are no studies on the classification and distribution of weedy rice, especially in the Mekong Delta, nor are there any integrated and systematic processes for the prevention and control of weedy rice. This review aims to estimate the risk assessment of weedy rice and provide control measures in a key area for rice production in Vietnam and some rice - growing countries.

2. WEEDY RICE

2.1. Origin and infestation of weedy rice

It has known that there are 26 species of wild rice in the *Oryza* genus, but only two species, *Oryza sativa* (Asia) and *Oryza glaberrima* (Africa), have been domesticated. Weedy rice, with its red - colored rice hull, is recognized by farmers, traders, agronomic agencies, agronomists, and rice experts in DSR cultivation areas. Weedy rice is known for causing problems such as increasing production costs, decreasing yields, and lowering market value of the rice crop. If not controlled properly, weedy rice can heavily contaminate arable land and make it unsuitable for rice production. Different stakeholders in the rice industry have varying perspectives on the significance and importance of weedy rice, particularly in the case of the dominant red - colored grains. Marketers and millers may view weedy rice as a quality element, which can impact costs and reduce profitability and reputation. Production input suppliers must take special precautions to produce and sell rice seeds that are not contaminated with weedy rice seeds. For agronomists and other professionals involved in agricultural extension, research, and other services, weedy rice is an extremely difficult problem to deal with, but it is highly contagious and invasive. The perception of weedy rice by different stakeholders is one –dimensional and it is a multidimensional issue that requires proper attention [6].

Weedy rice is generally defined as a plant in the *Oryza* genus that invades and competes with cultivated rice and other crops. The most harmful weedy rice variety is weedy rice with red rice, which produces a red or red grain of bran compared to the brown color of cultivated rice. Red bran or red seed color is an important characteristic that distinguishes red rice from other weedy rice. Most experts classify weedy rice, including red grain rice, as *Oryza sativa*. Some scientists, in the past, viewed weedy rice as wild rice *O. rufipogon* or *O. sativa* var. *rufipogon*, *O. nivara*, *O.* spp. Vaughan *et al.* (2001) analyzed red rice ecotypes collected from rice-growing regions in the US using simple sequence repeats (SSR) and found that most of them are closely related to *O. sativa indica* or *O. sativa japonica*, while some red rice lines are closely related to *O. rufipogon* and *O. nivara*. Several other species of the *Oryza* genus are classified as important weeds in rice - growing areas [7]. For example, in Central America, the Gulf of Mexico and the Caribbean, the weedy rice is classified as *O. latifolia*; in Italy, it is classified as *O. sativa* var. *sylvatica*, while in West Africa, it is classified as *O. barthii*, *O. longistaminata*, *O. punctate*, *O. glaberrima* and imported *O. sativa* [8].

The origin of weedy rice is a topic of ongoing debate, with various theories proposed through studies on the evolution of this weed. According to De - Wet and Harlan (1975), weedy rice may have originated from the selection and adaptation of wild rice in agricultural production. However, in areas where wild rice is absent, weedy rice can also arise from cultivated rice through adaptive mutations that accumulate during the degeneration of cultivated rice in natural ecosystems. It is also believed that contamination in cultivated rice seeds and wild rice can be a source of weedy rice in non - rice origins, such as Brazil and Italy. Another hypothesis suggests that the "crossbreeding or interfering (gene flow)" between cultivated rice and wild rice and/or re-creation between cultivated rice varieties, leads to the emergence of weedy rice. Genetic studies of evolutionary origins have proposed the emergence of weedy rice from crossbreeding, followed by subsequent degradation of cultivated rice populations [9].

In the most recent studies based on genetic traits, analysis of isozyme, genomic and molecular biology shows that weedy rice is more likely to arise from degeneration to adapt naturally from rice (de - domestication), from cross - breeding between japonica varieties, random interbreeding or gene flow due to unintentional hybridization between wild and cultivated rice [10]. The most recent studies based on genetic traits suggest that weedy rice is more likely to arise from degeneration to adapt naturally from rice (de - domestication), from cross - breeding between japonica varieties, random interbreeding, or gene flow due to unintentional hybridization between wild and cultivated rice. Weedy rice is a multidimensional issue that poses challenges for farmers, traders, agronomic agencies, agronomists, marketers, millers, production input suppliers and professionals involved in agricultural extension, research and other services. It increases production costs, lowers yield and reduces market value for rice crops and if not properly controlled, can heavily contaminate arable land, making it unsuitable for rice production.

