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Greening rice-fallow areas: integrating pulses and oilseeds for sustainable cropping in eastern India

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Rice-fallow areas, widespread in rainfed rice-growing regions of South Asia, remain uncultivated during the post-rainy (winter) season due to multiple challenges, including inadequate irrigation infrastructure, cultivation of long-duration rice varieties, and soil moisture imbalances. South Asia has approximately 22.3 million hectares of rice-fallow land, with India contributing the largest share (88.3%). Eastern Indian states, which account for 82% of India's rice-fallow area, presents significant opportunities for cropping intensification. However, several constraints—such as biotic (pest and disease), abiotic stresses (temperature extremes, drought, etc.), rapid soil moisture depletion, and disturbances from free-grazing livestock-hinder efforts to cultivate a second crop, perpetuating poverty among the small and marginal farmers. Introducing stress-tolerant rabi crops, particularly pulses (chickpea, lentil, lathyrus, field pea) and oilseeds (mustard, toria, safflower, linseed), offers a promising solution to enhance system productivity and improve the farmers' livelihoods. Policymakers have recently increased the public investment in rice-fallows intensification, yet fragmented and ad-hoc initiatives often fail to deliver sustainable outcomes due to complex and multidimensional challenges involved. This study critically examines the key issues affecting rice-fallow lands and provides strategic recommendations to convert these underutilized areas into the productive cropping systems during winter and spring. Additionally, it reviews Central and State Government programs related to rice-fallow management, emphasizing the need for research to align with ongoing policy initiatives for maximum impact. The findings of this study offers a valuable insights for the policymakers, planners, and stakeholders, highlighting the potential of pulses and oilseeds to enhance the food security, reduce poverty, and promote sustainable, climate-resilient agricultural production systems in the region.

KEYWORDS

crop diversification, cropping intensification, integrated crop management, oilseeds, pulses, rice-fallow

Highlights

- Crop diversification in rice-fallow lands can boost smallholder farmers' income and soil health.
- Integrating pulses and oilseeds into rice-fallow periods enhances the land use efficiency and overall system yield
- Short-duration, low-water-demanding crops thrive well in rice-fallow systems with supplemental life saving irrigation.
- Expanding pulse and oilseed cultivation by 4.0 million hectares can significantly boost the crop productivity.
- Sustainable rice-fallow intensification supports poverty reduction and aligns with sustainable development goals (SDGs).

1 Introduction

Rice-fallow areas are rainfed rice-growing regions where land remains uncultivated during post-rainy (winter) season. This practice persists due to the several challenges, including inadequate irrigation infrastructure, cultivation of the long-duration rice varieties that are harvested late (such as MTU 7029, BPT 5204, and traditional local varieties), and soil moisture imbalances at the time of crop establishment. Additionally, rapid soil moisture depletion caused by early withdrawal of monsoon coupled with disturbances from free-grazing livestock and blue bulls, further discourages winter cropping (Ali and Kumar, 2009).

In South Asia, approximately 22.3 million hectares of rice-fallow land are present, with India accounting for the largest share (88.3%), followed by Bangladesh (8.7%), Nepal (1.4%), Sri Lanka (1.1%), Pakistan (0.5%), and Bhutan (0.02%) (Kumar et al., 2020). In India, around 11.7 million hectares of rice-fallow land are primarily concentrated in the eastern region (82%), spanning the seven states—Bihar, Chhattisgarh, Odisha, Assam, eastern Uttar Pradesh, Jharkhand, and West Bengal (Kumar et al., 2018a,b). With growing demand for food due to population expansion, intensifying agricultural production in these areas is imperative (Kumar et al., 2016). These regions offer significant opportunities for expanding cultivated areas through targeted research and intervention (Kumar et al., 2020). However, cultivating a second crop in winter presents the multiple challenges, including biotic and abiotic stresses (NAAS, 2013). Addressing these constraints is essential for scientists, policymakers, and other stakeholders to fully utilize the untapped potential of rice-fallow lands in eastern India and similar regions globally.

