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# From Grains to Gains : Challenges and Opportunities in Rice-Based Cropping Systems

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**ABSTRACT**

Rice-based cropping systems (RBCS) are central to global food security, feeding billions of people and sustaining millions of farmers across Asia, Africa, and Latin America. With global rice demand projected to reach 584 million tons by 2050, maintaining the necessary annual growth is increasingly challenged by climate change, soil degradation, and growing resource scarcity. South Asia is especially vulnerable because of groundwater depletion, rapid population growth, and heavy dependence on non-renewable inputs. Historically, RBCS evolved from subsistence, rainfed monocropping to mechanized, market-oriented systems. The Green Revolution accelerated this transition through irrigated monocropping, followed by intensification via double cropping and expanded use of agrochemicals. While these changes delivered major yield gains, they also generated serious sustainability concerns, including productivity stagnation, nutrient mining, pest and disease build-up, herbicide resistance, and declining soil organic matter. Smallholders now face additional pressures from labour shortages, fragmented landholdings, and rising production costs. Sustainable transformation of RBCS demands a shift toward resilience-building and ecologically based management through regenerative agriculture approaches, with a strong focus on improving resource-use efficiency. Core strategies include deployment of stress-tolerant rice varieties, expansion of direct-seeded rice, adoption of conservation agriculture, use of precision farming tools, and improved water management. Diversification through pulses, maize, rice–fish systems, and better residue management can rebuild soil health, lower greenhouse gas emissions, and enhance farm incomes. Strong policy support, sustained research investment, and digital innovations led by national and international institutions are critical to scaling these solutions. Together, they can ensure that rice-based cropping systems become more resilient, profitable, and environmentally sustainable, in line with global development and climate goals.

**Keywords :** Climate Change, Regenerative Agriculture, Rice-Based Cropping Systems, Sustainability

## Introduction

Rice is a fundamental staple food for over half of the world's population, particularly in Asia, where it serves as a dietary cornerstone. Rice-based cropping systems (RBCS) contribute significantly to

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global food security by providing sustenance for billions (Roul and Dwibedi, 2023; Shahana *et al.*, 2022). These systems support the livelihoods of millions of farmers and agricultural labourers globally, particularly in countries across Asia, Africa, and Latin America, where rice is a key crop. Given the current pace of population growth and the need to cater to the rising demand for rice, it is projected that the global requirement for rice will reach 584 million tons (mt) by 2050. As per the estimates of the International Rice Research Institute (IRRI), an extra 75 mt of rice would have to be produced worldwide compared to 2020 (Pede *et al.*, 2023). Achieving this ambitious goal, which necessitates a 1.2% annual growth rate, is a challenging task, especially in the face of intensifying climate-related abnormalities and limitations within agricultural ecosystems. Even it is more complex since intensive RBCS involve intensive tillage practices, which demand more resources, damage soil quality, and reduce both crop yields and profit margins (Hoque *et al.*, 2023). Thus, RBCS offer valuable insights into the challenges and opportunities facing agriculture on a global scale. South Asia in particular faces a range of critical challenges, including the depletion of groundwater and land resources, yield reduction, climate change impacts, and rapid population growth (Bhatt *et al.*, 2021; Jat *et al.*, 2020; Nawaz *et al.*, 2019). The central issue is the need to feed the region's growing population with finite resources, which presents a significant challenge for farmers, scientists, and policymakers. Because, economic development in the region has not kept pace with population growth, leading to urbanization, shifts in food consumption patterns, and heavy reliance on non-renewable inputs such as water, chemical fertilizers, and pesticides. Current land-use practices in South Asia have negative environmental consequences, depleting groundwater supplies, and harming soil physicochemical qualities. Nevertheless, it remains feasible through diligent and ecologically sustainable management of RBCS. However, transforming rice-based agri-food systems in the coming decades must be achieved through building resilience and mitigating environmental impacts, with at least 30-50% increase in the efficiency of limited resources used while ensuring the accessibility of healthy and nutritious food for all individuals and significantly reducing negative environmental impacts associated with the agri-food systems (Jat *et al.*, 2020; Panneerselvam *et al.*, 2022; Shahid *et al.*, 2024). This review explores the global perspective of RBCS, shedding light on their significance, major challenges, potential opportunities and scalable solutions.