2.2. The distribution, diversity of phenotypes and biotypes of weedy rice in the world

The shift to DSR accompanied by widespread, often exclusive, use of herbicides for weed control in rice can rapidly result in major problems with weedy *Oryza* species. Due to many morphological and physiological similarities between weedy rice and rice plants, the control of weedy rice is a difficult and complex long - term endeavor [11]. The occurrence of weedy rice was first recorded in the world in 1898 in the United States and in 1916 in Korea. After 1960, the development and spread of weedy rice in many countries around the world was reported due to the application of DSR cultivation (Figure 1). Numerous studies based on molecular markers and single nucleotide polymorphism show the prevalence of polymorphism and differences in the molecular diversity of rice varieties. indica and japonica are found in the genome of weedy rice. So far, weedy rice has been recorded in almost all rice growing countries in Asia, the Americas and Europe, including Vietnam (Figure 1) [10].

In India, awareness about the problem amongst farmers and management of weedy rice are the major concerns as Indian growers tend to categorize weedy rice as harmless 'off-types' and manage it by occasional manual rouging of panicles only. Farmers tend to abandon rice cultivation once fields are heavily infested with weedy rice. With no selective herbicide available, land preparation practices are the sole method of its management. In a previous survey in the Philippines, about 40% of the growers did not know that seeds of weedy rice have dormancy [12]. In the same survey, cutting the weedy rice panicles at harvest was practiced by a majority of the respondents (82%). Both of these studies suggested a need to increase awareness about weedy rice among Asian growers. In recent years, there has been significant progress in weedy rice research, with a focus on understanding the genetic diversity, ecology, and management of this weed [13]. One of the key findings of recent research is that weedy rice is a highly diverse group of plants with complex genetic structures [14]. Scientists have identified several different types of weedy rice, each with its unique characteristics and adaptation to different environmental conditions. This has diversity made it challenging to develop effective management strategies that can control weedy rice populations.

Recent research has also shed light on the ecology of weedy rice and its interactions with cultivated rice. Studies have shown that weedy rice can easily crossbreed with cultivated rice, leading to the production of hybrid plants that can be difficult to manage [15]. Furthermore, weedy rice is highly adaptable and can rapidly evolve in response to changing environmental conditions [16]. In terms of management, research has focused on developing recent sustainable and environmentally friendly strategies to control weedy rice populations. These strategies include the use of herbicides, cultural practices, and crop rotation [17]. Researchers have also developed new rice varieties that are resistant to weedy rice, which can help reduce the impact of this weed on rice crops [18].

Figure 1. Global and Vietnam-specific distribution of weedy rice (indicated by red dots) [10]

Weedy rice is very diverse in phenotypes and biological properties through properties such as height, stem shape, cotton shape, early ripening and very easy - to - drop seeds with different degrees of shedding and long seed duration. Some types have a beard or no beard on the seed. The color of rice husks and silk husks is also very diverse. Weedy rice hulls vary in color from slightly white to brown and black, and silk (brown rice color) is brown, red or white (Figure 2) [10]. Weedy rice diversity exhibits a wide range of phenotypic and biological diversity, including variations in height, stem shape, panicle shape, early maturity, and seed shattering propensity, as well as differences in seed dormancy and longevity. The seeds may have or lack awns, and the color of the hulls and awns can vary from white to brown or black. Moreover, the color of the bran or pericarp can be brown, red, or white. Studies have identified up to 36 different types of weedy rice, based on characteristics such as plant height, tillering capacity, growth duration, and panicle morphology [19, 20]. Figure 2 provides a visual representation of the diversity of weedy rice.

