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Rice-based cropping systems under conservation agriculture: Pathways to climate-resilient and sustainable agriculture

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Abstract
Rice is a staple food for over half of the global population, yet conventional rice farming practices-characterized by intensive tillage, monocropping, and high water use pose significant environmental and economic challenges, especially under the growing pressures of climate change. Conservation Agriculture, which emphasizes minimal soil disturbance, permanent soil cover, and diversified crop rotations, has emerged as a sustainable alternative to traditional methods. The objective of this study is to evaluate the potential of rice-based cropping systems under conservation agriculture to enhance climate resilience, resource-use efficiency and long-term agricultural sustainability. This assessment draws upon recent field trials, meta-analyses, and farmer-based case studies from South and Southeast Asia, focusing on practices such as direct-seeded rice, crop diversification, residue management, and water-saving irrigation techniques like alternate wetting and drying. Results indicate that rice-based conservation agriculture systems can reduce water use by up to 40%, lower greenhouse gas emissions (especially methane) by 30-70%, and improve soil organic carbon levels. Crop diversification and residue retention further contribute to yield stability and enhanced soil health. Economic analysis also reveals a reduction in input costs and improved net returns for smallholder farmers adopting CA-based practices.

Keywords: Conservation agriculture, climate resilience, sustainable farming, direct-seeded rice, soil health, water-use efficiency, crop diversification

1. Introduction

Rice-based cropping systems hold immense importance in ensuring global food security, as rice is the staple food for more than half of the world's population. These systems are particularly vital in Asia, where countries like India, China, Bangladesh, and Vietnam rely heavily on rice not only for daily consumption but also for economic stability and rural employment. Beyond rice alone, these systems often include the cultivation of crops such as wheat, maize, pulses, and vegetables in rotation or intercropping patterns, which contribute to food and nutritional security, soil fertility, and diversified farm incomes. Given the growing global population and rising demand for food, the sustainability and productivity of rice-based cropping systems are essential for addressing hunger, poverty, and malnutrition across many regions of the world.

However, rice-based systems are now increasingly vulnerable to the impacts of climate change. Unpredictable weather patterns, extreme climatic events like floods, droughts, and cyclones, as well as rising average temperatures, are posing serious threats to the stability and productivity of these systems. Climate-induced water scarcity, declining soil fertility, pest outbreaks, and increasing greenhouse gas emissions further compound the risks. Traditional rice cultivation practices, such as repeated tillage and continuous flooding, although effective in the past, are no longer sustainable under current environmental conditions. These methods contribute to soil degradation, increased water use, and the release of methane—a potent greenhouse gas—thereby accelerating the effects of climate change while simultaneously making the systems more vulnerable to it.

In this challenging scenario, conservation agriculture (CA) offers a promising pathway toward more resilient and sustainable rice-based cropping systems. Conservation agriculture is based on three key principles: minimal soil disturbance, permanent soil cover, and crop diversification.

When integrated into rice-based systems, these practices improve soil structure, enhance organic matter, reduce erosion, and increase the efficiency of water and nutrient use. Furthermore, CA can help mitigate greenhouse gas emissions and build system resilience against climate variability by improving soil health and enabling better moisture retention. Crop rotations involving legumes and other complementary crops also help in pest and disease management, reduce dependency on chemical inputs, and promote biodiversity. The adoption of conservation agriculture in rice-based systems therefore not only supports environmental sustainability but also enhances long-term productivity and profitability for farmers.

The scope of conservation agriculture in rice-based systems is particularly significant in regions where resource degradation and climate vulnerability are most pronounced. For instance, in the Indo-Gangetic Plains, where rice-wheat cropping systems dominate, CA practices such as zero tillage, residue retention, and the use of cover crops have already shown positive outcomes improving soil health, reducing water usage, and maintaining yields under climatic stress. In rainfed and upland rice systems, CA also plays a vital role by improving drought tolerance and enhancing ecosystem services. Moreover, the mechanization of CA practices, supported by research and extension services, has made their adoption increasingly feasible for smallholder farmers. With proper policy support, capacity building, and financial incentives, conservation agriculture can be widely scaled up to transform rice-based farming into a more climate-resilient and sustainable agricultural system.

In conclusion, the future of rice-based cropping systems lies in balancing productivity with sustainability. Climate change presents serious threats, but it also opens an opportunity to transition from conventional, input-intensive practices to more ecologically sound and resilient approaches. Conservation agriculture provides a scientifically validated and practically viable solution for addressing the pressing challenges of climate change, environmental degradation, and food insecurity. By embedding CA principles into rice-based systems, we can ensure not only the long-term viability of rice production but also safeguard the livelihoods of millions of farmers and the food security of future generations.

