Review Article

Crop diversification with pulses for enhancing soil nutrient dynamics in conservation agriculture

Abstract

Cultivating rice and wheat continuously in the Indo-Gangetic plains (IGPs) has led to soil and environmental issues. Diversifying cropping systems with pulses is vital for sustainable resource use efficiency. Utilizing extensive rice fallow regions for pulse cultivation could expand by 1.0 M ha in the IGPs. Integration of pulses enhances soil fertility, water productivity, and reduces input costs, diseases, and pests, while their nitrogen-fixing ability and nutrient-rich residues contribute to soil health and nutrient cycling. This review emphasizes the importance of integrating pulses in conservation agriculture, focusing on nitrogen economy, nutrient recycling, and the broader benefits of pulse crops for sustainable agricultural practices.

Keywords: Conservation agriculture, Nitrogen economy, Productivity, Pulses

Introduction

The Indo-Gangetic Plains (IGPs) of South Asia, represent a highly fertile and productive area supporting approximately one-seventh of the global population. In the IGPs, rice and wheat are the predominant crops cultivated over an extensive area covering 13.5 million hectares. Additionally, maize, sugarcane, and cotton are other major crops grown in this area. The rice-wheat (RW) production system holds significant importance in ensuring food security within this region [1]. However, there are emerging concerns known as second-generation problems, including declining factor productivity, stagnant crop yields, reduction in soil organic matter (SOM), lowering groundwater levels, diminishing farm profits, and environmental degradation. These issues are largely attributed to the intensive conventional production systems [2]. In response to these challenges, there is a growing need to prioritize sustainability and adopt conservation agriculture (CA) practices within intensive production systems. CA technology has been globally practiced for six to seven decades and has shown benefits for both agriculture and the environment wherever it has been adopted [3]. Nevertheless, CA involves complex and sometimes overlooked factors that contribute to soil quality, productivity, and ecosystem services [4]. The ill effects of continuous cereal cultivation in CA were not evident in the beginning as the soil had an adequate reserve of plant nutrients. Over time, continuous cultivation of rice-wheat and maize-wheat (cereal-based) cropping systems has resulted in depletion of soil nutrients [5]. These challenges can be addressed by transitioning cereal-based cropping areas to diversified systems involving crop rotation, particularly by introducing pulses.

Integration of Pulses in Conservation Agriculture

The production of pulses has failed to keep pace with the rising demand, resulting in a widening disparity between demand and supply. Consequently, there has been a significant decrease in per capita net availability of pulses over recent years [6]. Despite India accounting for 25% of global pulse production, its contribution to total food grain production has declined from 16% in 1950 to 8% in 2022-23. Despite India's significant share of global pulse production (25%), its contribution to total food grain production has decreased from 16% in 1950 to 8% in 2022–

23, indicating a significant demand-supply gap. India is projected to produce 26 million tonnes of pulses by 2026, but to meet demand by 2050, an annual expansion of 2.2% is necessary [7]. The most promising technologies in pulse production encompass improved crop establishment and management practices, as well as integrated soil fertility. These advancements not only boost productivity and profitability but also ensure environmental and social sustainability, alongside enhancing nutritional security [8]. Therefore, integrating pulses into Conservation Agriculture (CA) systems shows considerable potential, given their positive impact on soil health and carbon sequestration. Pulse crop residues, including foliar and root residues, serve as organic material, enriching soil biota and promoting carbon sequestration [9]. Pulse cropping systems within CA frameworks can augment soil nitrogen (N) levels by harnessing the natural ability of pulses to fix atmospheric N in their root nodules through symbiosis with *Rhizobium* bacteria. The fixation process not only increases soil organic matter content but also helps to mitigate erosion [10]. Pulses can fix approximately 1.0–1.5 metric tons N ha^{-1}, reducing the need for industrial N production, which contributes to greenhouse gas (GHG) emissions [11]. Additionally, integrating pulses into crop rotations enhances root zone cation exchange capacity, accelerates crop biomass production, facilitates nutrient recycling, and promotes soil porosity. Thus, recognized as a key component of Resource Conserving Technologies (RCTs) [12-13]. Incorporating pulses into production systems aligns with the fundamental principles of CA, including minimal soil disturbance, maintaining permanent soil cover and implementing crop diversification.