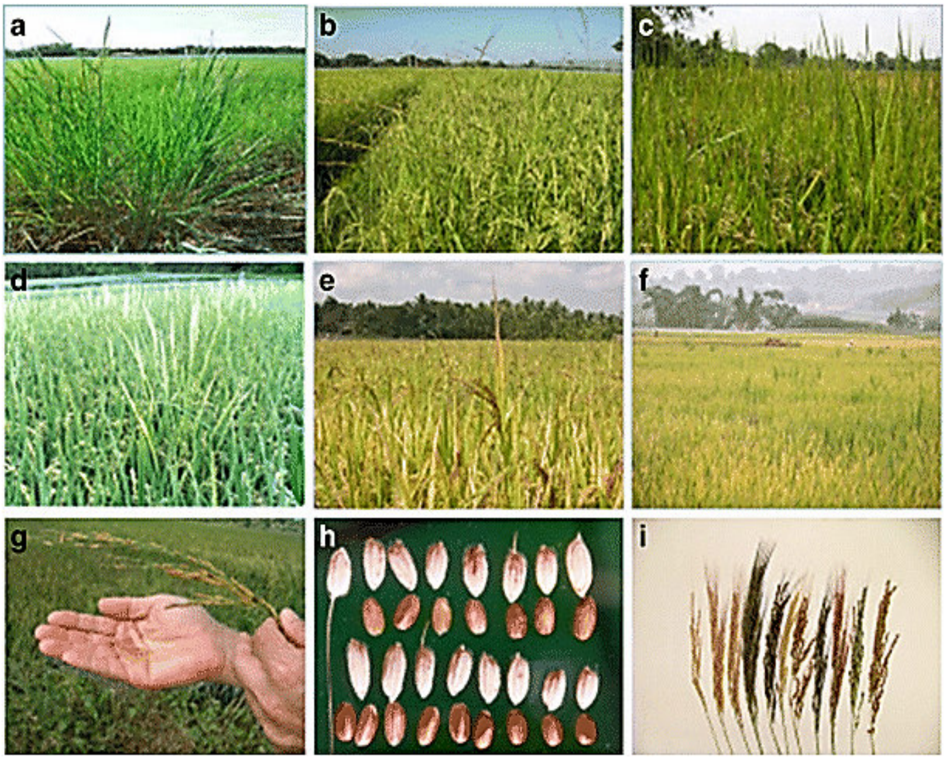

Figure 2. Presence of weedy rice growing on rice fields grown in: a) Burma, b) Malaysia, c) Nepal, d) Korea, e) Sri Lanka, f) China; characteristics of weedy rice, g) easy to shed seeds, h) rice husk color and silk hull, i) weed flakes with different grain shapes, sizes and colors [10]

2.3. Weedy rice charactersitics

2.3.1. Growth and development of weedy rice and their impact on rice yield

Weedy rice is capable of very strong growth and development from germination to maturity. Thus, the competitive effects of light, water and nutrients on the cultivated rice through tillering capacity, plant height, canopy area, leaf count and stem biological weight are superior and higher than that of cultivated rice [21]. Research by Burgos *et al.* (2011) in Arkansas, U.S showed that the low-cultivated Lemort rice variety was competitively affected by weedy rice at a density of 2 plants m^{-2} [1]. Therefore, in order to ensure optimal rice yield, it is necessary to minimize or not contain the mix of weedy rice. At weedy rice densities of 5 and 20 plants m^{-2} caused yield losses of 40% and 60%, respectively. Research on weedy rice competition to rice yield by Noldin *et al.*

(2006) showed that at levels 4, 14, 25 and 300 weedy rice crops m^{-2} cause losses in the yield of cultivated rice by 20%, 43%, 58% and 91% respectively [22]. Zhang *et al.* (2014) carried out a study on weedy rice density and yield loss of cultivated rice showed that the rice yield tended to decrease sharply when the weedy rice density increased [23]. Weedy rice density of 10 - 20 plants m^{-2} can reduce yield by up to 40%. At more severe infestation levels of 75 - 100 plants m^{-2}, rice yields can be lost up to over 80% (Figure 3).