2. Rice-Based Cropping Systems: An Overview

Rice-based cropping systems form the backbone of food production in many parts of the world, especially in Asia, where rice is a staple food for billions. These systems involve the cultivation of rice as a primary crop, either in monoculture or in rotation or intercropping with other crops such as wheat, maize, pulses, vegetables or oilseeds. The diversity of rice-based systems is shaped by a combination of climatic conditions, soil types, irrigation availability, socio-economic factors and traditional practices. As global challenges like climate change, land degradation and population pressure intensify, rice-based cropping systems are undergoing significant transformation, demanding more sustainable and resilient approaches. Globally, some of the most common rice-based cropping patterns include rice-wheat, rice-maize, rice-rice, rice-legume, and rice-fallow systems. Each of these systems is tailored to specific agro-ecological regions.

Over the years, scientists and researchers have emphasized the need to improve the productivity and sustainability of rice-based systems. The Green Revolution initially led to massive gains in rice production, particularly in Asia. However, those gains came with unintended consequences such as resource overuse, environmental degradation, and soil health decline. A review of scientific literature reveals that rice-based cropping patterns vary significantly across regions due to differences in climate, water availability, soil types, cultural practices, and market demand. According to Timsina and Connor (2001), the rice-wheat system is one of the most extensively studied and practiced rice-based cropping systems in the Indo-Gangetic Plains (IGP) of India, Nepal, Pakistan, and Bangladesh. It covers over 13.5 million hectares and supports the food security of over 400 million people. While it has been highly productive, researchers such as Ladha *et al*. (2003) [9] have highlighted issues such as declining soil fertility, groundwater depletion, and stagnating yields due to intensive tillage and high input use. Conservation agriculture, particularly zero tillage in wheat and residue retention from rice, has shown promise in reversing these trends. Kumar and Ladha (2011) [5] reported that rice-maize systems are gaining prominence, particularly in Southeast Asian countries like the Philippines, Vietnam, and Indonesia, as well as parts of Latin America, due to maize's higher economic return and better adaptation to dry seasons. This system is typically followed in irrigated and favorable rainfed lowland areas. Researchers emphasize the need for efficient nutrient and water management in this system, as maize is more sensitive to soil moisture and nutrient deficiencies than rice. Pingali *et al*. (1997) documented that double rice cropping, or rice-rice systems, are common in irrigated areas of countries such as China, Vietnam, and southern India. These systems are characterized by high cropping intensity but also face challenges such as increased pest and disease pressure, soil fatigue, and high water use. Cassman *et al*. (1996) emphasized that maintaining yield levels in rice-rice systems requires integrated nutrient management and improved varietal selection. Rao and Mathur (2005) observed that rice-legume systems, including rice-pulse (e.g., mungbean, chickpea, lentil) combinations, are common in both irrigated and rainfed ecosystems in South Asia. These systems help in improving soil nitrogen through biological fixation and breaking pest cycles. In Sub-Saharan Africa, rice-cowpea rotations are important in upland and lowland areas. Studies (e.g., Becker and Johnson, 2001) have shown that these systems contribute to improved soil fertility and food diversity for smallholders. In Eastern India and parts of Bangladesh, rice-fallow systems are widespread, where the land remains fallow after the monsoon rice crop due to limited irrigation, poor soil conditions, or socio-economic constraints. According to Saharawat *et al*. (2010), this represents a significant opportunity for sustainable intensification through short-duration pulses or oilseeds during the fallow period. Technologies such as zero tillage and drought-tolerant crop varieties have been recommended to improve land use efficiency. Upland rice is cultivated in rainfed, sloping, and non-irrigated terrains, especially in parts of Sub-Saharan Africa, Latin America, and upland Southeast Asia. As noted by Fageria *et al*. (1997), these systems are generally low-yielding due to poor soils and high susceptibility to drought and erosion. Scientists stress the need for erosion control measures, organic amendments, and stress-tolerant rice varieties to improve productivity in these systems. Studies by Pandey *et al*. (2012) [12] revealed that long-term tillage practices diminish soil organic carbon and total nitrogen leading to reduced rice yields under no-till or minimal tillage in some cases due to compaction and accumulation of harmful substances.