Some of the values associated with pulses as part of RCTs include:

Low water consumption in pulse production

Pulse crops have a lower water demand compared to cereals. Worldwide, cereals are estimated to utilize around 60% of water resources, whereas pulses only account for about 4% [14]. Pulses efficiently utilize water through their morphological and physiological traits, including deep root systems that enable moisture access from deeper soil layers and allowing them to thrive in dryland conditions [15]. For instance, the water productivity of chickpea is approximately 12.5 kg grain ha-mm^{-1} of water surpassing the grain yields of wheat (7 kg) and rice (2.5 kg) per the same water input [16]. The CA-based rice-wheat-mungbean system improved system productivity with 28% less irrigation water (2650 mm ha^{-1}) compared to conventional RW systems/farmers' practices [17].

Reduced tillage operation

Pulse crops thrive without requiring a finely prepared seedbed as they exhibit optimal growth on coarse seedbeds with adequate aeration [18]. Pulses such as lentils, lathyrus, urdbean, and mungbean are suitable for surface broadcasting in rice fallow areas.

Pulses as cover crops: Enhancing sustainability

Soil erosion from both agricultural and non-agricultural lands presents a significant global challenge. More than half of water erosion and approximately 60% of wind erosion occur on croplands responsible for producing a majority of the world's food [19]. The varying abilities of different crops to maintain soil cover necessitates the importance of implementing suitable crop rotation practices to mitigate erosion. Hence, cover crops are essential in agroecosystems, managing soil fertility, quality, water retention, weed control, pest and disease mitigation, as they contribute to sustainable agriculture by enhancing agroecosystems and potentially benefiting adjacent natural ecosystems [20]. Several pulse crops like grams, peas and beans possess dense canopies, thereby shielding the soil surface from the impact of raindrops and minimizing splash erosion [21]. Additionally, pulse crops such as pigeon pea and moth bean contribute to reducing wind erosion. Selection and management of cover crop varieties are influenced by biological, environmental, social, cultural, and economic factors within the food system [22]. Short-duration pulse crops such as cowpea, green gram, black gram and horse gram quickly develop dense canopies, providing effective soil cover, which helps to mitigate water erosion, enhances soil infiltration, reduces runoff and suppresses weed growth [23].

Crop diversification and intensification with pulses

The diversification of agricultural production systems is imperative for ensuring stable farm income and promoting employment opportunities within the agricultural sector. Pulse crops, due to their short growth duration and resilience to adverse climatic conditions, play a crucial role in crop diversification. There are four potential avenues for diversification of cropping systems through the inclusion of pulses: integrating short-duration pulse varieties as catch crops in irrigated regions, exploring new niches for pulse cultivation, replacing low-yielding crops in existing systems with pulses, and incorporating pulses as intercrops with wide-spaced planted crops or as relay crops [24]. The pulse-based cropping systems and varieties suitable for different agroecosystems increase the overall system productivity as detailed (Table 1). To sustain the viability of intensive cropping systems over the long term, there has been a significant increase in diversifying cereals, oilseeds, and other cash crops such as cotton and sugarcane with pulses, driven by the soil-enhancing properties of pulses and their reduced reliance on external nitrogen sources [25].

Table 1. Important pulse based cropping systems in cultivation with suitable varieties [26]

