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INNOVATIVE APPROACHES TO WEED MANAGEMENT IN AEROBIC RICE: A CLIMATE-SMART REVIEW

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ABSTRACT

Rice is one of the most important cereal crops globally, serving as a staple food for over half of the world's population. It provides a significant source of calories and nutrition, particularly in Asian countries where it forms the primary dietary component for billions of people. Given its centrality to food security and economic stability, optimizing rice production methods becomes imperative. Rice cultivation has traditionally been labour-intensive, with seedlings transplanted into flooded paddies. However, there has been a notable shift towards direct seeding in recent years. This shift is driven majorly by climate change and labour difficulties. However, weed management in direct-seeded rice (DSR) is a critical aspect of sustainable agriculture, and with changing climatic conditions, the need for climate-smart approaches has become increasingly evident. This review explores innovative strategies and technologies that address weed challenges in DSR, while considering the broader context of climate resilience. Traditional methods, such as pre-emergence and post-emergence herbicides, are complemented with sustainable and integrated weed management (IWM) practices to enhance efficacy and environmental sustainability. Direct Seeded Rice (DSR) offers climate resilience through reduced water usage and adaptability to fluctuating rainfall patterns, while also mitigating greenhouse gas emissions and promoting crop diversification, making it a feasible choice for sustainable rice growing in the face of climate change. Climate change creates huge obstacles for global agriculture, with direct-seeded rice (DSR) production especially vulnerable to changes in temperature, precipitation patterns and extreme weather events. This review examines weed invasion, shift and losses in dry DSR (DDSR). The current assessment of regional and worldwide scientific efforts under DDSR suggests clever weed-management solutions that can be used after further inspection.

Key words : Direct-seeded rice, Weed management, Climate-smart agriculture, Integrated weed management, Climate resilience, Sustainable agriculture, Adaptive strategies, Digital technologies, Climate-resilient rice varieties.

Introduction

Rice is a staple food for the majority of the 4 billion plus Asian population and a source of livelihood for millions of small and marginal rice farmers (Mohanti *et al*., 2020). Rice farming originated in Asia, specifically China, India and has spread across many climates and ecosystems, making it an essential component of many cuisines and agricultural systems. Rice is farmed on almost 45 million hectares in India, accounting for 32.14% of the total net cultivated area (Agricultural Statistics at a Glance). India's annual production of rice is 196.24 million tonnes (Source: FAO, 2022.). The difficulty is that under changing climate scenarios, this more rice must be produced with a lower environmental footprint (using less water, labour and agrochemicals) to provide both food security and sustainability. One strategy to attain this aim is to close rice yield gaps, especially in locations such as the Eastern States of India, where yield disparities are substantial (Panneerselvem *et al*., 2020). Between 1990 (598.67 mt rice production) and 2020 (756.74 mt rice), the use of high-yielding rice varieties, nutrient and soil management, improved water efficiency and significant global pest management (including weed management) increased global rice yield by 26.4% (FAOSTAT). Crop production faces a variety of biotic and abiotic restrictions, as well as socioeconomic and crop management challenges. Weeds are the most significant biotic restrictions on agricultural production in both developing and wealthy nations. In general, weeds present the biggest potential yield loss to crops together with pathogens (fungi, bacteria, etc.) and animal pests (insects, rodents, nematodes, mites, birds, etc.), which are less concerned (Oerke, 2006). Weeds compete with crops for sunshine, water, nutrients and available space; therefore, any technique that uses a crop to manage weeds is called a sustainable weed control practice. Such tactics must be used with other instruments to accomplish efficient weed control (Chauhan, 2020). Weeds are as old as agriculture, and farmers have long recognized their impact on crop productivity (Ghersa *et al.*, n.d.), which has resulted in the co-evolution of agro-ecosystems and weed control. Weeds pose a higher risk of yield loss in aerobic rice than in transplanted rice (Rao *et al.*, 2007). Herbicides are commonly employed to kill or inhibit undesired vegetation in chemical weed management. It is more popular among farmers than manual and mechanical methods due to its low labour cost, low input cost, and ease of usage at important periods (Shrestha *et al.*, 2021). A single method of control will not provide effective long-term weed management and will frequently result in the development of resistance (Chauhan, 2020). As the world's population grows; the pressures placed on agricultural production systems will put current agricultural practices to their limits. Furthermore, adequate food supply in the future can only be realized by using sustainable growing strategies that reduce environmental degradation and preserve resources while maintaining high yield and profitability in cropping systems (Meena *et al.*, 2015). Farmers employ various strategies for effective weed control to ensure optimal crop yields. Some commonly used methods are cultural practices, mechanical control, chemical control, and biological control (Monteiro and Santos, 2022).