## Rice-Based Cropping Systems: An Overview

Global status of RBCS is dynamic, and subject to change due to evolving environmental, economic, and technological factors. In the era before the green revolution (prior to the 1960s), the rice-based production system in Asia was primarily oriented towards subsistence nature with low intensification and rainfed monocropping without using external inputs, resulting in low rice yields. During the green revolution (1960-1970), the production scenario remained largely subsistence-focused moderate intensification, particularly in irrigated transplanted rice monocropping, with limited addition of external inputs that exhibited moderate improvement in yields. In the post-green revolution phase (1990s), the production orientation shifted towards being more market-oriented, becoming highly intensive and fully irrigated, involving transplanted double-cropping and extensive use of agrochemicals, resulting in improved yields (Roul and Dwibedi, 2023). Currently, the production orientation in the post-green revolution phase is primarily market-driven, high-intensive, mostly irrigated multiple cropping, direct-seeded mechanized precision farming, and off-season soil-less cropping, leading to significantly higher yields and profits (Rao *et al.*, 2017; Singh *et al.*, 2022a). All these stages of transformation in rice farming have been particularly applicable to irrigated systems, converging diverse production systems into a uniform, highly mechanized, intensive, and innovative approach (Roul and Dwibedi, 2023).

On the other hand, rainfed rice production, covering approximately 18 million hectares (m ha) of land in Southeast Asia alone, plays a critical role in ensuring household security in marginal areas of the countries like Cambodia, Myanmar, and Thailand (Rao *et al.*, 2017). However, the limited yield response to the addition of external inputs has often hindered the profitable adoption of capital-intensive innovations such as hybrid seeds, fertilizers, and farm mechanization. To address these challenges, the strategies undertaken in the localized areas of Bangladesh, Cambodia, India, and Thailand involve the cultivation of sticky, pigmented, and indigenous aromatic rice varieties for both self-consumption and local market sales (Rao *et al.*, 2017). Rice-wheat cropping systems (RWCS) are practiced on ~24.0 m ha of cultivated land in Asia, encompassing both irrigated and rainfed conditions, whereas South Asia accounts for ~13.5 m ha of lands, extending across the Indo-Gangetic Plains (IGPs) into the Himalayan foothills. In countries like Bangladesh, India, Nepal, and Pakistan, RWCS covers ~33% of the total rice area and ~42% of the total wheat area, contributing significantly to both rice and wheat production (Timsina and Connor, 2001). Earlier the Government of India identified rice-fallows in an area of 11.65 m ha in India (Subbarao *et al.*, 2001), accounting for ~79% of the total rice-fallows in South Asia, which was estimated at 15.0 m ha (NAAS, 2013). According to recent estimates (Gumma *et al.*, 2016; Kumar *et al.*, 2025), there are ~22.3 m ha of suitable rice-fallow areas in South Asia, the majority in India (88.3%), followed by Bangladesh (8.7%), Nepal (1.4%), Sri Lanka (1.1%), Pakistan (0.5%), and Bhutan (0.02%). In India, the majority of rice-fallows are concentrated in the eastern states, including Bihar, Chhattisgarh, eastern Uttar Pradesh, Jharkhand, Odisha, Upper Assam, and West Bengal (Panneerselvam *et al.*, 2022; Panneerselvam *et al.*, 2023; Pande *et al.*, 2012; Kumar *et al.*, 2018).

