Review Article

Sustainable Intensification and Climate Resilience in the Rice-Wheat Cropping System of North-Western India: Challenges and Strategies

Abstract

The rice-wheat cropping system (RWCS) is a cornerstone of agriculture in northwestern India. However, its continued use in this region has led to significant challenges and stagnation in productivity. Similar issues are also affecting the Indo-Gangetic Plains across Pakistan, Nepal, and Bangladesh. Key problems include soil nutrient depletion, declining soil health, groundwater depletion, rising production costs, labor shortages, environmental pollution from crop residue burning, increased greenhouse gas emissions, climate vulnerabilities, and herbicide resistance in weeds. To tackle these challenges, various sustainable intensification technologies have been introduced to cut down on irrigation and labor needs, reduce tillage, and manage straw more effectively. It is crucial to focus on raising awareness, building stakeholder capacity, and aligning policies to adopt effective, context-specific strategies. This paper includes a summary of the RWCS's current state and issues in India's northwest region, as well as precise management approaches for increasing production, profitability, and sustainability.

Keywords: Rice, Wheat, Cropping System, Challenges, Managment

INTRODUCTION

The rice (Oryza sativa L.)–wheat (Triticum aestivum L.) cropping system (RWCS) is crucial for global food security as it supplies essential staple foods to the world's population (Lalik et al., 2014; Banjara et al., 2021a). It is widely practiced and represents one of the most technologically advanced agricultural systems globally. In Asia, RWCS is cultivated over 13.5 million hectares (mha), with 57% of this area located in South Asia (Ahmad and Iram, 2006; Ladha et al., 2009). Within South Asia, more than 85% of RWCS is found in the Indo-Gangetic Plains (IGP; Banjara et al., 2021b). In India, the predominant rice-wheat system spans 9.2 mha, playing a critical role in the country’s food security (Jat et al., 2020).

In India, rice is cultivated over approximately 43.8 million hectares (mha), producing 177.6 million tons (mt) with a yield of 4,057 kg per hectare. Wheat is grown on 29.3 mha, yielding 103.6 mt with a productivity of 3,533 kg per hectare (FAOSTAT, 2021). Rice is a staple for more than 70% of the Indian population, while the remainder either consumes rice along with wheat or other grains (USDA, 2019).

The rice-wheat cropping system (RWCS) is predominantly found in the northwestern regions of India, including Punjab, Haryana, and Uttar Pradesh, where irrigation largely relies on groundwater (Ambast et al., 2006). The Green Revolution considerably increased food grain output because to technical breakthroughs; nevertheless, present RWCS practices are causing soil and water resource degradation, compromising the system's sustainability (Chauhan et al., 2012; Kumar et al., 2018). Although crop productivity has increased in the last decade, it has come at a cost to the environment, including detrimental effects on biodiversity, soil quality, and air quality as a result of inadequate input management (Tilman et al., 2011; Godfray and Garnett, 2014).

Agriculture accounts for about 16% of India’s greenhouse gas emissions, with 74% of these emissions coming from methane produced by livestock (38.9%) and rice cultivation (36.9%; Vetter et al., 2017). The remaining 26% is from nitrous oxide emissions related to fertilizer use. The RWCS in northwestern India is increasingly unsustainable due to rising production costs, depletion and degradation of natural resources, decreasing efficiency of inputs, and the impacts of climate change and socio-economic factors. Evidence from long-term studies indicates that productivity in the RWCS is either stagnating or declining, likely due to exhausted natural resources and adverse climatic changes (Chauhan et al., 2012; Bhatt et al., 2021).

Additionally, the high demand for labor, water, and energy further questions the sustainability of the system (Jat et al., 2009; Saharawat et al., 2010; Kumar et al., 2013b; Bhatt et al., 2021).

Traditionally, rice and wheat have had differing cultivation needs: rice seedlings required transplanting in puddled soil, while wheat thrived in well-tilled, aerobic soil. However, it is now known that rice can be successfully grown under non-puddled conditions or direct seeding without the need for continuous flooding, and wheat can also be cultivated effectively using no-till methods (Jat et al., 2019b; Panneerselvam et al., 2020).