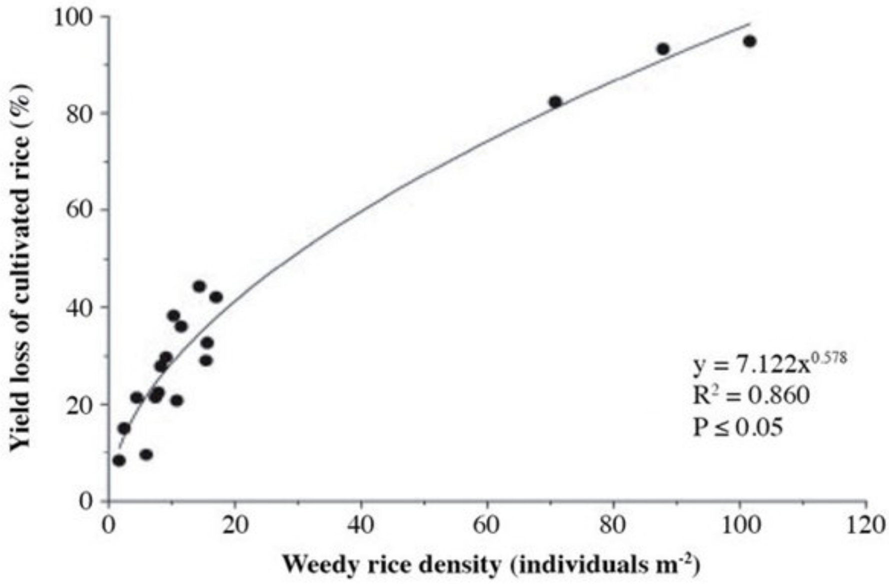

Figure 3. Correlation between weedy rice density and yield loss of cultivated rice (%) [23]

2.3.2. Spread and contagion of weedy rice

Although the origin of weedy rice is still a matter of controversy, however, the dispersed and contagious origin of weedy rice is well known. One of the main reasons is that mixed rice seeds with weedy rice led to the spread and contagion of weedy rice in America to Latin America and the Caribbean by importing rice seeds contaminated with weedy rice seeds from America. Harvesting and cleaning tools and machinery such as combine harvester also play an important role in the spread and contagion of weedy rice in the field. In addition, weedy rice seeds are bearded and likely to stick to the feathers of certain animals such as birds, ducks or even farmer's clothing, leading to the spread of weedy rice [6]. In a study and interview with rice farmers in Taiwan by Yung-Fen Huang *et al.* (2020) showed that the two main causes of dispersal and spread of weedy rice in Taiwan are the use of mixed rice varieties (55%, n = 408) and by combine harvesters (27%, n = 408) [24].

2.4. Measures to reduce the negative impact of weedy rice

Weedy rice control tactics are based on multiple approaches that embrace combinations of preventive, cultural, mechanical, chemical, and genetic tools. In the face of the threat to rice production from weedy rice issues with DSR systems, several management strategies have been established to be effective in rice systems in the Americas and Europe. One of the most effective methods for weedy rice management is the prevention of its further spread. For example, these strategies have been deployed in Californian rice monoculture, where weedy rice, accidentally introduced through contaminated seed, has been almost eliminated by the combination of water-seeding and the use of certified crop seed free of weedy rice seed [25]. It is essential to minimize or eliminate the occurrence of weedy rice in rice fields to ensure optimal rice yield. Farmers can adopt various management practices such as manual or mechanical removal of weedy rice, crop rotation, and the use of herbicides to control the spread of weedy rice.

Pre - plant herbs generally provide effective weed control of a significant proportion of the soil weed seed bank. However, despite the greater availability of herbicides, weedy rice is difficult to eradicate with herbicidal strategies and thus remains a serious global constraint. Post - emergence weedy rice control can be achieved with the use of herbicide - tolerant rice varieties. Otherwise, selective in - crop control of weedy rice with post - emergence herbicide would be extremely difficult, as rice and weedy rice respond identically to herbicides.