In India, major RBCS include rice-wheat, rice-rice, rice-oilseeds, rice-pulses, rice-vegetables, rice-maize, and rice-rice-rice, covering a total of >20.0 m ha and contributing significantly to the country's food basket (Bhaskar *et al.*, 2021). Among these systems, the combination of rice and wheat holds the largest share (Table 1). In the rice-growing regions of eastern India, common cropping sequences include rice-rice, rice-wheat, rice-rapeseed/mustard, rice-groundnut, rice-potato, and rice-pulses, whereas in South India, the rice-rice cropping system predominates. RWCS is mainly practiced in the IGPs, while the rice-maize system is adopted in tropical, subtropical, and warm temperate climates. West Bengal is the leading rice producing state in India. In West Bengal, rice dominates the agricultural landscape, where fertile soils and abundant rainfall favour its cultivation. Farmers in the state mostly grow rice during the *kharif* season, followed by *boro* rice, wheat or diverse crops such as pulses, oilseeds, and vegetables in the *rabi* season. Rice–potato, rice–mustard and rice-*rabi* pulses rotations are common, while rice–vegetable systems provide higher energy productivity and income. Such diversified patterns other than rice-rice/wheat not only stabilize yields but also improve soil fertility and reduce risks from climate variability. By integrating rice with other resilient crops with low input requirement, farmers can maximize land use and sustain livelihoods.

**Table 1. Rice-based cropping systems in major countries of South Asia**

| Cropping system | Area (m ha) | | | |
|---|---|---|---|---|
| | Bangladesh | India | Nepal | Pakistan |
| Rice-rice | 4.50 | 6.00 | 0.30 | NA |
| Rice-rice-rice | 0.30 | 0.04 | NA | NA |
| Rice-rice-potato | 0.18 | NA | NA | NA |
| Rice-wheat | 0.80 | 10.36 | 0.60 | 2.20 |
| Rice-maize | 0.35 | 0.53 | 0.43 | NA |
| Rice-pulses | NA | 3.50 | NA | NA |
| Rice-vegetable | NA | 1.40 | NA | NA |
| Rice-potato | 0.30 | NA | NA | NA |
| Rice-fallow | 1.93 | 19.69 | 0.31 | 0.11 |

NA : Areas exist but data not available. Modified after Ahmad *et al.* (2015), Kumar *et al.* (2025), Ladha *et al.* (2000), Timsina *et al.* (2010).

## Challenges in Rice-Based Cropping Systems

There exist a number of emerging challenges (Table 2) in sustaining rice-based food production systems to feed the burgeoning population. Climatic vulnerabilities continue to affect the overall agricultural production. However, the major challenges include soil health deterioration, groundwater depletion, environmental pollution (due to crop residue burning and enhanced greenhouse gas emission), labour migration (scarcity), fragmented and small landholding, escalating production cost, and diminishing profit margin. There is an urgent need to address these challenges for improving the livelihood, nutrition, resilience, and income of smallholder farmers and their families. Studies reveal that the productivity of RBCS has been either stagnated or declined in the post-Green Revolution era in most intensively cultivated areas. This is due to widespread occurrence of second-generation problems such as deteriorating soil health, over-mining of soil nutrients, declining factor productivity, rising water scarcity, growing labour/energy crisis, diminishing profitability, lowering of groundwater tables, buildup of pests (including weeds, diseases and insects), emergence of herbicide-resistant weeds, burning of crop residues, low soil organic matter (SOM) contents, deteriorating soil health, etc. All these problems, individually or collectively, are threatening the sustainability of these systems (Gangwar and Prasad, 2005). Intensive tillage practices, injudicious input use, burning or removal of crop residues, groundwater extraction, and climate change as a whole threaten the long-term sustainability of RBCS.

**Table 2. Major challenges and problems in rice-based cropping systems**

| **Major challenges** | **Problems** | **References** |
|---|---|---|
| Decline in factor productivity | Continuous mining of precious soil nutrient resources in rice-based systems in intensively cultivated areas; wider nutrient application gap between recommended fertilizer dose and farmers' fertilizer practices in various systems; widespread deficiencies of macro, micro, and secondary nutrients under rainfed conditions, especially deficiencies of organic carbon and nitrogen with particular visibility in rice systems; dominance of late-maturing rice varieties that allows little time for land preparation for wheat that ultimately delays the wheat cultivation etc. | Ahmad *et al.* (2015), Bhaskar *et al.* (2021), Gopinath *et al.* (2021), Roul and Dwibedi, (2023), Tandon and Sekhon (1988) |
| Soil degradation | Elemental toxicity and deteriorating soil aggregate composition due to intensive cultivation and continuous rice monoculture with soil puddling; soil erosion; loss of soil organic matter; nutrient depletion; soil health risks etc. | Sara *et al.* (2017), Shah *et al.* (2021), Roul and Dwibedi (2023) |