In the rice-wheat cropping system (RWCS) in northwestern India, farmers typically grow rice as a lowland crop from June to October, followed by wheat as an upland crop from November to April. The puddling process used in rice cultivation compromises soil structure by reducing aeration and increasing soil compaction (Kumar et al., 2008; Pathak et al., 2011). As a result of the RWCS's continued use, a hardpan has formed at shallow soil depths, impeding root growth and negatively impacting the development of the succeeding wheat crop.

Rice and wheat, as nutrient-demanding cereal crops, significantly deplete soil nutrients. This issue is exacerbated when farmers burn the rice residue left in fields after mechanized harvesting. The leftover residue can obstruct tillage and sowing for the subsequent wheat crop, leading many farmers to choose burning as a solution. Each year, approximately 2 million farmers in northwestern and some eastern parts of India burn about 23 million tons of rice residue (NAAS, 2017). This practice contributes to severe air pollution, which has been linked to increased premature mortality. In 2017, particulate pollution in several northwestern Indian cities was more than five times the safe daily limits, leading to serious health issues in both rural and urban areas (Central Pollution Control Board of India, 2017). Managing rice straw from the RWCS in a timely and cost-effective manner remains a significant challenge.

Given these concerns, farmers need alternatives to traditional intense tillage and crop planting procedures to save water, preserve soil health, and protect the environment. There is also a pressing need to create innovative technologies that conserve natural resources while increasing input efficiency. Figure 1 depicts the difficulties and potential solutions for the RWCS in northwest India. This review emphasizes the critical role of the RWCS in this region and discusses the existing and emerging concerns associated with its continuous use, alongside other sustainable intensification technologies and precision management strategies aimed at improving productivity, farm income, and overall sustainability.

Fig 1 : Depicts The Difficulties And Potential Solutions

Challenges

- Exhaustive nutrient pool of soil
- Deteriorating soil health
- Ground water depletion
- Escalating production cost
- Labour scarcity
- Crop residue burning
- Greenhouse gas emissions
- Climate vulnerabilities

Solutions

- Crop diversification
- Conservation agriculture
- Direct seeded rice
- Alternate dry and wet method of irrigation in rice
- Automated irrigation system
- Early sowing of zero-till wheat
- Residue management practices

1.Traditional production practices and challenges

Traditional rice cultivation in the rice-wheat cropping system (RWCS) involves several intensive practices. It starts with thorough puddling of the fields, followed by transplanting seedlings that are 25 to 30 days old. The fields are kept flooded for about two weeks, and irrigation is then reapplied two days after the standing water has been absorbed into the soil (Anonymous, 2020; Dhillon et al., 2021). This method provides certain advantages, including effective weed control due to poor oxygen levels that inhibit weed germination, consistent anaerobic conditions with a neutral soil pH, and enhanced availability of nutrients such as iron (Bhatt and Kukal, 2015). This delay causes yield losses of 32 kg per hectare per day in northwestern India after November 15 (Tripathi et al., 2005), which might reach 35 kg per hectare per day in other areas. Furthermore, using medium-duration (140 days) basmati rice or long-duration coarse rice types can help to postpone wheat sowing. Fields are often left fallow for two to three months between wheat harvest and rice installation. Effect of various traditional practices are:

1.1Soil Health

The traditional rice cultivation method involves puddling, which is tillage performed under wet conditions. This practice is intended to reduce water percolation losses, facilitate seedling transplantation, and control weeds. However, prolonged use of this method has negatively impacted soil health (Nandan et al., 2021). Repeated puddling, especially in coarse and medium-textured soils, has led to subsurface compaction, which impedes root growth and causes aeration issues for subsequent upland crops like wheat (Hossain et al., 2021; Saurabh et al., 2021).

Intensive tillage further contributes to soil degradation by breaking down large soil aggregates, resulting in reduced crop yields. The continuous rice-wheat cropping system (RWCS) also disrupts the nutrient balance in the upper vadose zone (Gill, 1992). Burning rice residues causes a significant loss of nutrients (Kumar et al., 2019), leading to increased fertilizer use and higher cultivation costs while degrading oil quality over time. Consequently, the RWCS has a severe impact on soil health, with a reported decrease in soil organic carbon of 0.9 tons per hectare over seven years in the Indo-Gangetic Plains of India (Sapkota et al., 2017).