Effect of changing climate scenario on rice production

The changing climatic situation presents considerable problems to rice production, which is a staple meal for a large section of the world's population. The majority of climate change impacts on rice production occur from fluctuations in rainfall and temperature, which lead to flooding, water scarcity and increases in insects and pests, illnesses and weeds (Mahdu *et al.*, 2019). Climate change is primarily connected with an increase in carbon dioxide (CO_2) concentration, temperature and the intensity and frequency of drought and flooding (Chauhan, 2020). Climate is one of the main determinant factors of agricultural production. There is great worry around the world regarding the impact of climate change and its variability on agricultural production. Researchers are concerned with the potential damages of climate change that rises in agriculture (Singh and Awais, 2019). Rice production must be increased to feed the world's population on less land with a degraded nutrient base by using fewer inputs and energy, while rice production contributes to global climate change by emitting large amounts of carbon dioxide, methane, and nitrous oxide. These gases trap infrared long waves released from the earth's surface in the atmosphere, increasing its warmth (Kumar Jena *et al.*, 2023). Rice grain yield reduces by 10% for each 1°C increase in growing-season lowest night temperature in the dry season, but the effect of maximum temperature on crop productivity is negligible. This research suggests that higher night-time minimum temperature reduces rice crop yield and is connected with global warming (Kumar Jena *et al.*, 2023). According to data, seven sister states in the North Eastern India region are visibly influenced by climate change, which may lead to droughts in the future owing to decrease in rainfall and increase in temperature (T & VK, 2018). Climate change would reduce rice yields in India by 4.5% to 9% by 2039 (T & VK, 2018). Various adaptation and mitigation measures, such as developing climate-resilient rice varieties, improving water management practices, and encouraging sustainable farming practices, can help mitigate the detrimental effects of climate change on rice productivity (Khaliq 2019).

Benefits of Direct seeded rice (DSR)

Direct seeding of rice refers to the practice of starting a rice crop from seeds sown in the field rather than transplanting seedlings from the nursery. Table 1 shows three methods of direct seeding rice (DSR): dry seeding (sowing dry seeds into dry soil), wet seeding (sowing pre-germinated seeds over wet puddled soils), and water seeding (sowing seeds into standing water) (Farooq *et al.*, 2011).

This approach is gaining popularity due to its potential benefits. DSR significantly reduces water consumption compared to traditional transplanting methods, enhancing efficiency, particularly in water-scarce regions (Kumar *et al.*, 2018). Direct seeding reduces labour-intensive tasks like nursery preparation and transplanting, resulting in cost savings and increased efficiency (Jat *et al.*, 2019). Appropriate management of DSR systems can

Table 1 : Classification of direct-seeded rice (DSR) systems.

Direct seeding system	**Seed condition**	**Seedbed condition and environment**	**Seeding pattern**	**Where practiced**
Dry direct-seeded	Dry	Dry soil, primarily aerobic	Broadcasting, drilling, or sowing in rows	Mostly in rainfed areas; some in irrigated areas with careful water control.
Wet direct seeded	Pre germinated	Puddled soil can be aerobic or anaerobic.	Various	Mostly in irrigated areas that have good drainage.
Water seeding	Dry or pre-germinated	Standing, mainly anaerobic.	Broadcasting over standing water	In irrigated areas with good land levelling and areas with red rice problems.

