Review Article

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

Abstract

In northwestern India, the rice-wheat cropping system (RWCS) is a key component of agriculture. However, the region's ongoing usage of it has resulted in serious problems and a halt in productivity. Similar problems are also present in Bangladesh, Nepal, and Pakistan's Indo-Gangetic Plains. Key issues include the loss of soil nutrients, deteriorating soil health, groundwater depletion, increased production costs, a lack of workers, pollution from burning crop residue, increased greenhouse gas emissions, climate vulnerabilities, and plants that are resistant to herbicides. To address these issues, a number of sustainable intensification methods have been proposed, such as crop diversification, zero tillage, or residue retention, which reduce tillage, handle straw more efficiently, and use less labour and irrigation. In order to adopt successful, context-specific tactics, it is necessary to concentrate on increasing awareness, developing stakeholder capacity, and coordinating policies. The current status of the RWCS and its problems in northwest India are summarised in this report, along with specific management strategies for boosting output, profitability, and sustainability.

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

INTRODUCTION

A large portion of the world's population depends on the rice-wheat cropping system (RWCS) for their staple foods, making it a major contributor to global food security (Lalik et al., 2014; Banjara et al., 2021a). It is one of the most technologically sophisticated agricultural systems in the world and is widely used. Over 13.5 million hectares (mha) of RWCS are grown in Asia, with South Asia accounting for 57% of this total (Ahmad and Iram, 2006; Ladha et al., 2009). The Indo-Gangetic Plains (IGP) contain almost 85% of South Asia's RWCS (Banjara et al., 2021b). The 9.2 mha predominant rice-wheat system in India is essential to the nation's food security (Jat et al., 2020). About 43.8 million hectares (mha) of rice are grown in India, yielding 177.6 million tonnes (mt) at a yield of 4,057 kg per hectare. With a productivity of 3,533 kg per hectare, wheat is produced on 29.3 mha, yielding 103.6 mt (FAOSTAT, 2021). Over 70% of Indians use rice as a staple, with the remaining people either eating rice alone or in combination with other cereals like wheat (USDA, 2019).

The northwest Indian states of Punjab, Haryana, and Uttar Pradesh are home to the majority of the rice-wheat cropping system (RWCS), where groundwater is a major source of irrigation (Ambast et al., 2006). Due to technological advancements, the Green Revolution significantly increased the production of food grains; nevertheless, current RWCS practices are degrading soil and water resources, endangering the sustainability of the system (Chauhan et al., 2012; Kumar et al., 2018). Crop productivity has grown during the past ten years, but at a considerable environmental cost. These include negative effects of inadequate input management on biodiversity, soil quality, and air quality (Tilman et al., 2011; Godfray and Garnett, 2014).

About 16% of India's greenhouse gas emissions are attributable to agriculture, with methane from rice farming (36.9%) and livestock (38.9%) accounting for 74% of these emissions (Vetter et al., 2017). Nitrous oxide emissions from fertiliser use account for the remaining 26%. Rising production costs, the loss and deterioration of natural resources, declining input efficiency, the effects of climate change, and socioeconomic variables have made the RWCS in northwest India less and less sustainable. Long-term research shows that production in the RWCS is either decreasing or staying the same, most likely as a result of depleting natural resources and unfavourable climate change (Chauhan et al., 2012; Bhatt et al., 2021). Further raising issues about the system's sustainability is the high demand for energy, labour, and water (Jat et al., 2009; Saharawat et al., 2010; Kumar et al., 2013; Bhatt et al., 2021). Rice seedlings needed to be transplanted in puddled soil, whereas wheat flourished in well-tilled, aerobic soil. Historically, rice and wheat have had different cultivation requirements. Nonetheless, it is now recognised that wheat may be successfully grown using no-till techniques, and rice can be produced in non-puddled circumstances or direct seeding without the requirement for constant flooding (Jat et al., 2019; Panneerselvam et al., 2020).