There are potential innovative solutions to achieve safe and selective weed rice control in rice crops by strategically and sequentially applying the two components (the herbicide active ingredient + a herbicide safener) of commercially available herbicides. Some can be toxic to germinating rice seedlings unless a specific herbicide safener is mixed with the herbicide compound in commercially available format products. Thus, it was hypothesized that the dissociated use of herbicide and a specific safener could allow effective weedy rice control without causing injury to the rice crop [26]. Roberto *et al.* (2017) also hypothesized that little damage or mortality in rice seeds exposed to the safener versus significant phytotoxicity and mortality in rice seeds treated with the herbicide only [11]. They tested whether the use of a safener applied directly to rice crop seeds before seeding could safely germinate rice seedlings against a herbicide applied post - seeding pre - emergence. The herbicide would be lethal to germinating weedy rice seedlings but not to rice seedlings. This proof - of - concept study suggests that the dissociated use of herbicide and specific safener could be an effective strategy for managing weedy rice.

Various tactics are used to control weedy rice, including preventive, cultural, mechanical, chemical and genetic tools. Prevention is one of the most effective strategies for managing weedy rice. For instance, water - seeding and the use of certified crop seed free of weedy rice seed have been employed in Californian rice monoculture to eradicate weedy rice, which was accidentally introduced through contaminated seed. Pre - plant herbs generally provide effective weed control of a significant proportion of the soil weed seed bank, but weedy rice is difficult to eradicate with herbicidal strategies and remains a serious global constraint.

2.5. Weedy rice in Vietnam

In Vietnam, the prevalence of weedy rice infestation and its associated damage is notably linked to the adoption of the DSR cultivation method, leading to adverse impacts on rice quality, yield, farmers' income, and the overall export potential of Vietnam's rice industry as mentioned in introduction secsion. Studies on rice shedding in floating and wild rice were conducted in An Giang and Dong Thap provinces, Vietnam from 1988 - 1990. However, the term "weedy rice" was first used in 1994 after experimental surveys conducted by the Cuu Long Delta Rice Institute, Vietnam in provinces such as Tien Giang and Long An during the Spring - Summer season. Several lines of weedy rice were discovered, including some that shed seeds easily, have dark brown or black seed lines, and have bearded lines on the seeds. Weedy rice lines that grow to the same height as cultivated rice and shed seeds easily at the near - harvest stage are particularly dangerous because they are difficult to distinguish. The use of rice seed contaminated with weedy rice seed is the primary source of infection and the main spread of weedy rice in the Mekong Delta. There has been no specific study to classify and identify weedy rice in Vietnam in general and in the Mekong Delta in particular.

At the 20th Asian - Pacific Weed Science Conference in 2005, hosted by the Cuu Long Delta Rice Institute in Ho Chi Minh city, Vietnam, scientists from the Associations of Weed Science in the Asian - Pacific region commented on the heavy grass infection in several places they visited, rice that contains weedy rice that is really an epidemic, a harm to the important rice production industry, and a new rice pest in Asian-growing countries, including Vietnam. Weedy rice is known for its self - shedding characteristics when it is about to ripen, and the accumulation of weedy rice seeds increases in the field. The viability of weedy rice seeds accounts for 56.8% after four months of burying the seeds in continuous wetlands, leading to spread from field to field. In addition to yield losses, rice quality is also affected by a high proportion of red rice grains in the Mekong Delta. Some outstanding features of weedy rice varieties, such as higher plant height than cultivated rice, early shedding, high rate of shedding, dark yellow - black seeds, red - brown-black seeds, and bearded rice seeds, make it easy to distinguish between weedy rice and cultivated rice. The higher the density of weedy rice, the higher the dry matter accumulation and the stronger competition with cultivated rice, reducing the biomass and yield of paddy [27].