Pulse based systems	Growing areas	Varieties
Rice-wheat-mungbean	Western U.P., Haryana, Punjab	Pant Mung 2, PDM 139, Narendra Mung 1, HUM 2
Rice-mungbean	Orissa, Parts of Karnataka, Tamil Nadu, A.P.	TARM 1 and Pusa 9072
Rice-urdbean	Coastal areas of A.P., Karnataka, Tamil Nadu	LBG 17 and LBG 402
Maize-potato-mung bean/urd bean Maize-mustard+ mungbean/urdbean	Punjab, Haryana and West U.P.	Mungbean: Pant Mung 2, HUM 2, PDM 11, SML 668, Pusa Vishal Urdbean: PDU 1, Uttara, Narendra Urd 1
Pigeonpea-wheat	Haryana, Punjab, North West U.P. and North Rajasthan	UPAS 120, Pusa 33, Manak, AL 15 and AL 201
Cotton + pigeon pea	MP, AP, Maharashtra, Gujarat, Karnataka, and Telangana	UPAS 120, Pusa 33, Manak
Maize-rajma-mungbean	Central U.P. and Bihar	Rajma: HUR 137, HUR 15, PDR 14, Amber Mungbean: Pant Mung 2, PDM 11, HUM 2
Spring sugarcane+ mungbean/urdbean	East U.P., Bihar, West Bengal	Mungbean: Pant Mung 2, PDM 11, Narendra Mung 1 Urdbean: PDU 1, Pant Urd 19,

Enhancing soil health through pulse cultivation

Pulses offer several soil health advantages, including increasing soil organic matter, improvement of soil porosity, nutrient recycling, enhancement of soil structure, reduction of soil pH, diversification of soil microorganisms, suppression of disease buildup, and mitigation of weed issues typically associated with grass-type crops. As most crop residues are rich in carbon relative to nitrogen, the nitrogen provided by pulses aids in the breakdown of crop residues and their conversion into organic matter, thereby enriching the soil [27]. CA-based rice/maize-wheat-mungbean increased soil organic carbon by 65–70% over conventional rice-wheat cultivation [28]. Additionally, the incorporation of urdbean and mungbean residues led to a 35.48% increase in organic carbon content compared to the control and other cropping systems as depicted (**Figure 1**).

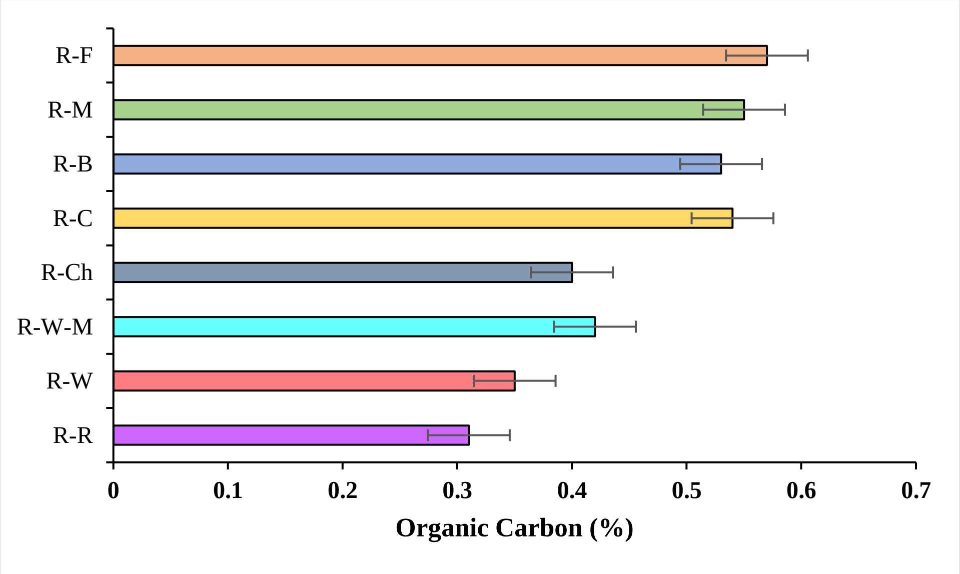

Figure 1. Enhancing the organic carbon through inclusion of pulses in the cropping system

*R-R: Rice-Rice; R-W: Rice-Wheat; R-W-M: Rice-Wheat-Mung bean; R-Ch: Rice-Chick pea; R-C: Rice-Cowpea; R-B: Rice-Black gram; R-M: Rice-Mung bean, R-F: Rice-Field bean [29-30].

