

Strategies for Sustainable Rice Production in Punjab

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Abstract

Punjab has played a pivotal role in ensuring India's food security through intensive rice cultivation. However, the current rice-based production system faces significant sustainability challenges, including groundwater depletion, declining soil fertility, excessive use of chemical fertilizers and pesticides, residue burning, greenhouse gas emissions, and increasing production costs. These issues threaten the long-term productivity, profitability, and environmental health of the region's agricultural systems. Sustainable rice production has therefore become essential to balance food security with the conservation of natural resources. This paper reviews the major challenges associated with conventional rice cultivation in Punjab and highlights practical strategies for enhancing sustainability. Key approaches include the adoption of water-saving technologies such as Direct Seeded Rice (DSR) and alternate wetting and drying (AWD), precision nutrient management through soil testing and site-specific nutrient management, integrated pest management (IPM), conservation agriculture practices, crop residue management using in-situ techniques, crop diversification, and the integration of organic amendments and bio-fertilizers. The role of climate-smart agriculture, mechanization, digital technologies, and supportive government policies in promoting sustainable rice production is also discussed. The successful implementation of these strategies can significantly improve water-use efficiency, reduce environmental degradation, enhance soil health, lower production costs, and maintain stable crop yields. A coordinated effort involving farmers, researchers, extension agencies, policymakers, and private stakeholders is essential for accelerating the transition toward sustainable rice production systems. Adopting these practices will not only ensure long-term agricultural productivity in Punjab but also contribute to climate resilience, environmental conservation, and national food security.

Introduction

Rice (*Oryza sativa* L.) is one of the most important staple food crops in the world, providing nourishment to more than half of the global population. In India, rice occupies a central position in food security, rural livelihoods, and agricultural development. Punjab, despite having only a small proportion of the country's geographical area, has emerged as one of India's leading rice-producing states due to the success of the Green Revolution. The state contributes significantly to the central food grain procurement system and plays a vital role in maintaining the nation's food security. The rice–wheat cropping system dominates Punjab's agriculture, accounting for the majority of cultivated land and contributing substantially to national rice production (Kumar et al., 2021).

The remarkable increase in rice productivity in Punjab has been achieved through intensive use of high-yielding varieties, assured irrigation, chemical fertilizers, pesticides, mechanization, and government procurement policies. Although these practices have ensured high production levels, they have also resulted in serious environmental and economic concerns. Continuous puddled transplanted rice cultivation has accelerated groundwater depletion, deteriorated soil health, increased greenhouse gas emissions, promoted residue burning, and reduced biodiversity. Rising labour costs, declining factor productivity, and increasing climate variability further threaten the sustainability of the existing production system. These challenges necessitate the adoption of resource-conserving and climate-resilient rice production strategies (Singh and Kataria, 2026).

Sustainable rice production aims to maintain or enhance productivity while conserving natural resources, minimizing environmental degradation, and ensuring economic viability for farmers. Several innovative technologies have emerged as promising alternatives to conventional rice cultivation in Punjab. These include Direct Seeded Rice (DSR), alternate wetting and drying (AWD), laser land leveling, precision nutrient management, conservation agriculture, integrated pest management (IPM), crop residue management through the Happy Seeder and Super Seeder, short-duration rice varieties,

and the use of digital agriculture and precision farming technologies. These practices have demonstrated significant potential to reduce water consumption, labour requirements, production costs, and greenhouse gas emissions while sustaining crop yields (Singh et al., 2023).

Recent policy initiatives by the Government of Punjab, Punjab Agricultural University (PAU), and international organizations such as the FAO have emphasized the large-scale promotion of water-saving technologies, particularly Direct Seeded Rice, to address the rapidly declining groundwater table and improve climate resilience. These initiatives complement national goals of sustainable agriculture and climate-smart farming while supporting farmers' income and long-term resource conservation (FAO, 2026).

Therefore, developing and adopting sustainable rice production strategies is essential for balancing food security with environmental conservation in Punjab. A comprehensive understanding of these strategies can assist policymakers, researchers, extension agencies, and farmers in designing interventions that enhance productivity while protecting soil, water, and ecological resources. This review discusses the major challenges confronting rice production in Punjab and examines the technological, agronomic, and policy interventions that can contribute to a more sustainable and resilient rice production system.