Efforts to address weedy rice infestation in DSR systems have also been explored through research initiatives. The results of a survey conducted by the Mekong Delta Rice Institute in 2006 showed that the average density of rice and grass in the winter - spring crop in An Giang was 31.36 plants m^{-2}, while in the Summer - Autumn crop, it to increased 57.97 plants m^{-2}. Rice yield decreased by 18.3% (Winter - Spring) and 30.6% (Summer - Autumn). In Soc Trang, the density of weedy rice was 3.56 plants m^{-2} (Winter - Spring) and 4.32 plants m^{-2} (Summer - Autumn), and the yield decreased by 5.6% (Winter - Spring) and 7.2% (Summer - Autumn). Similarly, in Long An, the yield of weedy rice decreased by 2.4% (Winter - Spring) and 11.1% (Summer - Autumn) [28]. The experimental study conducted by the Cuu Long Delta Rice Institute, Vietnam on the effect of weedy rice on the growth and yield of rice in the seasons 2006 - 2007 Winter - Spring and 2007 - 2008 Winter - Spring showed that sowing 200 grains of weedy rice m^{-2} led to 254.3 weedy rice shoots growing in the field and a yield of cultivated rice of 5.25 tons ha^{-1}, down by 17.3% compared to the control without weedy rice. At this infection level, the proportion of weedy rice seeds in the milled rice was 24.3%. However, if we sow weedy rice with a density of 800 seeds m^{-2}, the average number of weedy rice shoots growing in the field increases to 732.4 shoots m^{-2} and the yield of cultivated rice discussed to only 1.75 tons ha^{-1}, a decrease of 72.4% compared to the control. The percentage of weedy rice seeds in the milled rice increased to 79.4%. Rice seeds contaminated with 150 weedy rice kg^{-1} led to a decrease in the yield of cultivated rice. The average rice yield using 150 weedy rice seeds kg-1 of rice seed was 5.46 tons ha^{-1}, while the certified rice seed was 5.95 tons ha^{-1}, resulting in a yield difference of 8.2%. Correspondingly, the weedy rice seed mixed in the date milled rice is 198.3 seeds kg^{-1} of rice compared to 3.69 seeds kg^{-1} of rice, an increase of 53.7 times [28].

Another notable project is the study conducted by Chauhan *et al.* (2014) aiming to evaluate the efficacy of pretilachlor, a selective herbicide, in managing weedy rice and other weeds in wet-seeded rice cultivation. The study found promising results, indicating that increasing pretilachlor application rates from 300 to 900 g/ha led to a significant reduction in weedy rice biomass by 54% [21]. Importantly, these higher application rates did not exhibit any toxic effects on rice plants, demonstrating the selective nature of pretilachlor in targeting weedy rice while ensuring the safety of cultivated rice varieties. This research underscores the potential of herbicide-based approaches, such as pretilachlor application, in effectively managing weedy rice infestation in DSR systems, particularly in wet-seeded rice cultivation prevalent in South Vietnam. By providing insights into the optimal application rates and safety profiles of herbicides like pretilachlor, this study contributes valuable information for weed management practices in Vietnam's rice-growing regions. Furthermore, this research highlights the importance of continued investigation into novel weed management strategies tailored to the unique agroecological conditions and weed dynamics prevalent in Vietnam. By building upon the findings of studies like Chauhan *et al.* (2014), researchers and practitioners can refine and optimize weed control approaches to enhance productivity and sustainability in rice production systems [21].

Recently, researchers have been investigating various approaches to manage weedy rice infestations in Vietnam. One promising approach is the use of allelopathy, the ability of some plants to release chemicals that inhibit the growth of other plants. In a study conducted in the Mekong Delta, researchers found that some rice cultivars could release allelopathic chemicals that inhibited the growth of weedy rice [29]. The researchers suggest that incorporating allelopathic rice varieties into rice production systems could be an effective strategy for weedy rice management. Another strategy is the use of herbicides, which are widely used for weed control in rice production. However, the overuse of herbicides can lead to herbicide-resistant weedy rice populations. To address this issue, researchers in Vietnam have been investigating alternative weed management strategies, such as the use of cover crops and manual weeding [30]. In addition to these approaches, researchers are also exploring the genetic basis of weedy rice traits, such as seed dormancy and shattering, which contributes to its weediness. Understanding the genetic basis of these traits could lead to the development of new rice varieties that are resistant to weedy rice infestations [31].