In northwest India, farmers usually cultivate rice as a lowland crop from June to October and wheat as an upland crop from November to April under the rice-wheat cropping system (RWCS). By decreasing aeration and increasing soil compaction, the puddling technique utilised in rice farming compromises soil structure (Kumar et al., 2008; Pathak et al., 2011). The ongoing usage of the RWCS has resulted in the formation of a hardpan at shallow soil levels, which hinders root growth and adversely affects the growth of the next wheat crop.

As nutrient-demanding cereal crops, rice and wheat drastically reduce the amount of nutrients in the soil. When farmers burn the rice residue that remains in fields following mechanised harvesting, this problem is made worse. Many farmers turn to burning as a solution because the residue left over can make it difficult to plough and sow the next wheat crop. About 23 million tonnes of rice residue are burned annually by about 2 million farmers in northwest and some eastern India (NAAS, 2017). This technique increases premature death by contributing to severe air pollution. Serious health problems were caused in both rural and urban areas in 2017 when particulate pollution in a number of northwest Indian cities exceeded five times the permissible daily limits (Central Pollution Control Board of India, 2017).

In light of these issues, farmers require alternatives to conventional methods of crop planting and intensive tillage in order to conserve water, maintain soil health, and safeguard the environment. The development of novel technologies that improve input efficiency and preserve natural resources is also urgently needed. The challenges and possible solutions for the RWCS in northwest India are shown in Figure 1. The importance of the RWCS in this area is emphasised in this review. Along with other sustainable intensification technologies and precision management techniques meant to increase productivity, farm income, and sustainability overall, it addresses the current and new issues surrounding its ongoing usage.

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

This review highlights critical issues such as soil degradation, water depletion, and environmental pollution, while proposing sustainable intensification strategies like crop diversification and zero tillage. The review underscores the importance of context-specific solutions, policy alignment, and stakeholder engagement to enhance productivity, profitability, and sustainability. This work is a valuable resource for researchers, policymakers, and practitioners seeking to address the complexities of modern agriculture in South Asia.

1. Traditional production practices and challenges

In the rice-wheat cropping system (RWCS), traditional rice cultivation entails a number of demanding techniques. The fields are thoroughly puddled first, and then seedlings that are 25 to 30 days old are transplanted. Two weeks or more are spent flooding the fields, and two days after the standing water has been absorbed by the soil, irrigation is resumed (Anonymous, 2020; Dhillon et al., 2021). This technique has several benefits, such as stable anaerobic conditions with a neutral pH of the soil, improved availability of minerals like iron, and efficient weed management because low oxygen levels prevent weed germination (Bhatt and Kukal, 2015). In northwest India, this delay results in yield losses of 32 kg per hectare per day after November 15 (Tripathi et al., 2005). In some regions, these losses could exceed 35 kg per hectare per day. Additionally, wheat sowing can be delayed by utilising long-duration coarse rice varieties or medium-duration (140-day) basmati rice. Between the harvest of wheat and the installation of rice, fields are frequently kept fallow for two to three months. Various traditional practices have the following effects:

1.1 Health of the Soil

Puddling, or tillage done in a wet environment, is a part of traditional rice farming. Reduced water percolation losses, easier seedling transfer, and weed control are the goals of this technique. However, soil health has suffered as a result of this method's extended use (Nandan et al., 2021). Frequent puddling, particularly in soils with coarse and medium textures, has resulted in 20–30 cm of subsurface compaction, which hinders root development and creates problems with aeration for later highland crops like wheat (Hossain et al., 2021; Saurabh et al., 2021).

By dissolving big soil aggregates and lowering crop yields, intensive tillage further deteriorates the soil. Additionally, the upper vadose zone's nutritional balance is upset by the continuous rice-wheat cropping system (RWCS) (Gill, 1992). According to Kumar et al. (2019), burning rice leftovers results in a considerable loss of nutrients, which raises the cost of cultivation and fertiliser use while gradually lowering the quality of the oil. Accordingly, the RWCS has a negative effect on soil health; in the Indo-Gangetic Plains of India, it has been observed that over a seven-year period, soil organic carbon decreased by 0.9 tonnes per hectare (Sapkota et al., 2017).