Source: Farooq *et al*. (2011).

dramatically reduce methane emissions from flooded rice fields due to the non-constant presence of water (Linquist *et al*., 2015). Direct seeding expedites rice cultivation by eliminating the need for seedbed preparation and transplanting; resulting in more timely planting and potentially higher yields (Kassam *et al*., 2019). DSR systems, when combined with effective weed management practices, can considerably enhance crop output (Pandey *et al*., 2017). When the future of rice production is threatened by global water scarcity and rising labour costs, direct seeded rice (DSR) provides an appealing option (Farooq *et al*., 2011).

The study discovered that no-tillage and direct seeding procedures considerably enhance water and labour use, net income and crop output when compared to conventional practices (Bhushan *et al*., 2007). Another study found that DDSR and AWD can increase agricultural yields while decreasing water inputs, although more research is needed under a variety of environmental situations (Ishfaq *et al*., 2020).

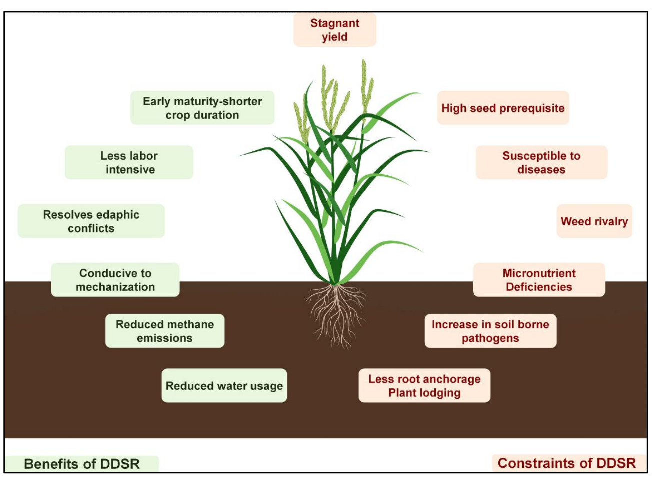

Fig. 1 : Dry direct-seeded rice (DDSR) offers advantages like reduced water usage, methane emissions, mechanization compatibility and shorter crop duration, but also faces challenges like disease susceptibility, weed rivalry and micronutrient deficiencies (Sagare *et al*., 2020).

Challenges in Direct-seeded rice

Direct-seeded rice (DSR) offers various advantages, yet there are also restrictions and obstacles, making it essential to recognize these for the effective and sustainable implementation of DSR practices (Fig. 1). DSR systems may face increased Weed competition, particularly in early crop growth, which can negatively impact rice yields if not managed properly (Kumar *et al*., 2018). Direct-seeded rice fields are more susceptible to pests and diseases like stem borers and blast disease due to the lack of a nursery phase and direct seed exposure. (Bouman *et al*., 2005). Uniform stand establishment in DSR can be challenging, leading to uneven crop emergence and potential yield losses due to plant competition (Kassam *et al*., 2019). DSR necessitates precise water management, as improper practices can result in reduced yields, seed germination, and early crop establishment. (Kumar *et al*., 2018). DSR faces challenges in nutrient availability, appropriate nutrient management strategies are required for optimal crop development and productivity (Singh *et al*., 2019). Direct-seeded rice is more susceptible to bird damage, extreme weather and suboptimal soil conditions, leading to seed mortality and reduced stands (Pandey *et al*., 2017).

Direct-seeded rice and weed shift

The term "weed shift" refers to the phenomena in which the composition and dominance of weed species in a given agricultural system vary over time, frequently in reaction to various management measures, including the use of herbicides. Continuous and indiscriminate use of herbicides can result in the development of herbicide-resistant weed populations, causing a shift in weed species composition (Powles *et al*., 2010). Crop rotation can affect the weed species that thrive in a field, either favouring or suppressing particular types (Mohler *et al*., 1996). Tillage practices can affect the weed community.