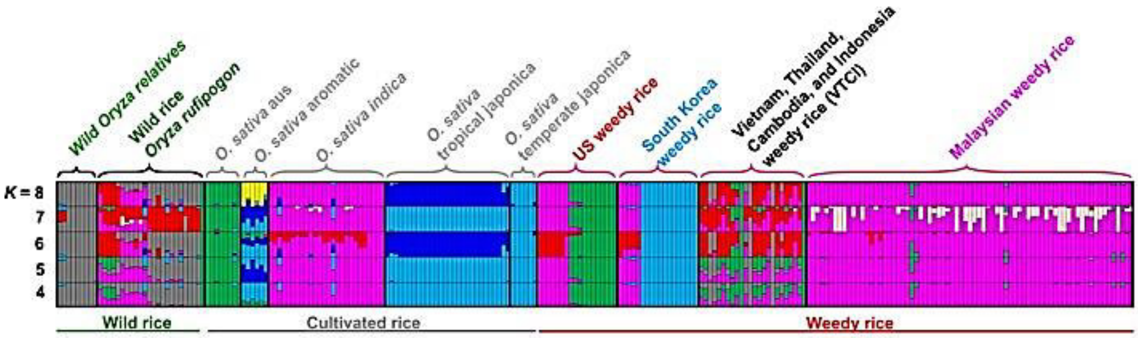

Figure 4. Population structure of 240 *Oryza* rice lines based on 44.769 SNPs (single nucleotide polymorphism). The maximum marginal similarity factor shows that K = 8 is the best fit for comparison and clustering. The results of the analysis show that the weedy rice in the United States, Korea and Malaysia is closely related to cultivated rice varieties. Forage rice from Vietnam, Cambodia, Thailand and Indonesia is closely grouped with wild rice and cultivated rice

Figure 5. Cotton form and grain pattern of weedy rice lines recorded in a farmer's field, Thoi Thuan commune, Can Tho city, Summer - Autumn crop, August 2019. Pattern of paddy rice (right flower jar - left picture) and paddy seed (bottom left row - right photo)

To date, there have been no genetic and molecular studies conducted in the country to determine the phylogenetic origin of weedy rice in Vietnam. However, a recent study by Vigueira *et* *al.* (2019) showed that weedy rice samples from Vietnam, Thailand, Cambodia and Indonesia had significant genetic similarities with wild rice samples and were genetically derived from different types of rice samples grown in the form of long-seeded indica (Figure 4) [32]. In Vietnam and the Mekong Delta, a very common wild rice variety growing in canals and swamps is *Oryza rufipogon*. According to Chin *et al.* (1999), the use of weedy rice seeds is the main source of infection and spread of weedy rice in the Mekong Delta [33]. In a survey conducted in Vietnam, weedy rice infestation was found to be the worst problem encountered in wet DSR. However, most growers were aware of the presence of weedy rice in their fields and the damage it could cause to the crop [21]. During a field visit in August 2019, we recorded at least six types of weedy rice on a farmer's field in Thoi Thuan commune, Can Tho city (10°3'35" degrees North, 105°25'57" east longitude). These weedy rice types could be distinguished based on the shape of their cotton and grain, which were very similar to those of cultivated rice (see Figure 5). According to a survey conducted by the Mekong Delta Rice Institute, Vietnam in 2006, weedy rice infestation caused significant yield losses in rice crops in several provinces in Vietnam. In An Giang, the average density of weedy rice was 31.36 plants per square meter in the Winter-Spring crop, and the yield decreased by 18.3% compared to the control. similarly, in Soc Trang and Long An, the density of weedy rice ranged from 3.56 to 57.97 plants per square meter and the yield decreased by 2.4% to 30.6%. A subsequent experimental study conducted by the Cuu Long Delta Rice Institute also showed that weedy rice infestation could cause a significant reduction in rice yield, with the proportion of weedy rice seeds in the milled rice ranging from 24.3% to 79.4%.

3. MANAGEMENT OF WEEDY RICE AND FUTURE RESEARCH

To effectively manage weedy rice infestation in DSR systems, integrated weed management strategies are imperative. These strategies should encompass a combination of cultural, mechanical and chemical control methods tailored to the specific challenges posed by each cultivation method. Cultural practices such as crop rotation, stale seedbed techniques, and timely planting can help reduce weed pressure, including weedy rice, while mechanical methods such as hand weeding and mechanical cultivation can provide additional weed control. Furthermore, judicious herbicide use, coupled with herbicide rotation and the adoption of herbicide-resistant rice varieties, can mitigate the development of herbicide - resistant weedy rice populations.