| | | |
|---|---|---|
| Residue burning | Poor feed quality and high silica content in straw; narrow time frame between rice harvest and wheat sowing; expensive residue handling machinery and labour-intensive removal processes; lack of storage and energy generation systems; environmental degradation by releasing CO, $CO_2$, $CH_4$, and particulate matter into the air; loss of valuable nutrients contained in the residue; global warming; deteriorating soil health etc. | Dobermann and Fairhurst (2002), Gupta *et al.* (2004), Singh *et al.* (2008), NAAS (2017) |
| Environmental sustainability concerns | Higher emissions of $CH_4$ under transplanted flooded conditions and $N_2O$ under direct-seeded conditions; depleting groundwater resources; soil erosion; contamination of water bodies, causing significant adverse impact on the environment; continuous flooding or frequent irrigation in rice, leading to nitrate leaching that affects grain quality and human and animal health etc. | Roul and Dwibedi (2023), Shahid *et al.* (2024) |
| Resource constraints | Limited land and water resources posing constraints on expanding rice production to meet the needs of a growing global population in the backdrop of growing urbanization and industrial sectors; declining underground water resources etc. | Bhatt *et al.* (2021) |
| Changing pest dynamics | Climate change and extreme weather events causing severe impact on pest and disease incidence in rice-based systems, requiring the use of pesticides that can have negative ecological and health impacts; higher incidence of plant hoppers and leaf blasts in rice; increasing richness and abundance of grass species and weedy rice along with sedges due to shift from PTR to ZT-DSR etc. | Azmi and Baki (1995), Bhowmick *et al.* (2022), Hossain *et al.* (2020), Kumar and Ladha (2011), Rao *et al.* (2007), Ali and Afzal (2026) |

CO: Carbon monoxide, $CO_2$: Carbon dioxide, DSR: Direct-seeded rice, $CH_4$: Methane, $N_2O$: Nitrous oxide, PTR: Puddled transplanted rice, ZT: Zero tillage

## Opportunities in Rice-Based Cropping Systems

Deploying resilient rice varieties along with novel agronomic management systems, including regenerative agriculture, alternative crop establishment methods, crop calendar adjustments, potential diversification options, *etc*. are essential to address the emerging and future challenges in the RBCS.

**1. *Resilient crop varieties :*** Deploying stress-tolerant rice varieties (STRVs) with enhanced resilience to flood, drought, salinity and/or heat constitutes the first line of defence against climate change. Multi-stress tolerant and improved rice varieties for efficient water and nutrient utilization can help crop plants to adapt climate change. Direct-seeded rice (DSR) has been seen as a climate-resilient technology for saving water, energy, and cost, besides reducing methane emissions (Kumar *et al.*, 2025). The latest breeding and scaling efforts around DSR suitable varieties, and low input responsive varieties are becoming more critical for the future. Planting short duration rice varieties (SDRVs) or low-methane rice varieties (LMRVs) can reduce greenhouse gases (GHGs) emissions and enable early harvesting of rice, thereby facilitating early sowing of wheat in RBCS which can help to avoid terminal heat during maturity period. Ensuring widespread adoption and scaling of climate-resilient varieties, replacing other normal high-yielding/ farmers' preferred varieties and strengthening seed system remains the critical avenue (Ismail *et al.*, 2022; Nayak *et al.*, 2022; Bhowmick *et al.*, 2020; Srivastava *et al.*, 2022). These efforts are targeted to ensure localized access of quality seeds and sustained adoption of the resilient varieties.