In rainfed, rice-based monocropping systems, small and marginal farmers often struggle with limited resources, trapping them in a cycle of poverty. Integrating a second crop after rice harvesting in eastern India's rice-fallow lands offers a viable solution to enhance agricultural productivity (NAAS, 2013). The selection of suitable rabi (winter) crops depends largely on their ability to withstand biotic and abiotic stresses (NAAS, 2013). Oilseeds such as safflower, mustard, toria, groundnut, sesame, and linseed, along with pulses like lathyrus, chickpea, and lentil, have been identified as promising options for improving system productivity of rice-fallow lands (Bandyopadhyay et al., 2016; Kumar et al., 2021).

Recently, issue of rice-fallow lands has gained significant attention from the policymakers, leading to increased public investment. However, ad-hoc investments (temporary solutions without a long-term strategy) in intensification efforts often fail to yield sustainable outcomes due to complex, multidimensional challenges, including biotic and abiotic stresses, policy constraints, and socio-economic limitations. This article analyzes the challenges of rice-fallow lands and offers strategic recommendations to transform these underutilized areas into highly productive systems during winter and spring.

Additionally, this paper reviews the ongoing Central and State Government programmes related to rice-fallow management, emphasizing the need for research initiatives to align with these efforts for greater impact. The study's findings will provide a valuable insights for policymakers and planners, for shaping the policies, designing effective programmes, and identifying priority areas for investment. Ultimately, this research aims to promote the sustainable and environmentally friendly agricultural management practices, contributing to the poverty reduction and ensuring the food and nutritional security in the region.

2 SWOT analysis of rice fallow

The SWOT analysis of rice-fallow areas in India highlights the significant strengths such as vast land availability and potential for high yields in pulses and oilseeds. However, challenges like poor seed accessibility, lack of irrigation, and abiotic stress persist. Opportunities include innovative farmers and rising demand for pulses and oilseeds, while threats like production uncertainty and market volatility pose risks. The detail is given in Figure 1.

3 Climatic variabilities

Eastern India experiences a hot and dry, sub-humid climate, characterized by scorching summers and relatively cooler winters. The annual average temperature ranges between 24–26°C, with summer

FIGURE 1
Strength, weakness, opportunity and threat of rice-fallow (modified from Singh et al., 2016).

temperatures (April to June) fluctuating between 29–32°C and peaking at 37–42°C in April and May. In winter (December to February), temperatures average around 16–18°C, with low reaching 8–10°C. The region receives annual rainfall between 1,200 and 1,500 mm, increasing up to 1,600 mm in eastern parts. The rainy season is marked by high humidity, excess water accumulation of 200–300 mm, and potential evapotranspiration (PET) between 1,400 and 1,700 mm (Bandyopadhyay et al., 2015). Crop cultivation typically begins with the onset of monsoon and lasts between 180–210 days, extending beyond 240 days in West Bengal. Soils in this region are generally shallow, poorly drained, and predominantly clayey to clay loam in texture.

4 Distribution of rice-fallow areas

The fallow lands offer an immense potential for cropping intensification through inclusion of short to medium-duration rice varieties, improved soil moisture conservation, and introduction of short-duration pulses and oilseeds, ultimately enhancing soil health and productivity (Kumar et al., 2019a).

Low water-requiring, short-duration pulses like chickpea, lentil, lathyrus, and black gram, along with oilseeds such as mustard, toria, linseed, groundnut, sesame, and safflower, present viable options for increasing smallholder farmers' incomes while improving soil health. Rice-fallow areas are predominantly found in rainfed agro-ecosystems, characterized by deep alluvial soils with neutral to acidic pH (Figure 2).

In states such as Bihar, West Bengal, and Chhattisgarh, crops like chickpea, lentil, and lathyrus are typically grown as utera crops, sown in the standing rice fields 10–12 days before crop harvesting to utilize the residual soil moisture (Gupta and Bhowmick, 2005; Rautaray, 2008; Mondal and Ghosh, 2005). Several districts in eastern India follow rice–fallow cropping systems (Figure 3).