According to Yadav et al. (2000), who examined data from long-term RWCS studies that were carried out at seven different locations over a period of 12 to 15 years, soil organic carbon rose in sites with lower initial levels (below 0.50%) but decreased at sites with higher initial levels (above 0.65%). Lowland rice-based systems were shown to be the most stable and efficient at preserving soil organic carbon by Lal (2004). However, because of the continued use of traditional methods, the RWCS shows signs of strain, resulting in decreased productivity and stagnant yields (Bhatt et al., 2016, 2021). There are numerous techniques, including as mulching, residue retention, zero-tillage, etc., that can be used to increase organic carbon at locations. The more organic carbon there is in the soil, the less the soil aggregates degrade.

1.2 Burning of Residue

In 2018, about 28.1 million tonnes (mt) of paddy straw were produced in Punjab and Haryana. 60% of this was managed via soil integration and other techniques, with the remaining 40% (11.3 mt) being burned in the fields (DACFW, 2019). 88% and 12% of the straw burning occurred in Punjab and Haryana, respectively (DACFW, 2019). One major problem with the rice-wheat cropping system (RWCS) is managing residue. Rice residue, which amounts to 6–8 tonnes per hectare, is less appropriate for dairy because of its high silica concentration, low protein content, poor palatability, and poor digestibility, whereas wheat residue is mostly employed in animal husbandry (Arora and Sehgal, 1999). Additionally, because of its high carbon-to-nitrogen ratio, adding undecomposed rice straw to the soil can immobilise nitrogen (Singh and Sidhu, 2014). As a result, burning rice residue is a common practice among farmers, which causes a number of issues.

Burning residues causes air pollution, which has serious negative effects on public health and the economy (Balwinder-Singh et al., 2019). In northwest India, catastrophic air pollution spikes are becoming more frequent, especially in the autumn after the rice harvest. According to Gupta et al. (2004), this burning emits aerosols, carbon dioxide, carbon monoxide, methane, and nitrous oxide, among other trace gases that alter the chemistry of the local atmosphere. With concentrations of over 700 µg/m³ in certain places, where concentrated burning is a major cause of poor air quality, fine particulate matter (PM2.5) becomes a serious concern (Balwinder-Singh et al., 2019).

Additionally, burning rice straw depletes vital minerals, particularly potassium, of which 80–85% is absorbed by leftover rice and wheat (Singh et al., 2008). More resistant weed species, including ***Leptochloa chinensis, Cynodon dactylon, Ischaemum rugosum, Paspalum distichum, Ludwigia hyssopifolia, Eclipta prostrata, Cyperus rotundus, Cyperus iria, Cyperus difformis, and Fimbristylis miliacea***, have emerged as a result of the continuous use of a single herbicide to control Echinochloa species in rice cultivation

(Mahajan et al., 2012; Shekhawat et al., 2020). Because paddy agriculture provides ideal circumstances for Phalaris minor germination, monocropping under the rice-wheat cropping system (RWCS) has also led to an increase in Phalaris minor infestations in wheat (Franke et al., 2003). Due to strong selection pressure brought about by the frequent application of herbicides with similar mechanisms of action, P. minor has become widely resistant, especially in Punjab and Haryana.

1.3 Loss of Groundwater

Groundwater levels have significantly decreased as a result of the rice-wheat cropping system's (RWCS) continued use, which has an effect on crop yields, land productivity, and water availability. Rice farming in the northwest Indian states of Haryana and Punjab has been alarmingly consuming natural resources (Dhillon et al., 2010). Rice cultivation using the old approach uses a lot of water (Bhatt and Kukal, 2018; Bhatt et al., 2020), and significant irrigation water loss occurs, particularly in the northwest Indo-Gangetic Plains' coarse-textured soils (Hira, 2009). Due to ongoing pumping, which started with the Green Revolution, groundwater levels have been gradually declining since the 1970s (Hira et al., 2004). Between 2000 and 2019, Punjab's average groundwater depletion was 8.91 meters.