**2. *Climate-smart farming practices :*** Adopting sustainable farming practices, such as conservation agriculture (CA), integrated nutrient management (INM), integrated pest management (IPM) including integrated weed management (IWM), and precision farming (PF), can mitigate the environmental impact of rice cultivation while maintaining or even increasing yields (Shahid *et al.*, 2024). With the introduction of stress-tolerant rice varieties (STRVs) and SDRVs, improved irrigation facilities and conservation practices, there is a tremendous scope for crop intensification to increase system productivity and farmers' income (Kumari *et al.*, 2025; Panneerselvam *et al.*, 2020; Jat *et al.*, 2021). Effective water management plays a pivotal role in adapting and mitigating climate change. Promoting alternate wetting and drying (AWD) methods of water management in irrigated ecology can reduce the use of irrigation water by 38% without compromising yield. Other water saving technologies like laser land levelling (LLL) can save water by 10-25% and micro-irrigation (*e.g.* drip irrigation) can save water up to 75%. Mechanized and precise dry-DSR can save irrigation water by 20-25%, reduce methane emission by 30-58%, and overall global warming potential by 20-44%. The potential options for GHG mitigation in cropping systems include soil carbon sequestration, reducing nitrous oxide ($N_2O$) emissions from fertilizers (*e.g.* introducing nano-fertilizers, drip fertigation), reducing methane ($CH_4$) emissions from paddy rice, and bridging yield gaps. Timely rice establishment with shorter-duration STRVs is important for improving the cropping system resilience and productivity, which enables early harvesting of rice and early sowing of succeeding *rabi* crops like wheat, lentil and mustard. Reducing tillage with DSR and zero-tillage (ZT) wheat in RWCS can improve soil structure, thereby improving the soil physical health. Crop diversification and residue management can increase labile organic matter and promote nutrient cycling in soils. Similarly, shifting from blanket and imbalanced application of inorganic nutrients and promoting bio-organic materials through INM and site-specific nutrient management (SSNM) can build SOM, better align soil nutrient supply with crop nutrient demand, improve nutrient use efficiency (NUE), and reduce environmental pollution through various ways. Capital and energy-intensive puddling in rice farming can be replaced with ZT-based mechanized planting, un-puddled transplanted rice (UPTR), dry-DSR and strip tillage-based planting, *etc.* (Roul and Dwibedi, 2023). Innovative crop establishment methods along with best-bet management options like LLL, AWD, SSNM, IWM, *etc.*, besides deploying different digital tools/apps (Rice Crop Manager, Easy Harvest, GHG Emission Calculator, Rice Doctor, Rice Knowledge Bank, SeedCast, WeRise, AutoMon$^{PH}$, CF-Rice, COMPARE, RIICE, MapAWD, SECTOR, PRiSM, etc.) and encouraging the establishment of custom hiring-based machinery banks for field-level adoption of large machines by medium and marginal farmers, not only reduce/optimize input use, but also minimize GHG emissions and address upcoming climate-related risks (Singh *et al.*, 2025; Singh *et al.*, 2016; Singh *et al.*, 2017; Singh *et al.*, 2020; Singh, 2021; Singh *et al.*, 2022b). Rural entrepreneurs can be trained to operate and maintain different machines and apps/tools for seed-to-seed mechanization with precision farming. IRRI has been working on the Geographic Information System (GIS) and related Earth-observing technologies like Remote Sensing (RS), Global Navigation Satellite System (GNSS), and Unmanned Aerial Vehicles (drones) to provide a variety of applications, including crop growth monitoring, modelling and forecasting, damage assessment, pesticide applications, rice-fallow mapping, data-driven dynamic agro-advisories *etc.*, which can help in increasing productivity and sustainability of RBCS. There is no dearth of solutions, but our focus will continue to be on increasing the affordability and scalability of the existing and innovative solutions to convince smallholder farmers through awareness development, capacity building, technical backstopping, etc.