Given the complexity and multidimensional aspects of weedy rice species, including red rice varieties, weed control measures require careful attention and adaptation in crop management. Successful management demands patience and persistence, as tactics for controlling weedy rice may vary between regions and necessitate frequent adjustment [8]. Therefore, the strategy should be continuously revised and tailored to the specific conditions and challenges encountered in each rice - growing area.

- Consider and take into account the emergence of new or different ecological lines of weedy rice.
- Adapt to changes in cultivated rice varieties, cropping systems, farming practices, water availability and marketing standards for rice grains.
- Take advantage of crop rotation with other crops, advancements in the development of chemical herbicides and biotechnology.
- The main strategies for controlling weedy rice species (including red - grained rice varieties) can be grouped as follows:
- Prevent the infiltration or reinfection of weedy rice through the use of standard grass seed cleaning.
- Limit and reduce the amount of weedy rice seeds that fall and remain in post - harvest soil by employing post - harvest and farming methods.
- Prevent germination and growth of weedy rice using different farming methods and water management techniques.

• Eliminate rice and grass during rice cultivation.

• Change the rice field environment by rotating crops with other crops or leaving bare land.

• Use biotechnology to create herbicide - resistant varieties.

• Use chemical herbicides.

Further research on weedy rice management in Vietnam should aim to synthesize implementation proposals across various dimensions, considering the complexities of weedy rice ecology, biology and management. Key areas for future investigation and implementation proposals include:

• Weedy rice ecology and biology, including Seed Bank Dynamics: Understanding the ecological and biological factors influencing weedy rice dynamics, including seed germination, emergence and persistence in the soil seed bank, is crucial for developing targeted management strategies.

• Climate change and Its Impact on weedy rice biology and management: Research into how climate change affects weedy rice distribution, phenology and herbicide efficacy can inform adaptive management approaches in the face of changing environmental conditions.

• Integration of herbicide use with non - chemical tools: Exploring the integration of herbicide use with non - chemical tools, such as competitive crops or true integrated weed management (IWM) packages, can enhance weed control efficacy while reducing reliance on herbicides and mitigating the risk of herbicide resistance.

• Nano - herbicides: Investigating the efficacy and environmental impacts of nano-herbicides, which utilize low doses of active ingredients, as a potential alternative or complement to traditional herbicides in managing weedy rice infestation.

• Harvest weed seed control: Researching the feasibility and effectiveness of harvest weed seed control techniques, such as weed seed destruction at harvest, to prevent the build - up of the weedy rice seed bank and reduce weed pressure in subsequent crops.

• Improvement of herbicide spray techniques: Developing and optimizing herbicide spray techniques, including nozzle selection, spray volume and application timing, to maximize herbicide efficacy while minimizing off-target drift and environmental impact.

• Potential of unmanned aerial vehicles (UAV): Exploring the potential of UAV technology for mapping weedy rice infestations and targeted herbicide application, allowing for precision weed management and reduced herbicide usage.

• Modelling weed emergence and dynamics: Utilizing modeling approaches to predict weed emergence patterns, assess the efficacy of different management strategies, and optimize resource allocation for weed control efforts.

• By addressing these research areas and implementing corresponding proposals, stakeholders can develop holistic and sustainable strategies for managing weedy rice infestation in Vietnam's rice cultivation systems, ensuring the resilience and productivity of agricultural landscapes while minimizing environmental impacts.

4. CONCLUSSION

Recent research on weedy rice has provided valuable insights into the genetic diversity, ecology and management of this important weed. These findings will be critical in developing effective strategies to control weedy rice and ensure the sustainability of rice production in the future. Weedy rice is also a major problem in Vietnam, causing significant yield losses in rice production. However, is has also identified promising strategies for weedy rice management, including the use of alternative weed management strategies and genetic approaches. These strategies could help to reduce the impact of weedy rice on rice production in Vietnam and other rice - growing regions worldwide. Overall, this review highlights the severity of weedy rice infestation in wet DSR in Vietnam and emphasizes the need for effective management strategies to prevent yield losses caused by this problem.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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