1 Water Management

- Promote DSR and AWD

Labour shortages, rising wage rates, and the continuous decline in groundwater levels have encouraged farmers in Punjab, India, to adopt alternatives to the resource-intensive puddled transplanted rice (PTR) system. In response to these challenges, dry-seeded rice (DSR) was introduced during 2009–10 as a more sustainable cultivation method. Compared with PTR, DSR reduced labour requirements by approximately 14 person-days per hectare and lowered irrigation water use by 18–20%. Initially, DSR produced yields that were 2–5% lower than those of PTR. However, as farmers gained experience with appropriate sowing practices and effective weed management, this yield gap was eliminated within one to two years. Furthermore, wheat grown after DSR recorded about 5% higher productivity than wheat following PTR, resulting in improved profitability. Overall, the DSR–wheat cropping system generated higher net returns, exceeding those of the PTR–wheat system by approximately INR 5,050–8,100 per hectare (Bhullar et al., 2018).

- Regulate groundwater extraction

The use of shallow tube-wells for irrigation in Punjab results in an annual ground water draft ranging from 0.27 to 2.59 hectare-meters (electric) and 0.21 to 2.3 hectare-meters(diesel), supporting the irrigation of approximately 1 to3 hectares of land per well (CGWB, 2022).

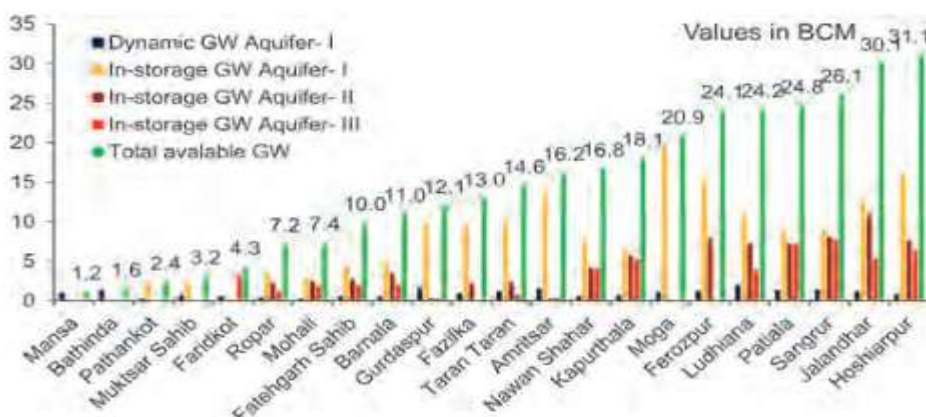


Fig. 1. District-wise variability in available groundwater resources in Punjab (upto 300 m depth); Depths of aquifer-I, II and II are 0 to 100, 100-200 and 200-300 m, respectively; figures excluding saline water.

Out of the 138 blocks in Punjab assessed for ground water, 109 blocks have been categorized as 'Over-exploited', two as 'Critical', five as 'Semi-critical' and 22 as 'Safe' with no saline block in the state. In Haryana, out of total 128 blocks assessed for ground water, 78 have been categorized as 'Over-exploited', three as 'Critical', 21 as 'Semi Critical' and 26 as 'Safe' (CGWB, 2019).

- Improve irrigation efficiency

Laser levelling improves irrigation efficiency and crop establishment by reducing irrigation needs and optimizing input resource usage. Efficient water management focuses on retaining water within the crop's root zone, which can be achieved by dividing fields into appropriately sized plots-typically 8 plots per acre for heavy soils and 16 plots per acre for light soils (Sindhu et al., 2024). Micro-irrigation technology which involves drip and sprinkler irrigation ensures increase in water use efficiency as much as 50- 90% due to reduced runoff, evaporation, seepage and deep percolation losses significantly. The on-farm irrigation efficiency of drip irrigation system properly managed and designed is estimated to be about 90 percent while in sprinkler irrigation sytem, water saving is up to 70 percent (INCID, 1994).

2 Crop Diversification

- Encourage maize, pulses, and oilseeds

Punjab emerged as the focal point of India's Green Revolution, bringing about major changes in the state's cropping pattern. Over time, the cultivation area under maize declined substantially, decreasing from 4.44 lakh hectares in 1966 to 1.09 lakh hectares by 2018. Similarly, the area devoted to pigeon pea reduced from 7.2 thousand hectares to 4.2 thousand hectares during the same period. Rapeseed and mustard cultivation also experienced a significant decline, with the cultivated area shrinking from 116 thousand hectares in 1966 to 30.5 thousand hectares in 2018 (Rakshit et al., 2021).