Due to the significant expenditures made in tube wells as a result of this drop, groundwater quality has declined and operating expenses and electricity consumption have gone up (GoI, 2017; Farmaha et al., 2021). In order to solve India's water shortage problems, groundwater management is essential. In the northwest Indo-Gangetic Plains, an over dependence on groundwater and a lack of alternative infrastructure have caused groundwater levels to drop by 0.1 to 1.0 meters annually (Hira et al., 2004; Bhatt et al., 2020). Only 16% of the 138 blocks in Punjab that were monitored were considered safe, with 80% of them being classed as overexploited, according to the Central Ground Water Board (CGWB, 2019). Of the blocks in Haryana, 20% were deemed safe, and 61% were overexploited. This situation has worsened due to the expansion of rice cultivation and the high levels of groundwater withdrawal required for irrigation.

Approximately 92–96% of groundwater in Punjab and Haryana is utilised for irrigation. Farmers are compelled to deepen their tube wells and convert from centrifugal to submersible pumps as a result of the water table's continued decline, which raises production costs and calls into question the cropping system's sustainability. According to Mahajan et al. (2011), the annual per capita water availability in northwest India is expected to drop from 1,600 m^3 to 1,000 m^3 by 2025. An annual decrease of roughly 150 mm in evapotranspiration from the RWCS is thought to be required to stop this decline (Humphreys et al., 2010).

1.4 Economics

Because rice production requires a great deal of labour, Punjab and Haryana mainly rely on migrant labour to produce their rice. In Haryana, labour prices increased from USD 1.27 to USD 3.78 per day between 2005–06 and 2018–19, while in Punjab, they increased from USD 1.35 to USD 3.22 per day (1 USD = 74.32 Indian rupees; Sudhir-Yadav et al., 2017). As a result, the price of transplanting rice increased every year, from about USD 47 per hectare in 2010 to USD 74 by 2015. To solve this problem, crop rotation must be implemented rather than depending just on the RWCS. Crop rotation can improve financial returns while preserving resources like water.

According to research done in Ludhiana, India, rotating crops such as maize-potato-onion, summer peanut-potato-pearl millet (fodder), and maize-potato-summer mung bean yielded 32, 25, and 23 tonnes of rice equivalent per hectare annually, respectively, while the RWCS only produced 12.9 tonnes per hectare annually (Walia et al., 2011). Additionally, it is more economical to switch from rice to crops like maize or sugarcane rather than sticking with the RWCS (Kang et al., 2009; Choudhary et al., 2018).

Additionally, even after controlling for inflation, the difference between the minimum support prices—which act as stand-ins for market prices—and overall cultivation costs for wheat and rice has widened over time. Farm income and profitability have suffered greatly as a result of this widening gap. The advantages of the rice-wheat farming system, such as guaranteed prices, marketing, and steady output levels, make it the go-to option in northwest India despite these economic challenges (Bhatt et al., 2021). Productivity has stagnated since the 1990s despite the rice-wheat cropping system (RWCS) being a staple for many years (Bhatt et al., 2021). This suggests that the productivity increases brought about by the Green Revolution are slowing down.

2. Alternative Production Methods and Associated Benefits

Finding workable, sustainable, and ecologically acceptable substitutes for the rice-wheat cropping system (RWCS) has been the subject of more research throughout the last three decades (Singh et al., 2020; Banjara et al., 2021b). Adopting sustainable agricultural methods is essential to addressing problems like declining soil health, groundwater depletion, residue burning, and environmental pollution as well as to sustainably increase farm earnings. Implementing water-saving technologies, controlling crop residues, diversifying crops, integrating legume crops into the system, and engaging in conservation agriculture are important tactics.

2.1 Diversification of Crops

Crop rotation is superior to the RWCS in a number of ways. As an illustration, substituting pulses or oilseeds for rice can enhance soil health, lower water needs, and boost water productivity (Arora et al., 2020). Research conducted in Punjab, India, revealed that, in contrast to the RWCS, the use of a soybean–wheat system with raised beds enhanced soil fertility and water conservation (Ram et al., 2013). Legumes raise nitrogen levels and promote system sustainability when added to the cropping system (Arora et al., 2020). Diversification based on conservation agriculture, like rice-wheat-mung beans or maize-wheat-mung beans, greatly raised soil organic carbon by 83% and 72%, respectively, in comparison to the conventional rice-wheat system (Choudhary et al., 2018b). Additionally, these varied systems improved the quality of the soil and reduced its bulk density.