Yadav et al. (2000) analyzed data from long-term RWCS experiments conducted over 12 to 15 years at seven locations, showing that soil organic carbon decreased at sites with high initial organic carbon (over 0.65%) but increased at sites with lower initial levels (below 0.50%). Lal (2004) identified lowland rice-based systems as the most stable and effective at conserving soil organic carbon. Despite this, the RWCS is exhibiting signs of strain due to the ongoing use of traditional practices, leading to yield stagnation and declining productivity (Bhatt et al., 2016, 2021).

1.2Residue Burning

In Haryana and Punjab, approximately 28.1 million tons (mt) of paddy straw were produced in 2018. Out of this, 40% (11.3 mt) was burned in the fields, while the remaining 60% was managed through soil incorporation and other methods (DACFW, 2019). Punjab and Haryana were responsible for 88% and 12% of the straw burning, respectively (DACFW, 2019). Managing residue is a significant issue in the rice-wheat cropping system (RWCS). While wheat residue is mainly used in animal husbandry, rice residue, which amounts to 6–8 tons per hectare, is less suitable for dairy due to its low digestibility, poor palatability, low protein content, and high silica (Arora and Sehgal, 1999). Additionally, incorporating undecomposed rice straw into the soil can lead to nitrogen immobilization due to its wide carbon-to-nitrogen ratio (Singh and Sidhu, 2014). Consequently, many farmers resort to burning rice residue, which leads to several problems.

Residue burning imposes severe public health and economic costs due to air pollution (Balwinder-Singh et al., 2019). In northwest India, particularly during the fall season following rice harvest, catastrophic spikes in air pollution are increasingly common. This burning releases trace gases like carbon dioxide, carbon monoxide, methane, nitrous oxide, and aerosols, which disrupt regional atmospheric chemistry (Gupta et al., 2004). Fine particulate matter (PM2.5) becomes a significant concern, with levels exceeding 700 µg/m³ in some cities, where concentrated burning is a major contributor to poor air quality (Balwinder-Singh et al., 2019). Moreover, burning rice straw results in the loss of essential nutrients, especially potassium, of which

80–85% is absorbed by rice and wheat residues (Singh et al., 2008). The persistent use of a single herbicide for controlling Echinochloa species in rice cultivation has resulted in the emergence of more resistant weed species such as Leptochloa chinensis, Cynodon dactylon, Ischaemum rugosum, Paspalum distichum, Ludwigia hyssopifolia, Eclipta prostrata, Cyperus rotundus, Cyperus iria, Cyperus difformis, and Fimbristylis miliacea (Mahajan et al., 2012; Shekhawat et al. Monocropping under the rice-wheat cropping system (RWCS) has also resulted in increasing infestations of Phalaris minor in wheat, as paddy cultivation creates favorable conditions for its germination (Franke et al., 2003). The repeated use of herbicides with comparable modes of action has generated significant selective pressure, resulting in widespread resistance in P. minor, particularly in Haryana and Punjab.

1.3Groundwater Depletion

The persistent use of the rice-wheat cropping system (RWCS) has led to a significant drop in groundwater levels, impacting crop yields, land productivity, and water availability. In the states of Haryana and Punjab in northwest India, rice cultivation has been depleting natural resources at an alarming rate (Dhillon et al., 2010). The traditional method of rice farming is highly water-intensive (Bhatt and Kukal, 2018; Bhatt et al., 2020), and considerable amounts of irrigation water are lost, especially in coarse-textured soils of the northwest Indo-Gangetic Plains (Hira, 2009). Since the 1970s, groundwater levels have been steadily falling due to continuous pumping, a trend that began with the Green Revolution (Hira et al., 2004). In Punjab, the average groundwater depletion was about 8.91 meters from 2000 to 2019 (Sidhu et al., 2021).