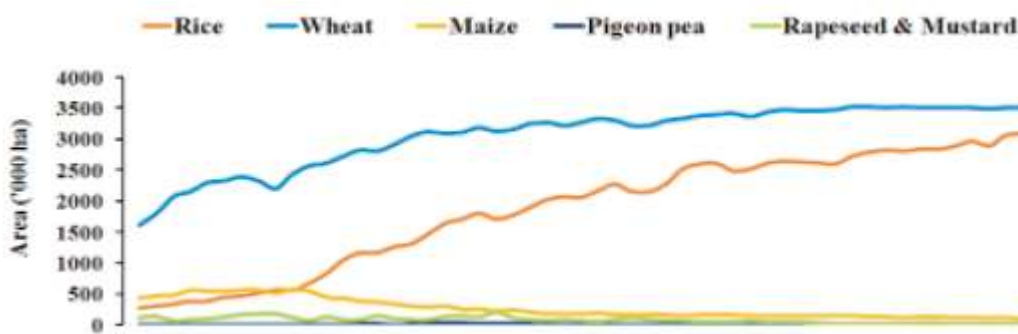


Fig. 2. Trends of area under rice, wheat, maize, pigeon pea, rape seed and mustard in Punjab

The rice–wheat cropping system practiced in the north-western Indo-Gangetic Plains has resulted in significant environmental, economic, and health concerns, highlighting the urgent need for crop diversification through the adoption of more sustainable production systems. Successful diversification should consider key factors such as crop water requirements, economic profitability, and market potential. Crops with lower water demand, including coarse cereals, pulses, and oilseeds, offer promising alternatives to water-intensive crops such as rice and sugarcane. Based on water-use efficiency, market opportunities, and expected returns, maize, pigeon pea, and soybean are suitable substitutes for rice during the kharif season, while mustard and chickpea can effectively replace wheat in the rabi season. In addition, the inclusion of short-duration mung bean in these diversified cropping systems can provide farmers with an extra source of income while enhancing soil fertility (Rakshit et al., 2021).

- Promote less water-intensive crops

Maize requires significantly less water than both rice and sugarcane, using nearly one-third of the water needed for rice and less than one-fourth of that required for sugarcane. Its crop duration of approximately 100–110 days is also shorter than that of rice (about 120 days) and substantially less than sugarcane (around 300 days). Producing one kilogram of

maize grain requires only 800–1,000 litres of water, whereas rice production demands approximately 3,000–3,500 litres per kilogram. Likewise, pulse crops have much lower water requirements than rice and offer multiple benefits, including improved food security, better public health, enhanced environmental sustainability, and support for climate change mitigation. Considering these advantages, replacing rice with pigeon pea in the rice–wheat cropping system represents a promising diversification strategy. In addition, India currently imports nearly 60% of its edible oil requirements, valued at around ₹78,000 crores. To satisfy the growing demand of a projected population of 1.43 billion by 2025, edible oil production must increase to approximately 33.4 million tonnes from an estimated 47.7 million tonnes of oilseeds. Therefore, soybean during the kharif season and mustard during the rabi season are viable alternatives to rice and wheat, respectively, for achieving sustainable crop diversification (Rakshit et al., 2021).