**3. *Sustainable residue management :*** In-field burning of rice-straw has been increased due to early harvest of rice fields in favour of wheat sowing. To maximize the best utilization of rice straw (as fodder, soil mulch, compost preparation, etc.), mechanization is most important to facilitate collection, hauling, and stacking or processing of available rice straw from the field. Sustainable rice straw management is crucial intervention to avoid straw burning (NAAS, 2017; Singh *et al.*, 2023). Scale-appropriate rice straw management technologies such as mechanized collection and optimized logistics for off-field options, and mechanized composting (combination of bio-physico-chemical processes) need to be promoted. Since mechanized collection of rice straw plays an important role in saving time, labour and cost, popularizing the use of rice straw balers (round baler, self-propelled baler, square baler) and straw-based composting will be an attractive business proposition for the rice straw value chain actors, including farmers, rice straw baler service providers and traders, mushroom and cattle feed producers, *etc.* Incorporating residues into the soil is an effective long-term management option that improves soil health, but it comes with challenges such as increased energy requirements and temporary nitrogen immobilization, raising cultivation costs. Another promising approach is retaining rice residue on the surface by direct-seeding of wheat or other crops using resource-conserving machines like ZT seed drills, strip-till drills, mulchers, punch planters, Happy Seeders, and Rotary Disc Drills. This method has multiple benefits, including reduced soil erosion, improved soil organic carbon (SOC), decreased water loss through evaporation, and fewer weed problems. Conservation tillage, including ZT and reduced tillage combined with anchored crop residue, can create a better soil environment, reduce environmental impact, and promote climate-resilient crop production systems (Shahid *et al.*, 2024). Direct drilling, a non-conventional seeding practice, allows for *in-situ* residue management and timely crop seeding, saving time, water (10-15%), and diesel (70-80%), while also being environmentally friendly. Efforts should focus on developing suitable seeding machines for multi-cropping systems under both conventional and conservation agriculture, and popularizing them on a larger scale. To effectively manage residue on a large scale, infrastructure development, establishment of residue collection centers at the block level, creation of strong supply chains, policy interventions, extensive training, and incentives for farmers are essential, especially for utilizing crop residue for industrial and energy applications. *In-situ* incorporation of rice residues and straw biochar application can enhance SOC pool in RBCS.

**4. *Regenerative agriculture practices :*** Regenerative agriculture (RA) in RBCS focuses on restoring soil health, enhancing biodiversity, and ensuring long-term sustainability while maintaining productivity (Meena *et al.*, 2025). A key principle is minimizing soil disturbance through reduced tillage or ZT, which preserves soil structure and microbial communities (Choudhari *et al.*, 2024). Cover crops, particularly legumes, enrich SOM, fix nitrogen, and reduce reliance on synthetic fertilizers. Crop diversification with pulses, oilseeds, and vegetables breaks pest cycles and improves nutrient dynamics. INM combines organic amendments—compost, farmyard manure (FYM), green manures, biochar, and residue mulch—with judicious fertilizer use to boost soil fertility and resilience. Water-saving techniques such as AWD, drip irrigation, and laser land levelling (LLL) conserve water, reduce methane emissions, and make rice cultivation more climate-friendly. Agroforestry and bund plantations around rice fields contribute to carbon sequestration, provide habitats for beneficial organisms, and diversify farmer incomes. Bio-intensive IPM, including natural predators, biopesticides, and IWM, reduces chemical dependency and supports ecological balance. Residue management through *in-situ* incorporation of rice straw enhances SOC while curbing air pollution. Livestock integration enriches soil fertility through manure and aids weed management *via* grazing. Practices such as rice-cum-fish culture further diversify production systems and strengthen ecosystem services. Collectively, these approaches improve SOC, water-use efficiency, and resilience to climate variability. They also reduce input costs, diversify income sources, and secure long-term productivity, thereby improving farmer livelihoods. Promising RA practices include CA, ZT-DSR and UPTR, which enhance soil aggregation, infiltration, and carbon storage (Choudhari *et al.*, 2024; Mishra *et al.*, 2024a and 2024b). Introducing legumes in rice fallows restores fertility, while straw management and managed grazing stimulate plant growth, biodiversity, and carbon sequestration. Overall, RA practices in RBCS offer a holistic pathway for sustainable food production, environmental restoration, and climate change mitigation, aligning ecological benefits with economic gains for farming communities.