- *Assam*: Karbi Anglong, Dibrugarh, Golaghat, Jorhat, Lakhimpur, Morigaon, Nagaon, and Sibsagar
- *Bihar*: Aurangabad, Banka, Bhagalpur, Gaya, Jamui, Katihar, Kishanganj, Nawada, and Sheikhpura
- *Jharkhand*: Deoghar, Dhanbad, Dumka, East Singhbhum, Gumla, Hazaribagh, Palamu, Ranchi, Sahibganj, and West Singhbhum
- *Chhattisgarh*: Bastar, Surguja, Jashpur, Raigarh, and Durg
- *Odisha*: Bhadrak, Cuttack, Dhenkanal, Kalahandi, Koraput, Mayurbhanj, Puri, Sambalpur, and Sundergarh
- *West Bengal*: Bankura, Bardhaman, Birbhum, Cooch Behar, Malda, Medinipur, Murshidabad, North Dinajpur, Purulia, and South 24 Parganas
- *Eastern Uttar Pradesh*: Bahraich, Balrampur, Bhadohi, Pilibhit, Chandauli, Etawah, Ghazipur, Gonda, Lakhimpur Kheri, Maharajganj, Mirzapur, Siddharthnagar, and Sonbhadra (NAAS, 2013; Annual Report, 2016–17).

According to the Expert Group on Pulses, approximately 2.46 million hectares of rice–fallow land in these eastern states have a high potential for pulses cultivation (Figures 4, 5).

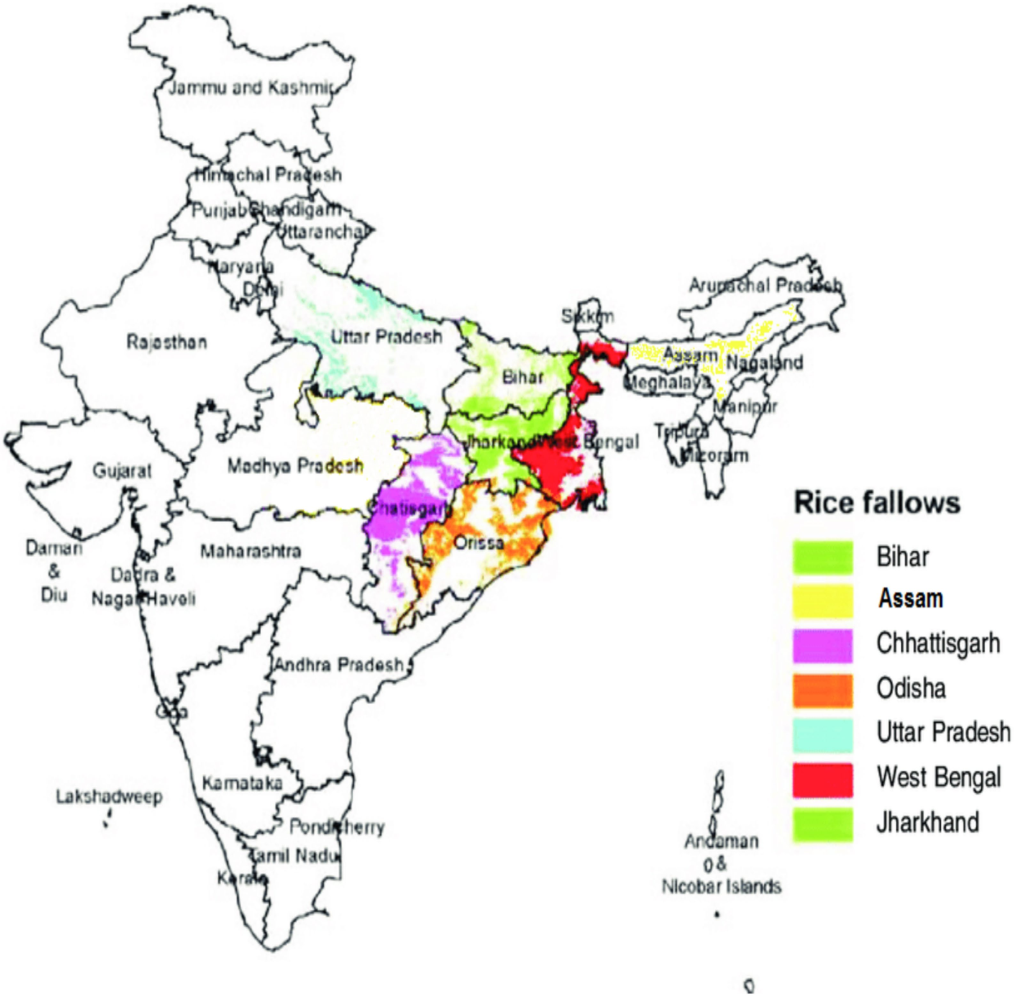

FIGURE 2
Prospective rice fallow areas (rainfed) in eastern India for cultivating pulses and oilseeds.