This decline has led to substantial investments in tube wells, which has increased operational costs and power consumption, while also degrading groundwater quality (GoI, 2017; Farmaha et al., 2021). Managing groundwater is crucial to addressing water scarcity issues in India. The over-reliance on groundwater and inadequate alternative infrastructure in the northwest Indo-Gangetic Plains has resulted in annual declines of 0.1 to 1.0 meters in groundwater levels (Hira et al., 2004; Bhatt et al., 2020). According to the Central Ground Water Board, 80% of the 138 blocks monitored in Punjab were classified as overexploited, with only 16% deemed safe (CGWB, 2019). In Haryana, 61% of blocks were overexploited, while 20% were considered safe. This situation has worsened due to the expansion of rice cultivation and the high levels of groundwater withdrawal required for irrigation.

In Punjab and Haryana, about 92–96% of groundwater is used for irrigation. As the water table continues to fall, farmers are forced to deepen their tube wells and switch from centrifugal to submersible pumps, further increasing production costs and challenging the sustainability of the cropping system. It is projected that annual per capita water availability in northwest India will decrease from 1,600 m^3 to 1,000 m^3 by 2025 (Mahajan et al., 2011). To halt this decline, it is estimated that a reduction of about 150 mm in evapotranspiration from the RWCS annually would be necessary (Humphreys et al., 2010).

1.4Economics

Rice cultivation is extremely labor-intensive, with Punjab and Haryana relying heavily on migrant labor for output. Between 2005-06 and 2018-19, labor prices in these states skyrocketed, growing from USD 1.27 to USD 3.78 per day in Haryana and USD 1.35 to USD 3.22 per day in Punjab (1 USD = 74.32 Indian rupees; Sudhir-Yadav et al., 2017). As a result, the cost of transplanting rice jumped from around USD 47 per hectare in 2010 to USD 74 per hectare by 2015, with costs continuing to rise annually. To address this issue, adopting crop rotation rather than relying solely on the RWCS is essential. Crop rotation can help preserve resources such as water and offer better economic returns. Research conducted in Ludhiana, India, demonstrated that rotating crops like maize–potato–onion; summer peanut–potato–pearl millet (fodder); and maize–potato–summer mung bean produced rice equivalent yields of 32, 25, and 23 tons per hectare per year, respectively, compared to just 12.9 tons per hectare per year with the RWCS (Walia et al., 2011). Furthermore, replacing rice with crops such as maize or sugarcane has been found to be more profitable than continuing with the RWCS (Kang et al., 2009; Choudhary et al., 2018a).

Furthermore, the gap between total cultivation costs and minimum support prices (which serve as proxies for market prices) for rice and wheat has grown over time, even after accounting for inflation. This expanding difference has had a severe impact on farm profitability and income. Despite these economic issues, the rice-wheat cropping system is still the preferred choice in northwest India due to its benefits, which include assured prices and marketing, as well as consistent yield levels (Bhatt et al., 2021). Although the rice-wheat cropping system (RWCS) has been a staple for many years, productivity has remained stagnant since the 1990s (Bhatt et al., 2021), indicating a slowing of productivity gains made during the Green Revolution.

2. Alternative Production Technologies and Associated Benefits

Over the past thirty years, research has increasingly focused on finding viable, sustainable, and environmentally friendly alternatives to the rice-wheat cropping system (RWCS) (Singh et al., 2020; Banjara et al., 2021b). To address issues such as deteriorating soil health, groundwater depletion, residue burning, and environmental pollution, and to improve farm incomes sustainably, it's crucial to adopt sustainable agricultural technologies. Key strategies include incorporating legume crops into the system, diversifying crops, managing crop residues, practicing conservation agriculture, and implementing water-saving technologies.

2.1.Crop Diversification

Crop rotation offers several advantages over the RWCS. For example, replacing rice with pulses or oilseeds can improve soil health, reduce water requirements, and increase water productivity (Arora et al., 2020). Research in Punjab, India, showed that using a soybean–wheat system with raised beds improved soil fertility and water conservation compared to the RWCS (Ram et al., 2013). Adding legumes to the cropping system boosts nitrogen levels and supports overall system sustainability (Arora et al., 2020). Conservation agriculture-based diversification, such as rice–wheat–mung bean or maize–wheat–mung bean, significantly increased soil organic carbon by 83% and 72%, respectively, compared to the traditional rice–wheat system (Choudhary et al., 2018b). These diversified systems also resulted in lower soil bulk density and better soil quality.