In order to increase water production and restore water levels during the monsoon, rice should be replaced in the summer with less water-intensive crops like cotton, maize, pearl millet, or legumes. For example, switching to a cotton-wheat or maize-wheat system from the RWCS significantly lowers the amount of irrigation water needed (Arora et al., 2008). A major benefit of maize is that it uses 80–85% less water than rice, and its water productivity rates are 8–22 times greater (Gathala et al., 2013). Comparing the maize–wheat system to the puddled rice system, the former improves microbial activity and soil health (Jat et al., 2012; Wei et al., 2015).

According to studies, switching from rice to zero-till maize can save 82–89% of water, reduce total energy input by 49–66%, reduce global warming potential by 13–40%, and increase profitability by 27–73% while preserving or increasing rice-equivalent yields (Kumar et al., 2018; Jat et al., 2020).

Changing cropping dates, choosing the right crops and varieties, and adjusting cultivation practices are some ways to control water demand and lessen residue burning. However, it has been challenging to diversify away from these commodities due to the current government policies in Punjab and Haryana, which promote the production of rice and wheat through guaranteed markets, subsidised electricity, and minimum support prices (MSP). The government has recently increased MSPs for pulse crops and promoted them. Changes in policy and increased campaigning could persuade farmers to switch from growing rice and wheat to more valuable crops that are more suited to their environments, like fruits, vegetables, and flowers.

2.2 Management of Crop Residue

One of the biggest challenges in the rice-wheat cropping system (RWCS) is managing crop residue. It is more difficult and energy-intensive to seed wheat using conventional tillage when there are loose and dispersed residues that disrupt tillage operations. As a result, farmers in northwest India frequently burn wastes, which leads to a number of issues. In situ integration and zero-till wheat planting using surface-retained rice residue are two of the creative methods for handling rice residues that have been developed over time. Compared to burning, these techniques provide a number of benefits, including better soil health, improved nutrient balance, less pollution in the environment, and less production costs. In order to preserve resources, safeguard the environment, and advance sustainability in northwest India, Singh et al. (2019) examined the significance of agricultural residue management in the RWCS. In Punjab, Haryana, and Uttar Pradesh, rice residue burning was tracked using satellite data equipped with temperature sensors throughout the September 30–November 30 rice harvest and wheat sowing season. According to the survey, there were 11% fewer burning incidents in Punjab in 2018 than there were in 2017 and 42% less than in 2016. In the same years, burning incidents decreased by 29% and 41% in Haryana and 24% and 32% in Uttar Pradesh.

It has been demonstrated that in situ agricultural residue management techniques are the most successful substitute for burning. Zero-tillage drills keep rice residue from being removed from the fields and allow straight wheat sowing without the need for previous tillage. Soon after rice harvest, wheat can be directly seeded into standing rice stubble using the Turbo Happy Seeder, an improved version of the zero-tillage drill (Sidhu et al., 2015). These solutions address possible adoption barriers like the cost of specialised equipment or the requirement for farmer training, while also being economically feasible and improving water efficiency.

Rice straw management equipment is available to farmers in a variety of forms. These include seeders made to be sown in straw conditions (e.g., rotary disc drills, Turbo Happy Seeders, zero-seed drills, spatial no-till drills, and super seeders); straw cutters for in situ incorporation or retention (e.g., rice straw choppers, straw shredders, super straw management systems, and mulchers); machinery for incorporating straw (e.g., reversible moldboard ploughs and rotary-till drills); and straw collection and disposal tools (scrapers and balers). The expense of specialised equipment or the requirement for farmer training are two possible obstacles to the implementation of these technologies.