Moreover, residue burning remains widespread in conventional systems. Meena *et al*. (2022) [11] reported that burning rice residues causes substantial loss of nutrients virtually eliminating carbon and nitrogen and heavily reducing phosphorus, potassium, and sulfur content while significantly degrading air

quality. This practice negatively impacts both environmental health and soil fertility.
There is a consensus among researchers like Hobbs and Gupta (2003) [3] that conservation agriculture practices such as minimum tillage, residue management, and crop diversification offer a pathway to sustain productivity and environmental health across various rice-based systems. Future research and policy support should aim to customize these practices regionally, considering specific challenges and opportunities within each cropping pattern.

3. Principles of Conservation Agriculture

Conservation Agriculture (CA) is a sustainable farming system grounded in the principle of working with, rather than against, natural processes. The concept was developed in response to the degradation of soil, water, and biodiversity under conventional agricultural systems, particularly those relying on intensive tillage, monocropping, and residue removal. Minimizing soil disturbance is the foundational pillar of CA.
Research by Hobbs, Sayre and Gupta (2008) [3] demonstrated that zero tillage improves soil structure, conserves moisture, and reduces input costs in rice-wheat systems in South Asia. Reduced disturbance also promotes carbon sequestration and helps mitigate greenhouse gas emissions. Maintaining a permanent soil cover using crop residues or cover crops protects the soil against erosion, suppresses weeds, moderates soil temperature, and supports the development of soil biota. Studies by Govaerts, Sayre and Deckers (2005) [10] in maize-wheat systems of Mexico showed that mulching improves water infiltration, enhances microbial biomass, and promotes nutrient cycling. Furthermore, residues serve as a slow-release nutrient source, contributing to long-term soil fertility and carbon storage. Diversification through rotation of cereals with legumes, oilseeds, or vegetables breaks pest and disease cycles, enhances soil nutrient balance, and stabilizes yields under climate variability. Lal (2004) [7] emphasized that crop rotation improves biological nitrogen fixation, reduces pressure on single crops, and improves resilience to climate extremes. In rice-based systems, rotating with legumes like mungbean or lentils can significantly enhance soil nitrogen levels and reduce the need for synthetic fertilizers. Das, *et al*. (2024) [1] demonstrated that, in Indo-Gangetic Plains (IGP) rice-wheat-mung bean systems, adopting zero-till direct-seeded rice with full residue retention increased total soil organic carbon (SOC) stock by up to 26.5% compared to conventional systems. Numerous long-term studies and global experiences confirm that CA can effectively address the ecological limitations of conventional agriculture and serve as a foundation for climate-smart and resource-efficient farming.

4. Integration of CA in Rice-Based Cropping Systems

The integration of Conservation Agriculture principles into rice-based cropping systems presents a transformative pathway toward sustainable intensification, especially in the face of climate change, resource degradation, and declining productivity in conventional systems. Rice cultivation is traditionally water- and energy-intensive due to practices such as puddling and continuous flooding. CA technologies such as direct-seeded rice (DSR), non-puddled transplanting, and residue retention have shown significant benefits in reducing irrigation demand and fuel use. Islam *et al*. (2023) [4] found that CA practices restored potassium balance in intensive rice systems while reducing tillage frequency and enhancing nutrient retention. Dutta *et al*. (2023) [2] observed that zero tillage with full residue retention and diversified rotations enhanced soil enzyme activity (β-D-glucosidase), carbon sequestration, and net returns compared to conventional tillage with residue burning. Kumar *et al*. (2024) [6] reported that rice-wheat-greengram systems under CA supported higher fungal operational taxonomic unit (OTU) richness and diversity than conventionally managed fields, indicating more robust soil biological health. The integration of Conservation Agriculture into rice-based cropping systems is scientifically validated to improve soil health, resource-use efficiency, biodiversity, and system resilience, while also sustaining or enhancing yields. It offers a sustainable alternative to conventional practices and a pathway toward climate-smart agriculture. Widespread adoption, however, depends on region-specific adaptation, access to machinery (e.g., zero-till seeders), farmer training, and supportive policy frameworks.