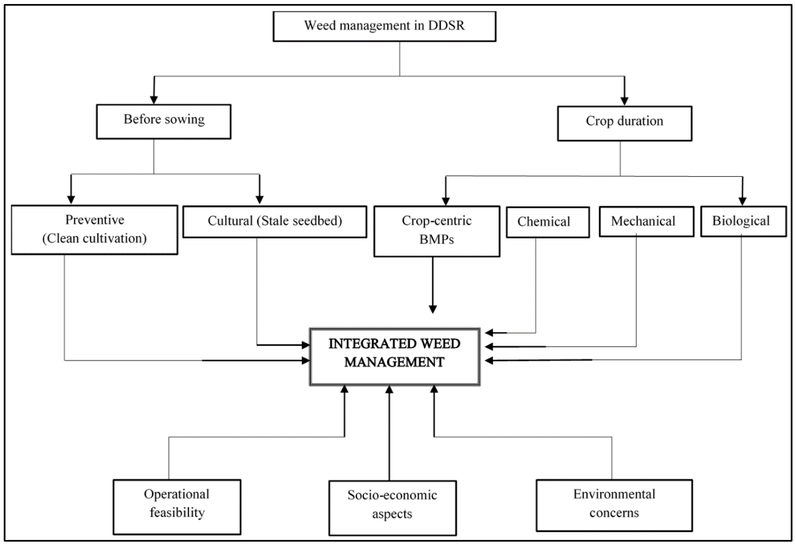

Fig. 2 : Integration of various management practices for successful weed control in DSR. Source: (Shekhawat *et al*., 2020).

Reduced tillage, for example, may favour weed species that can tolerate minimum soil disturbance (Liebman *et al*., 1997). Alterations in climate conditions, such as temperature and precipitation, can alter the distribution and dominance of weed species (Ziska *et al*., 2011). Cultural techniques, such as crop density or row spacing, can influence the weed ecology in a given area (Ogg *et al*., 1989). The genetic variety of weed populations can help them adapt to changing environmental conditions and management approaches (Neve *et al*., 2009).

Weed management and Climate Change

Rice crop yields and profitability rely heavily on effective weed management, utilizing integrated weed management approaches that combine cultural, mechanical, and chemical methods. Climate change's impact on direct-seeded rice (DSR) in India has sparked considerable concern. Climate change-induced temperature, precipitation patterns and extreme weather events can also have a significant impact on rice production productivity and sustainability, particularly in direct-seeded systems. Rising temperatures might cause heat stress during critical growth phases of direct-seeded rice crops, which affects germination, seedling establishment and overall crop development (Singh *et al*., 2002). Changes in precipitation patterns and increasing frequency of drought events might cause water scarcity in direct-seeded rice fields, impacting crop yield and quality (Wassmann *et al*., 2019). Changes in monsoon patterns can influence the time and distribution of rainfall, affecting the suitability of direct-seeded rice farming and planting schedules (Kumar *et al*., 2011). Coastal areas that use direct-seeded rice may experience saline intrusion as sea levels rise, limiting soil fertility and crop development (Hossain *et al*., 2016). Extreme weather events are becoming more frequent and intense, such as cyclones and storms, can cause physical damage to directly seeded rice fields and infrastructure (Hijioka *et al*., 2014). Adaptive methods, such as developing climate-resilient rice varieties, optimizing planting schedules, and improving water management practices, are crucial for mitigating the effects of climate change on direct-seeded rice in India (Wassmann *et al*., 2009).

Weed management in DSR

Weed management in direct-seeded rice (DSR) is essential for enhancing crop yield while decreasing competition for nutrients, water and sunlight. To effectively control weeds in direct-seeded rice (DSR), Integrated Weed Management (IWM) is combined with cultural, mechanical, biological and chemical methods.