Pulses also promote greater diversity between soil flora and fauna, stimulate increased biomass production in the soil by providing additional N, which soil microbes utilize to decompose carbon-rich residues of crops. Pulses enhance various physical properties like soil aggregates [31], pore space, bulk density [32] and chemical properties *viz*., organic carbon, pH, and other nutrients availability as detailed (**Table 2**). They also improve biological properties such as soil biota population, efficiency, and synergy, soil microbial biomass carbon aspects of soil [11, 33–35].

Table 2. Post-harvest nutrient status of soil under different cropping system [36]

Treatments	**Avail. N (kg/ha)**	**Avail. P_2O_5 (kg/ha)**	**Avail. K_2O (kg/ha)**
R-W	258.9c	18.1c	222.9c
R-Ch	272.5b	20.7ab	237.9b
R-W-M	286.3a	21.1a	262.2a

*R-W: Rice-Wheat, R-Ch: Rice-Chickpea, R-W-M: Rice-Wheat-Mung bean

Beneficial role of deep root systems in pulses

Most of the pulses possess taproots that can extend up to 6 to 8 feet deep and measure half an inch in diameter, creating pathways that penetrate deep into the soil. The nitrogen-rich residues left behind by pulses foster the presence of earthworms and the formation of burrows. These root channels and earthworm burrows facilitate air circulation and the infiltration of water deep into the soil, enhancing soil porosity. Therefore, enhancement of soil structure is attributed to the formation of more stable soil aggregates, facilitated by proteins like glomalin produced symbiotically with the roots of pulses [33]. These proteins act as a binding agent, promoting the formation of stable soil aggregates, which in turn increases pore space and soil tilth, ultimately reducing erodibility and soil crusting. Additionally, the deep root systems of most pulse crops enable them to access nutrients and moisture from deeper soil layers, with the roots of pigeon pea exhibiting exceptional strength capable of penetrating even hard soil pans through their robust growth [37].

Significance of biological nitrogen fixation in pulses

Pulses are notably rich in protein, a trait directly linked to their ability to fulfil a significant portion of their nitrogen (N) requirements through symbiotic relationships with rhizobia bacteria residing in their roots. When properly inoculated with suitable strains of rhizobia bacteria, pulses can independently supply up to 90% of their N requirement [38]. Depending on various factors such as rhizobia population, host crop and variety, management practices, and environmental conditions, they can fix N ranging from 30 to 150 kg ha^{-1} [39]. The widely acknowledged N-saving and synergistic effects of pulses, due to their inherent N-fixing ability, optimize N utilization in subsequent non-legume crops. Different pulse crops exhibit varying capacities for N fixation, in sequential cropping systems involving pulses, the preceding pulse crop may contribute between 18–70 kg N ha^{-1} to the soil, supplying a significant amount of N to succeeding crops. In the rice-wheat system, cultivating short-duration legumes like mungbean during the summer and incorporating their residues after harvest can lead to additional yields of approximately 600–700 kg ha^{-1} for rice and 500–700 kg ha^{-1} for wheat [40]. Furthermore, this practice enhances nitrogen efficiency by 40–60 kg ha^{-1}.

Optimising nitrogen through pulses

A study conducted at IIPR, Kanpur [41], investigated the impact of *kharif*, *rabi*, and summer season pulses on the productivity and nitrogen economy of subsequent cereal crops. The findings revealed that among the *kharif* pulse-based cropping systems, the soybean-wheat system exhibited the highest productivity, followed by the pigeonpea-wheat system. Preceding pigeon pea cultivation over sorghum resulted in a nitrogen economy equivalent to 51 kg N ha^{-1}. Regarding *rabi* pulses influence on productivity and nitrogen economy in succeeding rice crops, chickpea, rajma, and lentil were found to have the most favorable effects, economizing N by approximately 40 kg ha^{-1} and further N and energy saving with the inclusion of pulses in the cereal-based system as presented (**Table 3**).