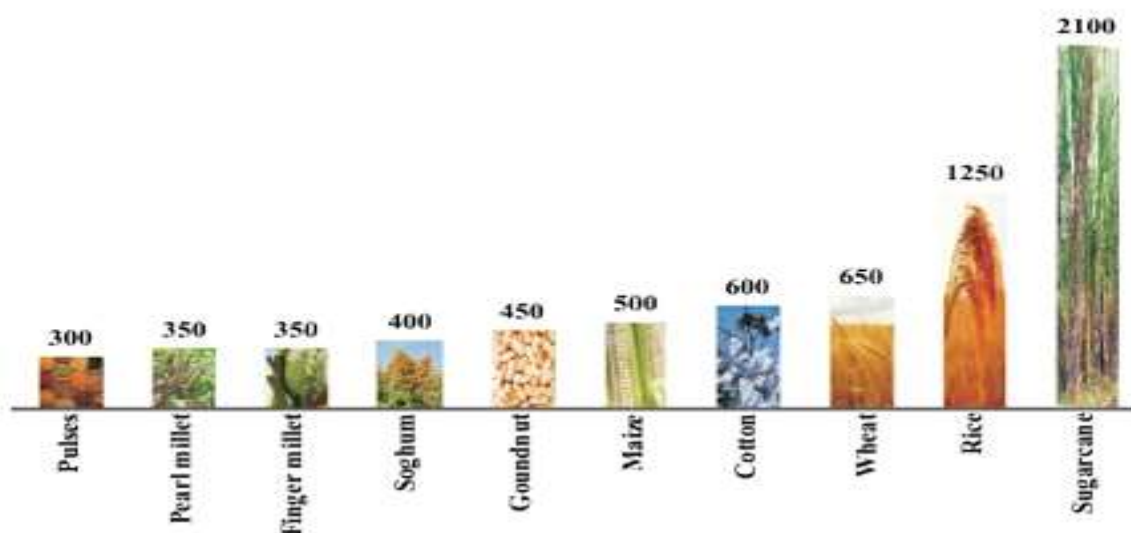


Fig 3. Relative water requirement of various crops (mm).

3. Policy Reforms

- Rationalize MSP incentives
- Encourage sustainable practices through subsidies

The Government of Punjab enacted the Punjab Preservation of Subsoil Water Act in 2009 to check groundwater depletion. The Act stipulates sowing of paddy nursery after 10th May and its transplantation after 20th June. The transplantation date fixed in 2009 Act was 10th June, which has been revised to 20th June during 2018 (Sharma, 2018).

4 Soil Health Improvement

- Integrated nutrient management

Farmers cultivating coarse-grain dry-seeded rice (DSR) reported considerable savings in irrigation water compared with puddled transplanted rice (PTR). Around 63% of farmers observed a reduction in irrigation water use of 10–20%, while 29–36% reported savings of 20–30%, and the remaining farmers achieved water savings exceeding 30%. On average, both coarse-grain and basmati DSR systems reduced irrigation water requirements by approximately 18–20% relative to PTR (Bhullar et al., 2018). Earlier studies conducted in the region also demonstrated that irrigation water could be reduced by 15–20% under DSR without adversely affecting rice grain yield when compared with conventional PTR (Yadav et al., 2011; Bhullar et al., 2016).

Rakshit et al. (2021) further reported that pigeon pea contributes nearly 40 kg N ha⁻¹ through biological nitrogen fixation, which is equivalent to approximately 87 kg of urea, thereby reducing fertilizer costs. Additionally, the crop returns 2–3 tonnes ha⁻¹ of leaf litter, flowers, and root residues to the soil, supplying about 8–16 kg nitrogen, 2.5–5 kg phosphorus,

and 13.5–24 kg potassium per hectare to the succeeding crop. Compared with rice, pigeon pea has lower fertilizer requirements and is widely recognized as a soil-improving crop that enhances soil fertility and sustainability.

- Use of organic matter and crop residues

Majority of the farmers of our country are poor having low budget for different agricultural inputs such as fertilizers. They spend money on nitrogenous fertilizers as compared to Phosphatic and potassium fertilizers. It is the dire need of today to include green manuring along with synthetic fertilizers in order to reduce the cost of fertilizers as well as to increase soil organic matter and to enhance the soil fertility on sustainable basis. This study was conducted with the objectives to evaluate the impact of Sesbania as green manure on soil organic matter, soil fertility status of soil as well as its impact in reducing the cost of synthetic fertilizers. Results revealed that the organic matter contents increased from 0.78% to 1.66% and 1.69% in Jantar + Full Fertilizer and Jantar + Half Fertilizer. As for as economics of green manuring is concerned it increased net profit from 108892 and 124403 per hectare/ annum in Jantar + Full Fertilizer and 72621 to 83584 per hectare per annum in Jantar + Half Fertilizer during the two series of experiments (Qazi et al., 2023).