Switching from rice to less water-intensive crops like cotton, maize, pearl millet, or legumes during the summer can help replenish water levels during the monsoon and improve water productivity. For instance, transitioning from the RWCS to a cotton–wheat or maize–wheat system substantially reduces irrigation water requirements (Arora et al., 2008). Maize, which requires 80–85% less water than rice, offers a significant advantage, with water productivity rates 8–22 times higher than rice (Gathala et al., 2013). The maize–wheat system also enhances soil health and microbial activity compared to the puddled rice system (Jat et al., 2012; Wei et al., 2015).

Studies have shown that replacing rice with zero-till maize can yield multiple benefits, including 82–89% water savings, 49–66% reductions in total energy input, 13–40% decreases in global warming potential, and 27–73% higher profitability, all while maintaining or improving rice equivalent yields (Kumar et al., 2018; Jat et al., 2020).

Strategies for managing water demand and reducing residue burning include changing cropping dates, selecting appropriate crops and types, and tweaking cultivation procedures. However, existing government policies in Punjab and Haryana, which encourage rice and wheat production through subsidized electricity, assured markets, and minimum support prices (MSP), have made it difficult to diversify away from these commodities. Recently, the government has focused on promoting pulse crops and increasing MSPs for them. Policy changes and more advocacy could encourage farmers to shift away from rice-wheat farming and into higher-value crops such as vegetables, fruits, and flowers that are more suited to their settings.

2.2Crop Residue Management

Managing crop residues in the rice-wheat cropping system (RWCS) presents a significant challenge. Loose and scattered residues interfere with tillage operations and make sowing wheat through conventional tillage more difficult and energy-intensive. Consequently, farmers in northwest India often resort to burning residues, which causes numerous problems. Over the years, several innovative strategies for managing rice residues have been developed, including in situ incorporation and zero-till sowing of wheat with surface-retained rice residue. These methods offer several advantages over burning, such as enhancing soil health, improving nutrient balance, reducing environmental pollution, and lowering cultivation costs.

Singh et al. (2019) reviewed the importance of crop residue management in the RWCS for conserving resources, protecting the environment, and promoting sustainability in northwest India. Satellite data with thermal sensors were used to monitor rice residue burning during the rice harvest and wheat sowing period from September 30 to November 30 in Punjab, Haryana, and Uttar Pradesh. The study found that Punjab saw a 11% reduction in burning events in 2018 compared to 2017, and a 42% reduction compared to 2016. Haryana experienced a 29% and 41% reduction in burning events in the same years, while Uttar Pradesh saw a 24% and 32% reduction.

In situ agricultural residue management strategies have been shown to be the most effective alternative to burning. The use of zero-tillage drills enables direct wheat sowing without prior tillage and prevents the clearance of rice residue from the fields. The Turbo Happy Seeder, an upgraded version of the zero-tillage drill, allows for direct seeding of wheat onto standing rice stubble soon after rice harvest (Sidhu et al., 2015). These solutions are economically viable and improve water efficiency.

Farmers have access to various types of machinery for managing rice straw, including seeders designed for sowing under straw conditions (such as rotary disc drills, Turbo Happy Seeders, zero-seed drills, spatial no-till drills, and super seeders), straw cutters for in situ incorporation or retention (such as rice straw choppers, straw shredders, super straw management systems, and mulchers), machinery for straw incorporation (such as reversible moldboard plows and rotary-till drills), and equipment for straw collection and disposal (such as rakers and balers).

2.3.Sustainable Intensification Technologies

Conservation agriculture has emerged as an effective approach for maximizing input efficiency and sustaining productivity in the rice-wheat cropping system (RWCS). This method is based on three key principles: crop diversification, zero or reduced tillage, and residue retention (Farooq and Siddique, 2014). These practices contribute to carbon sequestration and enhance the physicochemical properties of the soil (Jat et al., 2019a,b). Research indicates that implementing sustainable intensification technologies within conservation agriculture can significantly improve soil health after 3–5 years in the RWCS of northwest India (Bhatt and Kukal, 2015). Additionally, residue retention helps conserve soil moisture, regulate temperature, and boost water use efficiency (Kukal et al., 2014; Bhatt and Kukal, 2018).