Integrated Weed Management : IWM combines cultural, mechanical, and chemical approaches to control weeds (Fig. 2). It emphasizes a holistic approach to sustainable weed management (Opeña *et al*., 2017) or IWM is weed management that employs many, complementary strategies within a system rather than relying just on one way (Chauhan, 2020). IWM aims to reduce the development of resistance to single-weed management strategies (Chauhan *et al*., 2017). Rotate rice with different crops and diversify cropping systems to interrupt weed cycles (Oerke *et al*., 2006). Cover crops and mulching can help reduce weed development and improve soil health (Chauhan *et al*., 2010). Optimize sowing time and seeding rates to enable rapid crop establishment, while reducing weed competition (Olofsdotter *et al*., 2000). Use rotary weeders and cono weeders for mechanical weed management in DSR (Fischer *et al*., 2001). Use herbicide-tolerant rice types for effective weed control. (Busi *et al*, 2009). Integrate allelopathic crops, which emit compounds that prevent weed development (Olofsdotter *et al*., 2002). Investigate the use of bio-herbicides and microbiological agents for targeted weed control (Duke *et al*., 2007). The performance of IWM in direct-seeded rice is dependent on combining techniques according on local variables, weed species and agronomic practices.

Cultural weed management : Cultural weed management in direct-seeded rice (DSR) entails altering the cropping system, planting procedures, and overall farm management to limit weed competition. Adjust the seeding rate and planting periods to increase crop establishment and competitiveness against weeds (Kuk *et al*., 2004). Adjust row spacing and plant arrangement to improve crop competitiveness with weeds (Chauhan *et al*., 2011). Choose and use rice varieties that have intrinsic weed-competitive qualities (Olofsdotter *et al*., 2000). To inhibit weed development, follow suitable water management measures, such as intermittent flooding (Jabran *et al*., 2015). Use cover crops to decrease weed growth during fallow periods and promote soil health (Witt *et al*., 2000). Manage agricultural wastes effectively to prevent weed establishment and growth (Yaduraju *et al*., 2008). Using a range of cultural weed management measures can improve weed control in direct-seeded rice systems. Always examine local conditions and tailor solutions to the distinct weed flora in your area.

Mechanical weed management : Mechanical weed management in direct-seeded rice entails physically controlling weeds with a variety of methods and equipment. Cono weeders are manually operated equipment that uproot and bury small weeds, resulting in effective weed control (Barman *et al*., 2015). Rotary weeders are tractor-mounted instruments that use revolving blades to cut and remove weeds between rows (Sattar *et al*., 2014). Floating tine harrows are used to control weed growth and incorporate crop leftovers into the soil (Chauhan *et al*., 2011). Power tillers fitted with appropriate attachments can be utilized for inter-row cultivating and weeding in direct-seeded rice (Islam *et al*., 2015). Seed drills with integrated weed management attachments can plant seeds while also controlling weeds (Jabran *et al*., 2015). Ridge and furrow planting strategies produce elevated ridges for crops, which suppress weed growth (Baltazar *et al*., 1981). Manual weeding with hand-held equipment like hoes and knives can help manage weeds in small-scale farming (Shrestha *et al*., 2004). Weed clippers can be used to cut and remove weeds at ground level, offering an alternative to hand weeding (Vanden *et al*., 1980). Mechanical weed management strategies should be tailored to the specific weed spectrum and field conditions. Combining mechanical approaches with additional cultural and chemical measures can improve weed control in direct-seeded rice systems.