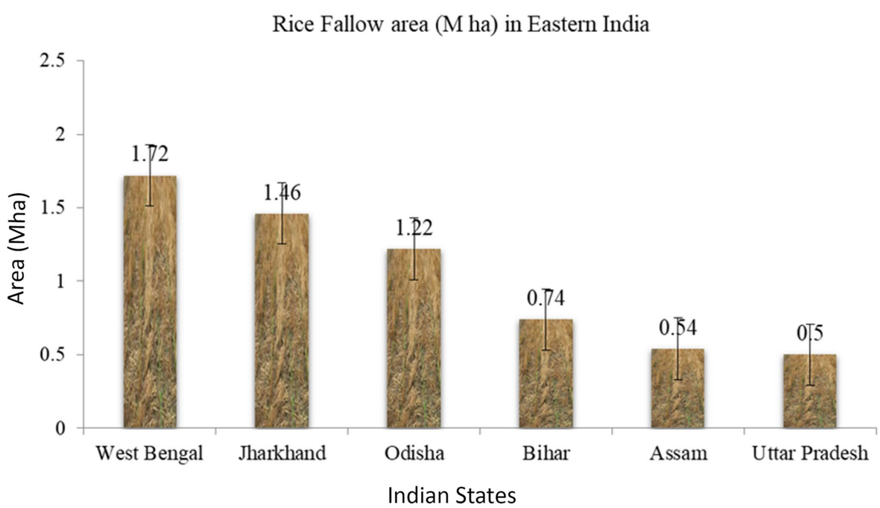

FIGURE 3
The current extent of the rice fallow in India's eastern states (source: Annual Report, 2016–17).

5 Categorization of rice fallows

India cultivates rice on about 43.4 million hectares, producing 104.3 million tonnes, with an average yield of 2,404 kg per hectare (Anonymous, 2015). However, lower crop yields are often attributed to the water scarcity during the peak growth stages and challenges related to biotic and abiotic stress management. While rice yields are generally satisfactory under puddled conditions, around 30% of cultivated area remains fallow during subsequent winter due to various agronomic and socio-economic constraints. Rice-fallow areas can be classified into four sub-groups based on the soil type and agro-climatic conditions:

5.1 Northeast region

This region experiences a warm, dry, and humid climate with cool winters and hot summers. Annual rainfall ranges from 1,200 to 1,500 mm, with higher precipitation in the eastern states like Bihar, Jharkhand, Odisha, and West Bengal. Crop growth is often limited by deep alluvial soils deficient in organic carbon, phosphorus, and zinc. Lowland regions frequently face excessive moisture or waterlogging during winter (October–November). Additionally, stray cattle pose a significant challenge to subsequent crops. The growing season lasts between 180 to 210 days in the northern areas and up to 240 days in the eastern regions. Lentil, chickpea, and lathyrus are commonly grown as relay or paira crops after rice. However, in Odisha, higher humidity favors black gram and horse gram, while mung bean thrives in mild winter conditions. States such as Chhattisgarh, Jharkhand, Bihar, and West Bengal favor small-seeded varieties of lentil, mung bean, urd bean, lathyrus, and peas under utera cropping system. The region holds a great potential for pulse and oilseed cultivation on fallow lands.

5.2 Central region

This region has a hot and dry sub-humid to moist-humid climate, with dry-summers and cool winters. Annual rainfall ranges from 1,000 to 1,200 mm, particularly in Maharashtra, Madhya Pradesh, and Chhattisgarh. The clayey soils in this region are nutrient-deficient, hard, and prone to deep cracking when dry. During winter cropping season, early rainfall and soil moisture stress are the common challenges. Typically, primed lathyrus and lentil seeds are broadcasted in standing rice fields using utera production system.

5.3 Coastal peninsula

This region, encompassing the coastal areas of Andhra Pradesh, Karnataka, and Tamil Nadu, features a dry sub-humid climate with hot summers and mild winters. Average annual rainfall ranges between 1,000 to 1,200 mm, and soils are predominantly deep clay. Mild winters and excessive soil moisture create favorable conditions for urd and mung bean production. The region is also benefited from bi-modal rainfall patterns.