5. Climate Resilience through Conservation Agriculture (CA)

Conservation Agriculture through its core principles of minimum soil disturbance, permanent organic soil cover, and diversified rotations plays a vital role in enhancing the climate resilience of rice-based cropping systems. Scientific studies increasingly demonstrate that CA helps stabilize yields, improve resource efficiency, and bolster resistance to climatic stressors.
A long-term study in Northwest India assessed CA scenarios such as zero-till direct-seeded rice, maize-wheat-mungbean systems, and subsurface drip irrigation. Compared to conventional rice-wheat systems, CA setups achieved 27% higher wheat yields, 12% higher rice-equivalent yields, and a 35% increase in overall system productivity. Additionally, bulk density decreased and water infiltration improved (~99% in some scenarios), with soil organic carbon rising by 69-83%, indicating stronger resilience under stress.
South Asia's rice-wheat systems concluded that CA practices such as direct seeding, zero tillage, and residue retention enhance ecosystem health, water productivity, nutrient efficiency, and yield stability. Furthermore, CA contributes to mitigation of greenhouse gases and climate-change adaptation.
The Indo-Gangetic Plains long-term trial (2009-2016) comparing conventional and CA cropping scenarios revealed that full CA (rice-wheat-legume with no-till and residue retention) increased total organic carbon (TOC) stocks by 14.6% over conventional practices, while also sustaining higher rice-equivalent yields.
Over 3 to 5 years at sites in the Indo-Gangetic Plains, CA practices like zero tillage and raised bed systems showed measurable gains in soil carbon stocks, particularly coarse particulate organic matter a key early indicator of soil carbon accumulation and improved crop productivity.

6. Future Research and Development Priorities

Despite strong evidence supporting the ecological and economic benefits of Conservation Agriculture (CA) in rice-based cropping systems, several knowledge gaps and operational challenges persist that limit its widespread adoption. Addressing these gaps through targeted research and development (R&D) is essential to enhance the adaptability, scalability, and impact of CA under diverse agro-climatic and socio-economic contexts. Below are key future research and development priorities:

Location-Specific Adaptation of CA Practices

Most CA recommendations are generalized, but rice-growing regions vary significantly in terms of climate, soil type, water availability, and socio-economic conditions. Future research must:

- Develop agro-ecology-specific CA models (e.g., rainfed uplands, irrigated lowlands, coastal areas).
- Optimize non-puddled transplanting and direct-seeded rice (DSR) techniques suited for different rice ecologies.

Crop Diversification and System Intensification

There is a need to design site-appropriate diversified cropping sequences that integrate legumes, pulses, oilseeds, and vegetables to enhance soil fertility, break pest/disease cycles, and improve incomes. Priority areas include:

- Evaluating rice-legume-vegetable rotations for nutrient use efficiency and carbon sequestration.
- Identifying short-duration, climate-resilient crop varieties that fit within intensified cropping calendars.

Soil Health, Microbial Dynamics, and Carbon Sequestration

Understanding the long-term effects of CA on soil biological indicators and carbon pools under rice-based systems is crucial. Future research should:

- Employ advanced molecular tools (e.g., metagenomics) to study soil microbial diversity and function.
- Quantify carbon sequestration rates under CA versus conventional tillage across different regions.

Precision Agriculture and Digital Technologies in CA

Technological innovations can significantly enhance CA adoption. Future efforts should focus on:

- Developing low-cost, sensor-based tools for moisture and nutrient monitoring.
- Leveraging AI, machine learning, and remote sensing for real-time decision-making in CA-based rice systems.

Mechanization and Equipment Development

Adoption of CA in smallholder rice systems often faces constraints due to a lack of suitable equipment. Future R&D must:

- Innovate and disseminate affordable, lightweight, multi-functional CA machinery (e.g., zero-till seeders, residue managers) tailored to smallholder conditions.
- Evaluate custom hiring models and machinery cooperatives for resource-poor farmers.

Climate Change Mitigation and Adaptation Studies

As rice is a major contributor to methane emissions, research is needed on:

- Comparing GHG emissions across different CA scenarios (e.g., DSR vs. puddled transplanting).
- Developing climate-resilient CA packages that integrate water-saving, residue management, and carbon credit schemes.

Long-Term Monitoring and Data Integration

To support evidence-based decision-making, future R&D should:

- Establish long-term experimental sites and on-farm trials to track productivity, profitability, and sustainability outcomes.
- Create open-access databases integrating agronomic, economic, and environmental data for policy and extension planning.

Socio-Economic and Policy Research

Technology alone does not guarantee adoption. Understanding the human dimension is vital. Key areas for research include:

- Identifying barriers and enablers of CA adoption among smallholders, women farmers, and marginal communities.
- Assessing the impacts of subsidies, incentives, and carbon markets on adoption behavior.

7. Conclusions and Way Forward

Rice-based cropping systems are central to global food security, particularly in Asia, where they form the backbone of rural livelihoods and nutrition. However, conventional practices such as intensive tillage, puddling, monocropping, and residue burning have led to severe degradation of soil health, inefficient use of water and nutrients, increased greenhouse gas emissions, and reduced system resilience. These challenges are exacerbated under current and projected climate change scenarios.

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