Dry direct-seeded rice (DDSR) has become a viable alternative to the traditional puddled transplanted rice. In the DDSR system, rice seeds are sown either with or without prior tillage and irrigation, with irrigation applied intermittently to maintain soil moisture. This method can save between 11 and 18% of water compared to puddled transplanted rice and reduce labor requirements by 11–66%, depending on the season and location (Kumar et al., 2009; Rashid et al., 2009). DDSR also offers benefits such as easier planting, improved soil health, and reduced methane emissions (Pathak et al., 2009; Kumar and Ladha, 2011). Furthermore, rice grown using DDSR matures 7–10 days earlier than puddled transplanted rice, allowing for timely planting of the subsequent wheat crop (Singh et al., 2006). However, DDSR faces challenges, including higher weed infestation and greater diversity of weed species compared to puddled transplanted rice, which can lead to significant yield losses of 50–90% (Chauhan and Johnson, 2011; Chauhan and Opena, 2012).

Initially, from 2010 to 2015, DDSR saw strong adoption rates in northwest India, with Punjab's area under DDSR reaching up to 160,000 ha in 2016. However, this number dropped to 5,000 ha by 2018 due to issues like the lack of suitable rice varieties for late planting, overly wet soil for dry seeding, and high weed infestations, which led some farmers to revert to plowing. Nevertheless, during the COVID-19 lockdown, labor shortages prompted a resurgence in DDSR adoption, with estimates of the area under DDSR in Punjab rising to 200,000–250,000 ha in 2020 (Humphreys and Christen, 2020). Reports indicate that the area under DDSR in Punjab reached 500,000 ha in 2020. Encouraged by this response, the Punjab state government set a target of 800,000 ha for 2021. The latest figures suggest that the area under DDSR in Punjab and Haryana in 2021 was approximately 600,000 ha and 20,000 ha, respectively (Kaushal, 2021).

Zero-till sowing has significantly enhanced soil quality by preventing erosion, boosting soil microbial activity, reducing weed and termite infestations, and improving resource-use efficiency (Hobbs et al., 2008). A major challenge with direct wheat sowing in fields harvested for rice is that loose rice straw can interfere with the sowing process, leading to uneven seed placement and germination. This issue has largely been addressed through innovations such as the Turbo Happy Seeder and rotary disc drill (Sidhu et al., 2007). These tools effectively mulch the rice straw while sowing wheat directly under zero-till conditions. Introduced between 2002 and 2005 in northwest India, zero-till wheat sowing is now supported by over 2,500 seed-cum-fertilizer drills in Haryana and 3,400 in Punjab. These drills have enabled wheat seeding with minimal or reduced tillage, cutting down from the traditional 4-6 plowings to just 1-2. The Happy Seeder, which was commercially launched in northwest India nearly 15 years ago, has undergone multiple improvements and gained widespread adoption. As of the 2018-19 report, approximately 2,400 units were operational in Haryana, and 9,800 units were used in Punjab, covering 0.053 and 0.45 million hectares of wheat, respectively (Singh, 2018). The total area covered by DDSR and zero-till wheat/Happy Seeder in India is about 7.2 million hectares (Pradhan et al., 2018) and 0.8 million hectares (Singh, 2018), respectively. Super seeders, which combine the Happy Seeder with a rotavator, are also used to sow wheat in fields with full rice residues in one pass. However, they require high energy (50-60 HP tractors) and fuel (~20 liters per hectare). Issues such as uneven germination, poor tillering, and lower yields have led to decreasing interest in super seeders among farmers. To address these challenges, the governments of Punjab and Haryana have mandated that all self-propelled combine harvesters be equipped with a "Super Straw Management System," which helps chop and distribute straw evenly. Uniform straw distribution is crucial for effective use of the Happy Seeder. Using the Turbo Happy Seeder under rice residue conditions has been reported to increase wheat yields by 3.2% compared to conventional tillage methods (Sidhu et al., 2015; Bhatt et al., 2021). Zero-till sowing with rice residue retention improves RWCS productivity, nutrient balance, and soil health (Sah et al., 2014). The state governments of Haryana, Punjab, Uttar Pradesh, and Delhi are providing subsidies (50% for individual farmers and 80% for cooperatives) for machinery to manage rice straw and control pollution from residue burning. They are also running awareness campaigns through demonstrations, educational programs, and various communication technologies to promote effective crop residue management. The availability of service providers and custom hiring centers, supported by government subsidies, has improved farmers' access to these machines.