Table 3. Nitrogen and energy savings through integrating pulses in cereal-based systems [42]

Main cereal crop	Pulse crop	N savings (Fertilizer equivalent kg ha^{-1})	Energy saved (10^6J ha^{-1})*
Rice	Chickpea	40–45	2575
	Mung bean	40	2424
	Cowpea	40	2424
Wheat	Pigeon pea	35–40	2272
	Mung bean	30	1818
	Cowpea	43	2605

Maize	Chickpea	60–70	3939
	Pigeon pea	20–49	2696
	Lentil	30	1818
	Lathyrus	36–48	2545
	Peas	20–32	1575

*Conversion factor for N to energy used was 60.6 MJ kg^{-1} N ha^{-1}

Additionally, an enhancement in the nitrogen budget of the soil, as indicated by the residual NO_3-N content post-harvest of *rabi* pulses, was observed. Chickpea exhibited the highest contribution to residual NO_3 in the soil profile, followed by field pea and lentil. Among the genotypes studied, chickpea cv. BG 1003, lentil cv. DPL-62, and field pea cv. Rachana demonstrated the greatest capacity to increase nitrate content in the soil [43].

Nutrient recycling capacity of pulses

Pulses, as deep-rooted crops, efficiently recycle nutrients deep within the soil profile, reducing nutrient losses beyond the root zone of shallow-rooted crops in crop rotations, while their symbiotic association with *Vesicular Arbuscular Mycorrhizae* (VAM) enhances nutrient and water availability to crop plants. Pulses contribute to soil organic matter (OM) through leaf litter, root biomass, and readily degradable crop residues, while also releasing organic acids into the soil to facilitate the mobilization of unavailable soil nutrients [29], thus holding significant potential for enriching soil organic matter through residue recycling. Upon incorporation into the soil, organic materials undergo extensive biodegradation facilitated by soil biota, including earthworms, bacteria, fungi, actinomycetes, and protozoa, with microbial decomposition and mineralization processes being further enhanced when chopped residues are incorporated followed by irrigation.

Incorporating residues also increased soil availability of N, P and K by 24.6%, 11.5% and 18.5% respectively, over initial fertility levels [30]. In a rice-chickpea cropping sequence, chickpea yield significantly increased with the incorporation of rice residues, particularly when chopped straw was used followed by irrigation, whereas, removing rice residues resulted in the lowest yield. Similarly, incorporating chopped mungbean residues followed by irrigation led to a 38% increase in wheat yield compared to the control. Furthermore, the incorporation of urd bean and mungbean residues positively affected soil microbial biomass carbon levels [43].

Diverse benefits of pulses beyond nitrogen

Incorporating legumes into cropping systems not only optimizes nitrogen (N) utilization but also enhances the efficient utilization of native phosphorus, facilitated by the secretion of specific acids that aid in the solubilization of various forms of phosphorus. This ability of legumes enables them to effectively access phosphorus in different forms present in the soil. The increased availability of phosphorus is attributed to the acquisition of phosphorus from insoluble phosphates through the release of root exudates [44]. For instance, chickpea exhibits the capability to access phosphorus that is typically inaccessible to other crops by mobilizing sparingly soluble calcium phosphate through the acidification of the rhizosphere *via* citric acid root exudation, particularly in Vertisols. Similarly, in Alfisols, pigeon pea has been identified for their capacity to dissolve iron phosphate [14]. A study conducted at IIPR, Kanpur, demonstrated that incorporating mungbean stover into the rice-wheat system after pod picking significantly enhanced the soil's available P content, attributed to the secretion of root exudates capable of mobilizing sparingly soluble phosphorus. *Rabi* pulses were found to contribute 3–5 kg P and 8–20 kg K ha^{-1}, while pigeon pea contributed 2.5–5.0 kg and 13.5–24.0 kg of P and

K respectively ha^{-1} through leaf litter during the crop growth period [25]. The leaf-shedding nature, a distinctive characteristic of pulses, contributes significantly to soil enrichment (**Table 4**).