5 Climate-Resilient Varieties

- Heat- and drought-tolerant rice varieties

During year 1973 with the release of cv RP 5–3, the first major jump in rice yield was achieved, i.e., the rice yield crossed the yield level of 3000 kg/ha. Thereafter, high-yielding and heat and drought tolerant cv PR 106 (1975), PR 103 (1977) PR 108 and PR 109 (1985), PR 111 (1993), PR 113 (1997), PR 114(1998), PR 116 (1999), PR 118 (2002), PAU 201 (2006), PR 121 and PR 122 (2013), PR 124 (2014), PR 126 (2016) and PR 127 (2017) were subsequently released during the 49 years' time slice (Kaur et al., 2021). DRR Dhan 44 (Hardinath 3), one of the most recently released drought-tolerant rice varieties in India and Nepal, combines high yield potential with superior grain quality. The variety exhibits resistance to blast disease and moderate resistance to bacterial leaf blight (BLB), making it suitable for cultivation under drought-prone conditions. Another improved cultivar, DRR Dhan 46, is a short-duration, high-yielding variety developed to replace existing low-yielding cultivars of similar maturity during both the *kharif* and *rabi* seasons. It possesses strong drought tolerance and can produce an additional yield of approximately 1.0–2.0 t ha⁻¹ compared with other rice varieties of comparable duration when grown under drought stress (APART, 2017).

- Short-duration crops

Punjab has introduced several high-yielding, short-duration rice varieties, including PR 126 (125 days) and PR 124 (135 days), along with the basmati variety Pusa Basmati 1509 (105 days), which possess yield potential comparable to that of traditional long-duration cultivars (Anonymous, 2017). These improved varieties are well suited to the recommended June sowing period for direct-seeded rice. In 2017, they were approved for adaptive research trials on farmers' fields and were subsequently considered suitable for large-scale promotion under dry-seeded rice cultivation in the state. The adoption of short-duration rice varieties has increased steadily, as reflected by the decline in the area under long-duration cultivars from more than 40% in 2012 to less than 20% in 2016. This trend indicates that farmers are readily adopting shorter-duration varieties when they provide grain yields comparable to those of conventional long-duration rice cultivars (Bhullar et al., 2018).

6 Mechanization and Innovation

- Promote precision farming

Precision farming could help to achieve desired rice production by using proper technologies in field preparation, weed management, irrigation water management, fertiliser application, insect and pest control, crop harvest, and post-harvest operations. Laser land levelling is frequently used for proper rice field levelling due to its numerous advantages. Rice cultivation using mechanised direct seeding is a cost-effective and efficient method that is gaining popularity among farmers, owing to labour shortages and rising rice production expenses. Precision seeders for sowing of rice crop are

getting worldwide popularity due to their cost effectiveness and efficiency. Automated farming robots for direct seeding of rice, on the other hand, may be a viable option as they can control the number of rice seeds per dropping, maintain the spacing between the dropping points, and navigate the field automatically (Bhattacharyya et al., 2022).

Many researchers have created and validated GPS guided trans planters using similar methodologies. Recently, an on-the-go soil sensor with a 6-row rice trans planter equipped with an ultrasonic sensor to correctly detect topsoil depth was developed and validated (Morimoto and Hayashi, 2017). A rice trans planter can also be upgraded and outfitted with a ground-based integrated sensor and instrumentation system to monitor field conditions in real time (Singh and Sharma, 2017).

- Strengthen extension services

During the Green Revolution and thereafter, extension services played a crucial role in transferring improved technologies, empowering farmers and enhancing their skills, thereby increasing food production and making India self-sufficient (Baranwal and Jain, 2025). Agricultural extension, the mainspring of agricultural development, has long been empowering the farmers to adopt information and technologies to enhance their livelihoods (Anderson & Feder, 2007). Alzahrani et al. (2023) revealed that a vast majority of the rice farmers were poorly satisfied with the public extension services. The results of the Spearman Rank-Order Correlation showed that landholding size had a significant effect on deciding extension contact; public extension agents are more likely to visit and serve those rice farmers who possess large landholders and therefore have the tendency to intentionally neglect small-scale rice farmers. For enhancing rice production, farmers believed that the provision of subsidized agricultural inputs and a minimum support price for rice is indispensable. Based on findings, they suggest that to make public extension services more effective, public extension agents should particularly focus on the capacity building of small-scale farmers rather than large-scale farmers. Moreover, there is a need to broaden the scope of public extension services from simple crop protection measures to a set of comprehensive sustainable agricultural practices for increasing agricultural productivity, resource-use efficiency, as well as resilience toward adverse impacts of climate change.

Conclusion

In conclusion, sustainable rice production in Punjab is both an environmental necessity and an economic imperative. By combining scientific innovations, sound natural resource management, supportive public policies, and active farmer participation, Punjab can transition towards a resilient and sustainable rice production system that safeguards food security, conserves natural resources, mitigates climate change, and ensures the livelihoods of future generations. This transformation will not only benefit the state but also serve as a model for sustainable rice cultivation in other intensively farmed regions of South Asia.

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