5.4 Northeastern hills (NEH region)

The NEH region has a humid climate with cool winters and hot summers. Central Brahmaputra Valley, including Assam, receives an average annual rainfall of between 1,600 and 2000 mm. However, pulses productivity faces challenges due to decreasing availability of arable land, increasing population pressure, rising food demand, and deteriorating soil health. Pulses cultivation remains low due to several constraints, including soil acidity, poor fertility, aluminum toxicity, and an undulating topography that creates an unfavorable microclimate. High rainfall leads to excessive leaching, further

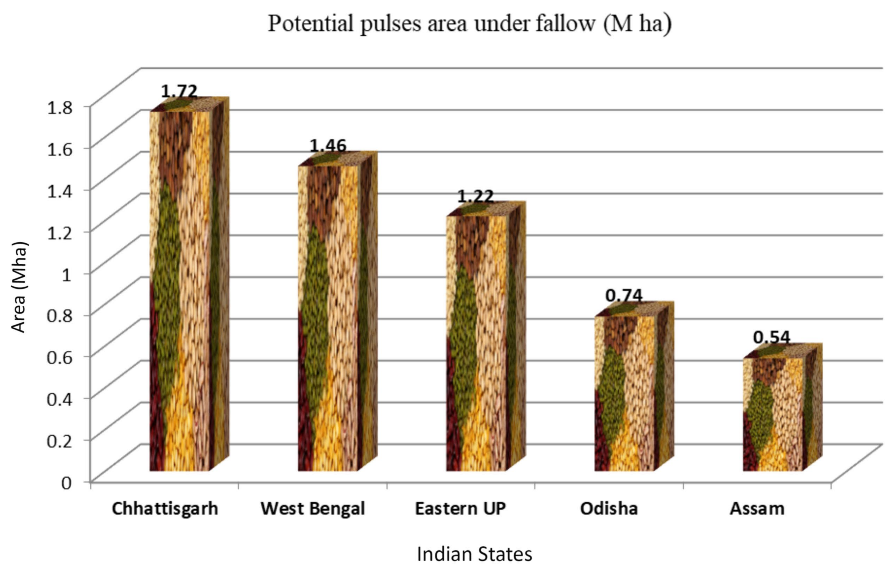

FIGURE 4
Possible areas for growing pulses in India's rice-fallow regions (source: Annual Report, 2016–17).