Table 4. Nutrient contribution through leaf litter quantity by various pulse crops [44-47]

Characters (kg/ha)	Chickpea	Lentil	Pigeon pea	Mungbean	Urdbean
Leaf litter	1100–1700	1300–1600	1300–2800	873–1048	850–1024
Nitrogen	7–14	8–10	8–16	25.6–36.8	25.1–48.5
Phosphorous	3–5.5	3.5–4.5	2.5–5	2.2–4.8	1.7–3.2
Potassium	8–20	12.5–19	13.5–24	32–37	3.5–9.5

Various pulse crops exhibit substantial leaf fall, resulting in the deposition of leaf litter onto the soil. As these leaves decompose, they release nutrients, thereby enhancing soil fertility [45, 48]. Regular incorporation of cowpea, and mungbean as green manuring enhances the availability of micronutrients such as zinc, iron, manganese, and copper in the soil compared to summer fallows [49].

Reducing nitrate pollution and Green House Gases (GHGs)

The contamination of groundwater due to nitrate leaching is a relatively recent concern in India, yet adopting suitable cropping systems and management practices can mitigate nitrate leaching while also enhancing nitrogen use efficiency, as intercropping legumes with cereals in wider row configurations has shown to reduce nitrate leaching [50]. Additionally, employing parallel multiple cropping, which involves cultivating two dissimilar crops with minimal competition, such as sugarcane with urd bean or pigeon pea with maize, has been found to result in lower nitrate nitrogen levels in the soil profile compared to sole cropping [17]. In India, the agricultural sector contributes approximately 22% of total GHGs, primarily from methane emissions from rice fields and enteric fermentation in ruminants, as well as nitrous oxide emissions from the use of nitrogen fertilizers. However, pulses play a significant role in mitigating GHGs emissions due to their capacity for carbon sequestration, biological nitrogen fixation, and resilience in adverse climate conditions[51]. CA-based rice-wheat-mungbean systems improved system productivity by a reduction in the global warming potential by 23% (1.5 Mg CO_2 eq yr^{-1}) [17].

Pulses improve productivity and net returns

The sustainability of cereal-based cropping systems is crucial for ensuring food security, yet the long-term productivity of cereal-cereal rotations has shown a decline, emphasizing the need for sustainable alternatives. In evaluating different long-term crop rotations, the productivity of the base crop, which is the common crop in various rotations, can serve as a crucial indicator of sustainability. A study assessed the impact of incorporating pulses into lowland rice-wheat (R-W) and upland maize-wheat (M-W) rotations on the productivity and profitability of the system base crop. The positive effect of legume inclusion in the R-W system on rice crop productivity (**Figure 2**). The inclusion of mung bean in the R-W rotation led to a significant increase in rice grain yield by 10-14%. Similarly, in upland areas, incorporating mung bean into the M-W rotation resulted in a 5-11% enhancement in wheat grain yield. Substituting wheat with chickpea in the R-W rotation also contributed to a 5-8% increase in rice grain yield [51]. Incorporating pulse crops into cereal systems (RW/MW) resulted in a system productivity of 18% and 15% in net returns[53,42]. CA-based rice-wheat-mungbean systems improved system productivity by 11% (12.3 Mg ha^{-1}) and profitability by 24% (85,800 ha^{-1}) compared to conventional RW systems [17].