Chemical Weed Management : Chemical weed management in direct-seeded rice entails strategically using herbicides to control and suppress weed development. To control specific weed species in DSR, use selective herbicides wisely (Johnson *et al*., 2009). Apply pre-emergence herbicides to reduce weeds before they emerge and provide early-season control (Pandey *et al*., 2017) or Pre-emergence herbicides are administered before weed emergence, producing a barrier in the soil that prevents weed development. Common pre-emergence herbicides for direct-seeded rice are Butachlor, Pendemethalin, Oxadiargyl and Pretilachlor (Mandal *et al*., 2018). Post-emergence herbicides are used after weeds have emerged, but before the crop reaches a critical growth stage. Some common post-emergence herbicides are Bispyribac-sodium, Cyhalofop-butyl, Quinclorac, and Pyrazosulfuron-ethyl (Chauhan *et al*., 2012). Use post-emergence herbicides to target emerging weeds in direct-seeded rice fields (De Datta *et al*., 1981). Use rice varieties that have been genetically modified for resistance to specific herbicides, which allows for successful weed management (Duke *et al*., 2009). To prevent the establishment of herbicide-resistant weed populations, use various herbicides with diverse modes of action (Heap *et al*., 2014). Plan successive herbicide applications based on the weed spectrum and growth stages for successful control (Johnson *et al*., 2009). Implement measures for managing and delaying the emergence of herbicide-resistant weed populations (Powles *et al*., 2010). When applying chemical weed management, it is critical to adhere to the prescribed application rates, timings and safety measures. Additionally, monitoring herbicide resistance management strategies is critical for long-term weed control in direct-seeded rice systems.

Recommendations to farmers

Climate change has a significant impact on agriculture, namely weed management in direct-seeded rice. Observe weather patterns. Stay current with local climate trends and changes. Use weather forecasting systems to anticipate changes in temperature, precipitation and other climatic elements that may impact weed growth. Use crop rotation and diversification to disrupt weed life cycles and lessen reliance on a single crop. This can help increase resilience to shifting climate conditions. Be adaptable in weed management tactics dependent on climate circumstances. For example, modify herbicide treatment times and rates to account for temperature and precipitation changes. Use cultural practices like cover cropping, mulching, and intercropping to organically control weeds. These methods can enhance soil health and water retention. Water control is frequently required when seeding rice directly. Efficient water utilisation can help control the weeds and mitigate the effects of climate change. Implement technologies such as alternating wetting and drying (AWD) to conserve water while also controlling weeds. Select rice varieties that are tolerant of shifting weather conditions and have natural weed resistance. Consult agricultural extension services or local specialists to determine which kinds are appropriate for your location. Regularly check fields for early symptoms of weed infestation. Early detection enables prompt and targeted intervention, which reduces the impact on rice yield. Collaborate with neighbouring farms and local agricultural extension services to share climate change and weed management knowledge and experiences. Collective efforts can result in more effective adaptation techniques. Stay current with the newest farming methods and technologies. Attend conferences, seminars, and training programs to learn more about climate-resilient farming techniques and weed management. Focus on preserving and increasing soil health by incorporating organic matter, managing nutrients properly, and conserving soil. Healthy soils lead to improved weed control and crop resilience. Climate Change's Impact on agriculture varies by location; therefore, it is critical to customise these ideas to local conditions and engage with agricultural specialists for region-specific guidance.

Conclusion

Farmers face both obstacles and opportunities when dealing with climate change and weed management in direct-seeded rice. Climate change impacts weed dynamics and cultivation practices, requiring adaptation measures to encourage sustainable rice production. Weed management strategies must be adjusted to account for climate change, including flexibility in herbicide application, timely interventions and cultural traditions. Crop diversification and rotation can interrupt weed life cycles, reduce pest burdens, and promote sustainable agricultural systems. Optimizing water management approaches, such as alternate wetting and drying techniques, can save water and influence weed development. Selecting and cultivating rice types that are resilient to changing climate conditions and naturally resistant to weeds is crucial. Collaboration between agricultural research institutions and extension services can help find and promote such varieties. Farmers can respond quickly by monitoring weather trends and detecting early plant infestations, enabling focused and effective weed treatment. Knowledge-sharing platforms, training programs, and Community engagement can contribute to a more resilient agriculture sector. Understanding the interplay of climate change and weed management in direct-seeded rice requires a comprehensive and adaptable approach. Farmers can limit climate change's effects while building a sustainable future for rice agriculture by adopting new techniques, harnessing technology, and staying informed about agricultural tactics.

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