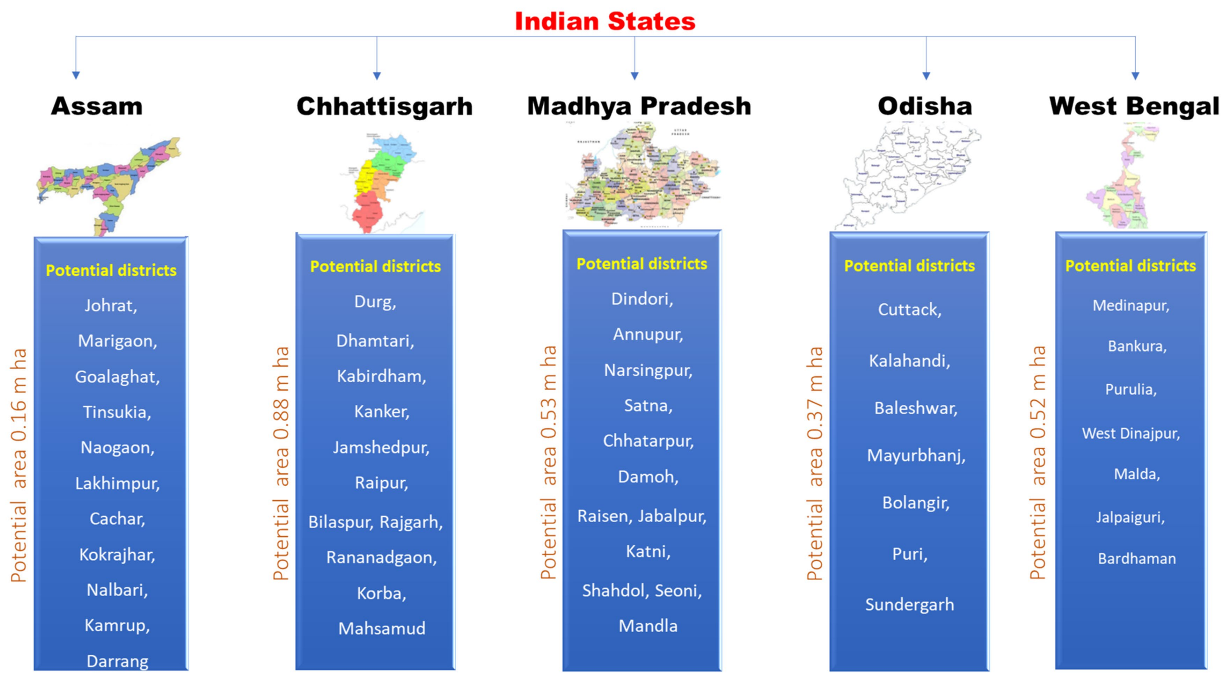

FIGURE 5
Available potential areas in various states for growing pulses in rice-fallow regions (source: Singh et al., 2016).

degrading the soil health. Small-seeded lentil and urd bean varieties are commonly grown in this region.

6 Challenges of rice-fallow cultivation

According to Bandyopadhyay et al. (2015), eastern region of India spans 73.7 million hectares, accounting for 22% of the nation's total land area. The net cultivated area in this region is 33.6 million hectares, which constitutes approximately 45% of India's total farmland. The region contributes 34.6% of country's total food production. In eastern India, productivity of food crops is ranked as follows: West Bengal > Eastern Uttar Pradesh > Bihar > Assam > Odisha > Jharkhand > Chhattisgarh. Cropping intensity varies significantly across these states, ranging from 115% in Chhattisgarh to 177% in West Bengal. Despite housing 38% of India's population, agricultural development in this region remains below its full potential.

The cultivation of pulses and oilseeds in rice-fallow areas faces the several challenges, including soil degradation and poor management practices (Pande et al., 2012). One of the major yield-limiting factors is soil moisture deficit, particularly during the later crop growth stages. Reliance on residual soil moisture from rice harvesting often results in inadequate moisture availability, leading to decline in water tables and mid-to-terminal droughts during flowering and pod-filling stages. These conditions significantly affect crop productivity of pulses and oilseeds in rice-fallow systems. Additionally, terminal drought and heat stress can cause premature maturation, reducing crop yields by 50% in tropical regions, particularly when rainfall is scarce (Ali et al., 2014).

Rice-fallow systems also suffer from poor soil structure, reduced aeration, and mechanical resistance in the seeding zones, negatively affecting seed germination, seedling emergence, and crop establishment (Kumar et al., 2020). Soil hardening, a major constraint in puddled rice fields, deteriorates the soil's hydraulic properties, disrupting moisture distribution and thus, limiting the growth of deep-rooted pulses and oilseeds (Ali et al., 2014). These conditions weaken microbial activity, reduce the nutrient availability, and confine root growth to the top-soil, thus restricting the water and nutrient uptake. Additionally, combination of compact soil coupled with low levels of organic matter, which is common in tropical and sub-tropical areas, further depletes the soil fertility, rendering it unsuitable for profitable crop cultivation.

Physical deterioration of the puddled transplanted rice soils affects moisture retention, plant root penetration, and microbial life, leading to inefficient nutrient absorption in the subsequent crops. Two major approaches in rice-fallow production systems are-relay cropping and crop rotations, which have potential but face implementation challenges (Kumar et al., 2019b; Kumar et al., 2020). Pulses are particularly suitable for these systems due to their short duration, low input requirements, and adaptability to the surface broadcasting in standing rice fields. In coastal regions, urd and mung bean are commonly cultivated (Kumar et al., 2019b). However, relay cropping is often constrained by poor plant populations, inadequate seed-to-soil contact, seed rot, and patchy soil dryness, all of which reduce the seed germination, plant density, and crop yield potential.

Weed management in standing rice fields remains a major issue, even after harvest, due to inadequate land preparation. Problematic weeds such as *Cuscuta* can severely impact pulse crops (Mishra et al., 2016). In contrast, crop rotations require ploughing immediately after rice harvesting to remove stubbles, delay sowing of winter pulses. This leads to formation of large soil clods that hinders the seed germination and accelerate moisture evaporation from the top soil, causing water stress during critical growth stages of pulses such as chickpea, lentil, and black gram.