2.3. Technologies for Sustainable Intensification

In the rice-wheat cropping system (RWCS), conservation agriculture has become a successful strategy for maintaining productivity and optimising input efficiency. Three fundamental ideas underpin this approach: residue retention, zero or reduced tillage, and crop diversity (Farooq and Siddique, 2014). These methods improve the physicochemical characteristics of the soil and aid in the storage of carbon (Jat et al., 2019a,b). In the RWCS of northwest India, studies show that using sustainable intensification technology in conservation agriculture can greatly enhance soil health after three to five years (Bhatt and Kukal, 2015). Furthermore, residue retention improves water use efficiency, controls temperature, and preserves soil moisture (Kukal et al., 2014; Bhatt and Kukal, 2018).

An effective substitute for the conventional puddled transplanted rice is dry direct-seeded rice (DDSR). Rice seeds are planted in the DDSR technique with or without previous tillage and irrigation, with sporadic irrigation to keep the soil moist. Depending on the season and region, this technique can save 11–18% of water compared to puddled transplanted rice and 11–66% of labour (Kumar et al., 2009; Rashid et al., 2009). Additional advantages of DDSR include decreased methane emissions, enhanced soil health, and simpler planting (Pathak et al., 2009; Kumar and Ladha, 2011). Additionally, DDSR-grown rice grows 7–10 days earlier than puddled transplanted rice, enabling the next wheat harvest to be planted on schedule (Singh et al., 2006). In contrast to puddled transplanted rice, DDSR has some drawbacks, such as higher weed infestation and a wider variety of weed species, which can result in yield losses of 50–90% (Chauhan and Johnson, 2011; Chauhan and Opena, 2012).

DDSR was first widely used in northwest India between 2010 and 2015; in 2016, Punjab's DDSR area grew to 160,000 hectares. However, by 2018, this amount had fallen to 5,000 hectares because of problems like heavy weed infestations, too wet soil for dry seeding, and a lack of acceptable rice types for late planting, which caused some farmers to turn back to ploughing. The area under DDSR in Punjab is estimated to have increased to 200,000–250,000 ha in 2020 as a result of labour shortages during the COVID-19 lockdown (Humphreys and Christen, 2020). According to reports, Punjab's DDSR size grew to 500,000 hectares in 2020. The Punjab state administration established a goal of 800,000 hectares for 2021 after being encouraged by this response. According to the most recent data, the area under DDSR in Punjab and Haryana was roughly 600,000 hectares in 2021 and 20,000 hectares in 2021, respectively (Kaushal, 2021).

By minimising erosion, increasing soil microbial activity, decreasing termite and weed infestations, and increasing resource-use efficiency, zero-till sowing has greatly improved soil quality (Hobbs et al., 2008). Uneven seed placement and germination can result from loose rice straw interfering with the sowing process, which is a significant problem when direct wheat planting is done on rice-harvested fields. Innovations like the rotary disc drill and Turbo Happy Seeder have significantly solved this problem (Sidhu et al., 2007). When planting wheat directly under zero-till conditions, these instruments efficiently mulch the rice straw. Zero-till wheat planting was first implemented in northwest India between 2002 and 2005, and it is currently supported by more than 2,500 seed-cum-fertilizer drills in Haryana and 3,400 in Punjab. By reducing the need for the conventional 4-6 ploughs to just 1-2, these drills have made it possible to seed wheat with little to no tillage. Since its commercial debut in northwest India almost 15 years ago, the Happy Seeder has experienced numerous enhancements and expanded in popularity. About 2,400 units were in operation in Haryana and 9,800 units were in use in Punjab as of the 2018–19 report; these units covered 0.053 and 0.45 million hectares of wheat, respectively (Singh, 2018). In India, zero-till wheat/Happy Seeder and DDSR cover over 7.2 million hectares of land overall (Pradhan et al., 2018) and 0.8 million hectares (Singh, 2018), respectively. In fields with complete rice residues, wheat is also sown using super seeders, which combine the Happy Seeder with a rotavator. However, they need a lot of energy (tractors of 50–60 horsepower) and fuel (around 20 litres per hectare). Farmers are becoming less interested in super seeders as a result of problems like uneven germination, poor tillering, and decreased yields. The governments of Punjab and Haryana have taken action to address these issues by requiring that all self-propelled combine harvesters feature a "Super Straw Management System," which aids in the uniform chopping and distribution of straw. For the Happy Seeder to be used effectively, the straw must be distributed evenly. In comparison to traditional tillage techniques, it has been found that using the Turbo Happy Seeder in rice residue circumstances increases wheat yields by 3.2% (Sidhu et al., 2015; Bhatt et al., 2021). RWCS yield, nitrogen balance, and soil health are all enhanced by zero-till planting combined with rice residue retention (Sah et al., 2014). The state governments of Delhi, Haryana, Punjab, and Uttar Pradesh are subsidising machinery to manage rice straw and reduce pollution from burning residues, with 50% going to individual farmers and 80% to cooperatives. In order to encourage efficient agricultural residue management, they are also conducting awareness campaigns using educational initiatives, demonstrations, and a variety of communication tools. Farmers now have better access to these machines thanks to the existence of service providers and custom-made hire centres that are funded by government grants. According to the Punjab Remote Sensing Centre (2019), Happy Seeders have been used to seed 0.55 million hectares of Punjab. However, it was not feasible to use remote sensing to assess residue incorporation. Using a Happy Seeder and a zero-till drill, about 0.8 million hectares (19%) of land in Punjab and Haryana were planted with zero-till wheat during 2018–19. Zero-till techniques should be used to grow both wheat and rice for optimal outcomes.