**5. *System diversification, intensification, and optimization :*** Diversification in RBCS by incorporating other crops in rotation or intercropping can improve soil health, reduce pest pressures, and provide additional sources of income for farmers (Panneerselvam *et al.*, 2022; Panneerselvam *et al.*, 2023; Choudhari *et al.*, 2024). Cropping systems with greater productivity and low input demand are considered as efficient towards sustainability. Atmospheric pollution can be reduced by adopting energy–efficient cropping systems which require less external inputs, thus providing an economically viable production choice for the future. Hence, alternate cropping systems with diversified crops as intercrops or cropping sequences enhance the cropping system resilience. The inclusion of maize, pulses and oilseeds in rice-fallows based on resource availability can substantially enhance system productivity and provide extra income in addition to soil fertility improvement (Kumar *et al.*, 2025). Besides right positioning of appropriate genotypes, the efforts to “keep time” through improved management of the annual cropping calendar can boost food security, profitability, and climate resilience both now and as a foundation for adaptation to progressive climate change (McDonald *et al.*, 2022). Short- to medium-duration STRVs can create new potentials for transforming rice-based systems through diversification, intensification, and optimization when combined with alternate crop establishment methods and scale-appropriate mechanization. Appropriate rice inbreds and hybrids of short- to medium-duration group can also create new potentials for transforming RBCS through diversification, intensification, and optimization when combined with alternate crop establishment methods and scale-appropriate mechanization (Sagwal *et al.*, 2022; Singh *et al.*, 2022b). As experienced with the Cereal Systems Initiative for South Asia (CSISA), timely rice establishment along with shorter-duration STRVs like Sahbhagi Dhan (115-120 days) allows better utilization of residual soil moisture for the succeeding crop and permit mustard planting in early October, followed by mungbean or maize in spring. This results in an increase in system level productivity by ~63% and system level net income by 88-122%, compared with the current practice of growing long-duration rice varieties followed by late planting of wheat (Singh, 2021). When combined with proper technological interventions and best management practices (BMPs), the introduction of *rabi* pulses (lentils, lathyrus, field pea, and chickpea) in rice-fallows under *paira* (*utera*) conditions with residual moisture conservation not only aids in the conversion of mono-cropped areas into double-cropping systems but also expands the opportunities for improving system productivity, soil health, and diet nutrition (Singh *et al*., 2020; Bhowmick *et al*., 2005 and 2015; Biswas and Bhowmick, 2015).

Mechanized sown maize under BMPs offers significantly higher net income compared to traditional methods like *beushening* or puddled transplanted rice (PTR), especially in regions with erratic monsoons and limited irrigation. Mechanized DSR in non-puddled conditions during the wet season, followed by diversified crops in the dry season, or rice-maize diversification with improved cultivars and tailored agronomy, presents emerging opportunities. Evidence from the CSISA project shows that *vattar* DSR followed by ZT wheat (ZTW) under BMPs increases yield gains by 2.69% in rice and 18.61% in timely sown wheat over the farmers' practice of PTR followed by conventional-till late sown wheat in the eastern IGP. DSRC experiments further highlight higher system productivity in *vattar* DSR-ZTW-ZT mungbean and ZT DSR-ZTW-ZT mungbean rotations under full conservation systems. This enables inclusion of a third short-duration crop like mungbean across alluvial plains of Bangladesh, eastern India, and eastern Nepal. In eastern India, rice-fallow areas can be intensified using residual soil moisture with pulses and oilseeds adapted through improved agronomy. In a study at IRRI South Asia Regional Centre (ISARC), DSR-ZTW systems with drip fertigation significantly enhanced sustainability and productivity compared to PTR-ZTW system, where $CH_4$ emissions were reduced by 70-80% and global warming potential reduced by 56%, despite higher $N_2O$ emissions. Besides, DSR-ZTW with subsurface drip fertigation recorded the highest system productivity (12.8 t $ha^{-1}$), minimized water losses, and improved nitrogen use efficiency. The study underscores the potential of integrating CA, drip fertigation, and DSR to enhance productivity, conserve resources, and improve the sustainability of RWCS (Reddy *et al*., 2025). To sustain rice-based agri-food systems in South Asia, a multi-pronged strategy involving crop diversification, fallow intensification, mechanization, value addition, and market access is essential (Pathak *et al*., 2019). Additionally, shifting from monoculture to rice-fish farming enhances soil fertility, microbial activity, labile carbon pools, and environmental sustainability, reinforcing the benefits of diversified and conservation-based farming systems.