The Punjab Remote Sensing Centre (2019) reported that 0.55 million hectares of Punjab have been seeded with Happy Seeders. However, evaluating residue incorporation using remote sensing was not practicable. During 2018-19, about 0.8 million hectares (19%) of land in Punjab and Haryana were planted with zero-till wheat (using a Happy Seeder and a zero-till drill). For the best results, both rice and wheat should be cultivated utilizing zero-till methods. DDSR in moist soil has proven beneficial in a variety of settings and is becoming increasingly significant in Punjab and Haryana, owing to labour constraints during the COVID-19 epidemic (Workie et al., 2020; Kaur and Kaur, 2021).

In various districts of Punjab, methane emissions from puddled transplanted rice ranged between 0.8 to 1.9 tons CO2 equivalent per hectare, while dry direct-seeded rice (DDSR) emitted only 0.1 to 0.3 tons CO2 equivalent per hectare (Gartaula et al., 2020). The overall global warming potential, considering carbon dioxide, methane, and nitrous oxide, was 2.91 tons per hectare for transplanted rice, compared to 1.94 tons per hectare for DDSR (Gartaula et al., 2020). Gupta et al. (2016) noted that methane emissions in DDSR were significantly lower, by 82–87.2%, compared to puddled transplanted rice. DDSR, especially when using short or medium-duration rice varieties or hybrids with early maturity, helps conserve residual soil moisture, which benefits rotational crops. It also extends the time available for effective residue management and facilitates timely sowing of long-duration wheat varieties, ultimately improving system productivity, profitability, and sustainability. However, to achieve widespread adoption of DDSR, it is essential to raise awareness, enhance farmer skills, and establish robust policy support.

2.4.Water Saving Technologies

True water savings involve minimizing water losses and applying only the amount necessary for plant growth. The extent of water saved can vary depending on the spatial and temporal context. In the rice-wheat cropping system (RWCS), water savings mean increasing productivity while using less water than is currently employed. Reducing water usage also has additional benefits, such as lowering cultivation costs (including pumping and water charges) and improving water productivity. Puddled transplanted rice is particularly water-intensive, leading to low water productivity. To address this, various water-saving technologies can improve water use efficiency. These technologies include growing short-duration crop varieties and transplanting them at the optimal time (Sharma et al., 2020; Singh et al., 2020).

Key technologies for efficient water use in the rice-wheat cropping system (RWCS) include tensiometer-based irrigation scheduling, laser land leveling, direct seeding of rice, bed planting, subsurface drip irrigation, furrow irrigation, and alternate wetting and drying or irrigation at hairline cracking. Micro-irrigation systems, such as drip and sprinkler irrigation, significantly reduce water usage by minimizing surface runoff, thus improving irrigation efficiency by up to 50% compared to flood irrigation (Sidhu et al., 2019). These systems also enable fertigation, which provides nutrients directly to the crop, and reduce labor requirements through automation, ultimately lowering production costs.

Switching from puddled transplanting to direct-seeded rice (DDSR) saves 20–30% more water and eliminates the need for irrigation during puddling and transplanting. Similarly, the alternate wetting and drying (AWD) method reduces irrigation needs by 30–40% after crop establishment, whether in puddled transplanting or direct seeding. Using short-duration rice cultivars instead of longer ones further enhances water use efficiency by reducing evapotranspiration losses (Singh et al., 2020). Drip and sprinkler irrigation in DDSR also offer promising opportunities for water savings (Chauhan and Abugho, 2013; Sharda et al., 2017). Drip irrigation systems, both surface and subsurface, deliver water and nutrients directly to the root zone, maximizing their effectiveness. Automation in irrigation, particularly with drip systems that use sensor networks and communication technologies, addresses water-use inefficiencies (Sidhu et al., 2021). Switching to a multi-cropping system, such as summer mung bean-maize-wheat, using subsurface drip irrigation and fertigation, could save 30% on irrigation water (Brar et al., 2021). Optimizing irrigation practices can also help to lower methane emissions and the rice-wheat system's net global warming potential (Sapkota et al., 2020).