Due to shortages of labour during the COVID-19 pandemic, DDSR in moist soil has shown promise in a number of contexts and is growing in importance in Punjab and Haryana (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 (CO_2), methane, and nitrous oxide (N_2O) , was 2.91 tons per hectare for transplanted rice, compared to 1.94 tons per hectare for DDSR (Gartaula et al., 2020). According to Gupta et al. (2016), methane emissions in DDSR were 82–87.2% lower than those in puddled transplanted rice. Rotational crops benefit from DDSR's ability to preserve residual soil moisture, particularly when short- or medium-duration rice types or hybrids with early maturity are used. In the end, it increases system productivity, profitability, and sustainability by facilitating the early seeding of long-duration wheat varieties and extending the period available for efficient residue management. However, increasing awareness, improving farmer skills, and establishing strong policy backing are necessary to enable widespread adoption of DDSR.

2.4. Technologies for saving Water

Reducing water loss and just using what is required for plant growth are key components of true water conservation. Depending on the time and spatial circumstances, different amounts of water can be saved. Water savings in the rice-wheat cropping system (RWCS) refer to boosting output while consuming less water than is now used. Lowering agricultural costs (including pumping and water charges) and increasing water yield are two more advantages of reducing water usage. Low water productivity results from the unusually high water requirements of puddled transplanted rice. Numerous water-saving solutions can increase water consumption efficiency in order to address this. Growing short-duration crop types and transplanting them at the right moment are examples of these technologies (Sharma et al., 2020; Singh et al., 2020).

Tensiometer-based irrigation scheduling, laser land levelling, direct rice seeding, bed planting, subsurface drip irrigation, furrow irrigation, alternate wetting and drying, or irrigation at hairline cracking are important technologies for effective water use in the rice-wheat cropping system (RWCS). By reducing surface runoff, micro-irrigation methods like drip and spray irrigation drastically cut down on water use, increasing irrigation efficiency by as much as 50% when compared to flood irrigation (Sidhu et al., 2019). Additionally, by automating labour requirements and facilitating fertigation—which delivers nutrients straight to the crop—these systems minimise production costs.