**6. *Strengthening rice value chain and policy support :*** Nursery entrepreneurship in the rice value chain encompasses various business models that contribute to the development and supply of quality (healthy) seedlings to farmers. As evidenced from the District of Cooch Behar in West Bengal, the rice nursery enterprise (RNE) model can benefit both the entrepreneur and the farmer by opening up seasonal livelihood opportunities for rural youths and women farmers with a strong solution. RNEs ensure timely crop establishment by supplying healthy rice seedlings as and when required at an affordable price, addressing the critical situation of monsoon variability or even under normal weather conditions. It saves money and conserve resources as the entrepreneurs follow the BMPs for raising healthy seedlings in order to sustain their business reputation. They play a crucial role in ensuring the availability of healthy and high-yielding seedlings, thereby enhancing the productivity and resilience of rice farming. Appropriate business model can be implemented through individual entrepreneurs / Farmer Producer Companies (FPCs)/ Self-Help Groups (SHGs)/ Start-ups.

National and international research organizations play a pivotal role in advancing sustainable rice production through resource management, R&D, and credit access for smallholder farmers, guided by government policies aligned with development agendas and the Sustainable Development Goals (SDGs). IRRI prioritizes a holistic approach spanning crop planning to post-harvest, deploying improved genotypes, advanced technologies, best-bet practices, and scale-appropriate mechanization to strengthen resilience, productivity, and profitability of RBCS in fragile, stress-prone environments. IRRI also builds comprehensive farm household survey databases covering farm characteristics, household resources, rice yields, input use, labour, prices, income, demographics, perceptions on technological needs, adoption patterns, constraints, and impacts at the field level. Drawing on impact assessments, IRRI envisions future scenarios, policies, and strategies for rice-based agri-food systems, shaping forward-looking, market-driven, climate-resilient, and gender-responsive breeding profiles, production standards, technologies, and institutional innovations to ensure sustainable growth and food security.

**Conclusion**

Rice-based cropping systems remain indispensable to global food security, livelihoods, and cultural heritage, feeding billions across Asia, Africa, and Latin America. Yet, they are increasingly threatened by climate change, resource depletion, soil degradation, and stagnating yields. Rainfed systems are particularly vulnerable, as reliance on traditional varieties and suboptimal practices heightens risks. In South Asia, especially India, groundwater depletion, population pressure, and dependence on non-renewable inputs exacerbate sustainability challenges, while post-Green Revolution productivity has plateaued due to nutrient mining, pest resurgence, herbicide resistance, and declining soil organic matter. A transformation of RBCS demands integrated, climate-smart strategies. Resilient short- to medium-duration rice varieties (STRVs) provide yield stability and enable diversification with pulses, maize, oilseeds, and rice-fish farming, enhancing resilience, nutrition, and profitability. DSR conserves water and reduces emissions, while precision farming, conservation agriculture, and efficient irrigation improve productivity with lower ecological footprints. Sustainable residue management—via mechanization, composting, and biochar—restores soil health and farmer income, replacing destructive burning practices. In a holistic approach, regenerative agriculture increases qualitative gains in crop yields and production efficiency while sequestering carbon and strengthening ecosystem services, making it a powerful driver of climate change mitigation and long-term sustainability.

Beyond production, strengthening value chains through nursery entrepreneurship empowers rural youth and women, ensuring timely crop establishment and livelihoods. Supportive policies, research, and innovations from institutions of national and international repute are critical to align RBCS with the Sustainable Development Goals. Ultimately, resilient varieties, diversification, and robust policy frameworks can deliver higher efficiency gains, safeguard nutrition, and secure livelihoods—ensuring rice systems endure as a cornerstone of sustainable agriculture amid mounting global challenges.

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