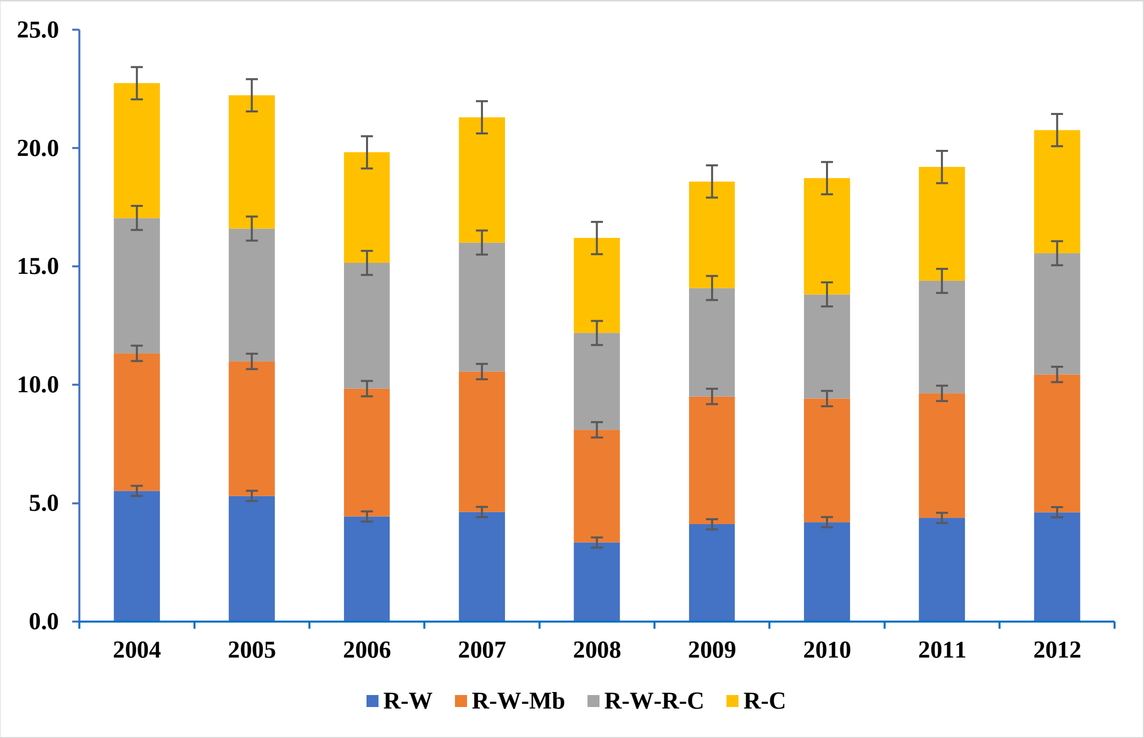

Figure 2. Rice grain yield over the long term as influenced by different crop rotation treatments. The error bar represents standard error of the mean.

R-W: Rice-Wheat; R-W-M: Rice-Wheat-Mung bean; R-W-R-C: Rice-wheat, Rice-cowpea; R-C: Rice-Chick pea [Modified from 52].

Technological interventions to overcome production challenges [8, 34]

1. Promotion and adoption of short-duration, disease, and pest-resistant high-yielding legume cultivars suitable for intensive cropping systems
2. Addressing physiological and genetic attributes such as low harvest index, flower drop, indeterminate growth habit, and poor response to fertilizers and water in most grain legumes
3. Critical attention to phosphorus deficiency in pulse-growing soil areas, emphasizing the need for phosphorus management in pulse production systems
4. Diversification of pulse crops to non-traditional areas like rice fallows in central and eastern parts of the country, including Bihar, Madhya Pradesh, Chhattisgarh, Odisha, eastern Uttar Pradesh, and West Bengal
5. Introduction of short-duration pigeonpea varieties in irrigated cropping systems in northern and central India, aligning with wheat cultivation.
6. Cultivation of summer pulses (black gram, green gram, cowpea) in irrigated areas following the harvest of *rabi* crops.
7. Utilization of existing rice fallows in the eastern Indo-Gangetic Plains (IGPs) by growing chickpea, lentil, and khesari (lathyrus) after rice cultivation.

8. Replacement of high-water-demand crops with low-water-intensive pulses in command areas to ensure irrigation water availability at critical crop growth stages through effective water scheduling.
9. Adoption of relay cropping techniques in standing rice, transitioning towards direct seeding methods such as zero-till drills or turbo-type Happy Seed drills in Conservation agriculture.

Conclusion

Pulses are crucial for diversifying crops within Conservation Agriculture (CA), enhancing sustainability in cereal-based cropping systems. CA-based systems conserve resources, reduce cultivation costs, promote timely planting, and mitigate environmental pollution. With limited room for expanding cultivable land, production can be amplified through CA-based intensification. Integrating pulses into cereal-based cropping systems offers promising solutions to agricultural challenges in the Indo-Gangetic Plains (IGPs) as it increases cropping intensity and productivity per hectare through enhancing resilience to climate change, improving soil health, crop productivity, and overall sustainability. Improved crop management practices and the adoption of pulses in CA are essential for sustaining pulse production in India.

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