Direct-seeded rice (DDSR), as opposed to puddled transplanting, uses 20–30% less water and does not require irrigation during the transplanting and puddling processes. Similarly, whether using direct sowing or puddled transplanting, the alternate wetting and drying (AWD) approach lowers irrigation requirements by 30–40% after crop establishment. By lowering evapotranspiration losses, using short-duration rice cultivars rather than longer ones improves water use efficiency even further (Singh et al., 2020). Additionally, there are encouraging prospects for water conservation with drip and sprinkler irrigation in DDSR (Chauhan and Abugho, 2013; Sharda et al., 2017). Both surface and subsurface drip irrigation methods maximise their effectiveness by supplying water and nutrients straight to the root zone. Water-use inefficiencies are addressed by irrigation automation, especially with drip systems that make use of sensor networks and communication technology (Sidhu et al., 2021). 30% less irrigation water might be used by switching to a multi-cropping system, like summer mung bean-maize-wheat, with fertigation and subsurface drip irrigation (Brar et al., 2021). Improving irrigation techniques can also reduce methane emissions and the net global warming potential of the rice-wheat system (Sapkota et al., 2020).

An alternative to flood irrigation, furrow irrigation in raised bed systems has the potential to boost water production, particularly for upland crops. Furrow-irrigated bed planting in wheat greatly increased water productivity and conserved almost 40% more water than flat planting, according to Kumar et al. (2010). According to Kumar et al. (2013a), rice yields and characteristics stayed comparable to those obtained using traditional techniques, whereas wheat yields increased using furrow-irrigated raised beds. Raising rice on raised beds has potential, but there is little proof that it uses less water. Particularly in Punjab, India, furrow-irrigated raised beds do not necessarily perform better than traditional flat fields in terms of productivity or water savings (Singh et al., 2009). To improve these techniques for better outcomes in various landscapes, more research is required.

2.5. Improving soil health

Farmyard manure is a widely available raw material that can be used to improve soil health in fields that have lost organic matter due to puddling. Using microbial decomposers and in situ crop residue strategies to manage rice stubble can improve soil organic matter. Furthermore, in the rice-wheat cropping system (RWCS), employing bio-fertilizers provides a means of reducing dependency on chemical fertilisers (Khan, 2018).

In the RWCS, site-specific nutrient management (SSNM) can improve production and nutrient use efficiency, especially when implemented with technologies such as Nutrient Expert® (NE). In northwest India, SSNM combined with no-tillage methods reduces greenhouse gas emissions from wheat agriculture while increasing yields, nutrient efficiency, and profitability (Sapkota et al., 2014). By lowering fertiliser costs, SSNM implementation has been demonstrated to boost net returns by 34 to 43 USD per hectare when compared to conventional fertiliser application techniques (Parihar et al., 2020). In conservation agriculture systems, nitrogen use can be decreased by 20–30 kg per hectare using optical sensor-based SSNM approaches while yields remain comparable. In the RWCS, integrated nutrient management (INM) supports nutrient balance and soil health. According to long-term studies on the rice-wheat sequence, the highest grain yields were achieved when 50% of the nitrogen was supplied by farmyard and green manure, with no loss of nitrogen or potassium when half of the nitrogen was replaced by organics (Saha et al., 2018).

2.6. Suggested Policy Changes

To increase the uptake of equipment for in situ residue management, it is imperative to improve the availability of crop succession data. Additionally, farmers might be encouraged to diversify their production by raising the Minimum Support Prices (MSPs) for different crops. Micro-irrigation system acceptance can also be increased by increasing subsidies and demonstrations. Infrastructure for the ex situ use of agricultural waste, such as the construction of bio-ethanol and biogas plants, should be funded by the government.

Conclusion

In order to feed the expanding population, rice and wheat production are vital in northwest India. Degradation of the ecosystem, dwindling groundwater levels, and soil fertility are some of the major sustainability issues facing the conventional Rice-Wheat Cropping System (RWCS). In order to solve these problems, conservation agriculture—which embraces methods that support sustainable crop production—must replace traditional methods. Reducing evapotranspiration losses and residue loads can be achieved by prioritising the development of short-duration, high-yielding rice varieties. The farming system's total productivity can be increased by using short-duration legumes like mung beans. Sustainable agriculture also requires investigating less water-intensive crops as substitutes for rice, such as maize. Water utilisation inefficiencies can be addressed by irrigation automation. Scaling up sustainable technologies like Direct Dry Seeding of Rice (DDSR) and zero-till wheat, supporting them with appropriate crop types, raising awareness through efficient extension services, and bolstering policy support are all critical to enhancing farm revenue and sustainability.

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