Furrow irrigation in raised bed systems offers an alternative to flood irrigation, potentially increasing water productivity, especially in upland crops. Kumar et al. (2010) found that furrow-irrigated bed planting in wheat saved about 40% more water compared to flat planting and significantly boosted water productivity. Kumar et al. (2013a) observed that while wheat yields improved with furrow-irrigated raised beds, rice yields and attributes remained similar to those in conventional methods. Although there is potential for raising rice on raised beds, evidence of water savings in rice is limited. Furrow-irrigated raised beds do not always outperform conventional flat fields in water savings or productivity, particularly in Punjab, India (Singh et al., 2009). Ongoing research is needed to refine these methods for better results across different landscapes.

2.5.Soil health improvement

To improve soil health in fields that have lost organic matter due to puddling, incorporating farmyard manure can be beneficial, as it uses readily available raw materials. Managing rice stubble through in situ crop residue techniques, along with microbial decomposers, can enhance soil organic matter. Additionally, using bio-fertilizers offers a way to decrease reliance on chemical fertilizers in the rice-wheat cropping system (RWCS) (Khan, 2018).

Site-specific nutrient management (SSNM), particularly with tools like Nutrient Expert® (NE), can enhance productivity and nutrient use efficiency in the RWCS. Combining SSNM with no-tillage practices boosts yields, improves nutrient efficiency, and increases profitability, while also reducing greenhouse gas emissions from wheat production in northwest India (Sapkota et al., 2014). Implementing SSNM has been shown to increase net returns by 34 to 43 USD per hectare compared to traditional fertilizer application methods, by cutting fertilizer costs (Parihar et al., 2020). Optical sensor-based SSNM techniques can reduce nitrogen use by 20–30 kg per hectare while maintaining similar yields in conservation agriculture systems. Efficient nitrogen management also minimizes nitrous oxide emissions by preventing losses through volatilization, leaching, and denitrification. SSNM offers significant potential for improving crop productivity, profitability, and nutrient efficiency across various environments. Subsurface drip irrigation further enhances nitrogen use efficiency by 20% compared to flood irrigation in rice/maize systems (Jat et al., 2019c).

Integrated nutrient management (INM) promotes soil health and nutrient balance in the RWCS. Long-term experiments on the rice-wheat sequence have indicated that the maximum grain yields were obtained when 50% of the nitrogen was provided through green manure and farmyard manure, with no loss of potassium or nitrogen when organics replaced half of the nitrogen (Saha et al., 2018).

2.6.Suggested Policy Changes

To enhance the adoption of machinery for in situ residue management, it is crucial to improve the availability of data on crop succession. Additionally, promoting crop diversification by increasing Minimum Support Prices (MSPs) for various crops can incentivize farmers to diversify their production. Expanding subsidies and demonstrations for micro-irrigation systems can also boost their adoption. The government should invest in infrastructure for the ex situ utilization of farm residues, such as establishing bio-ethanol and biogas plants.

Conclusion

Northwest India plays a crucial role in rice and wheat production, essential for feeding the growing population. However, the traditional Rice-Wheat Cropping System (RWCS) faces significant sustainability challenges, including soil fertility depletion, declining groundwater levels, and environmental degradation. To address these issues, it is necessary to transition from conventional practices to conservation agriculture, adopting practices that promote sustainable crop production. Emphasizing the development of high-yielding, short-duration rice varieties can reduce evapotranspiration losses and decrease residue loads. Incorporating short-duration legumes, such as mung beans, can enhance the overall productivity of the cropping system. Exploring less water-intensive crops, like maize, as alternatives to rice is also essential for sustainable agriculture. Automation in irrigation can address inefficiencies in water use. To improve farm income and sustainability, it is important to scale up sustainable technologies like Direct Dry Seeding of Rice (DDSR) and zero-till wheat, support these with suitable crop varieties, increase awareness through effective extension services, and strengthen policy support.

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