Soil acidity in Eastern India and Northeastern Hill (NEH) region, along with alkalinity or salinity in the lower and middle Indo-Gangetic Plains, further diminishes soil productivity (Kumar et al., 2019b). The anaerobic conditions created by puddled rice fields are detrimental to beneficial soil microbes like *Rhizobia*, impairing biological nitrogen fixation (BNF) in leguminous crops. Additionally, pulses and oilseeds in rice-fallow systems are vulnerable to high incidences of insect pests due to unstable soil–plant-atmosphere interactions. Chickpea crops in states such as Chhattisgarh, Jharkhand, and Madhya Pradesh are particularly susceptible to pod borer (*Helicoverpa* spp.), while root-knot nematodes (*Meloidogyne* spp.) are also prevalent. Urd and mung bean often suffer from powdery mildew during winter, while lentil are affected by rust and *Fusarium* wilt.

Limited employment opportunities in agriculture contribute to widespread poverty and malnutrition in these regions. The per capita availability of cultivated land in our country is just 0.15 ha (Kumar et al., 2016). Farming in these areas is dominated by the small and marginal landholding, which complicates the adoption of mechanized farming techniques.

Although this region receives 1,100 to 1,200 mm of annual rainfall—which is sufficient to meet the crop water demands but high variability in spatial and temporal rainfall distribution causes farming instability. By the end of winter, these soils dry and crack, making it difficult to sustain a second crop. Additionally, post-harvest plowing results in large, hard clods, further restricting seed germination and root penetration, ultimately reducing yields (Kumar et al., 2020).

Resource-poor farmers face additional challenges due to the high costs of irrigation and fertilizers needed for growing winter crops, further discouraging the second cropping. Pulses and oilseeds can effectively utilize the residual soil moisture, but optimal moisture management strategies and research-driven solutions are essential for maximizing their productivity.

Rice, the primary crop, is typically cultivated through transplantation during rainy season. To facilitate its growth, farmers practice puddling, a method that disrupts the soil macro-pores and aggregates, increasing bulk density. After the rainy season, these puddled soils dry and crack, restricting the moisture availability for winter crops. Furthermore, ploughing after rice harvesting creates large, hard soil clods, impeding the root growth and leading to reduced yields in subsequent crops. Resource-limited farmers often struggle with high cost of irrigation and fertilizers required for winter cropping, further constraining their ability to sustain agricultural production throughout year.

Pulses and oilseeds can effectively utilize the residual soil moisture left after rice harvesting, making efficient moisture management critical for establishing a second crop. By implementing well-researched strategies, fallow lands can be converted into productive agricultural areas. In states like West Bengal, Odisha, Chhattisgarh, and Jharkhand, conventional rice-pulse cropping systems are commonly practiced. However, challenges such as poor crop establishment of pulses like chickpea and oilseeds like mustard, toria, and safflower significantly reduce the region's yield potential. Kumar et al. (2016) identified key limitations affecting plant populations in rice-fallow systems, including inadequate seed-soil contact, low soil moisture, and severe weed infestations.

In lowland rice areas with higher soil moisture levels, lentil and lathyrus are better suited for cultivation than chickpea, mustard, and linseed (Mishra et al., 2016; Mishra and Kumar, 2018). The productivity of pulses and oilseeds in rice-fallow lands is further affected by site-specific nutrient deficiencies, particularly phosphorus, zinc, sulfur, boron, and molybdenum, as well as soil acidity and low organic carbon levels. Addressing these constraints is essential for achieving the optimal yields in rice-fallow cropping system.

Farmers in rice-fallow areas also face challenges due to the dominance of long-duration rice varieties, which take 155 to 160 days to mature (e.g., MTU 7029, BPT 5204, and local traditional cultivars). The extended growing period delays the sowing of subsequent crops, such as pulses and oilseeds, resulting in reduced crop yields due to soil moisture deficits during flowering and maturation stages. Additionally, lack of high-quality seeds and superior crop varieties exacerbates these challenges. Weed infestations pose another major issue, particularly in utera/paira cropping systems, where rapid surface soil moisture loss complicates manual weeding, further affecting crop establishment and productivity. Utera cropping (also known as paira cropping) is a traditional relay cropping system in which next crop is sown in standing rice crop before its harvest, utilizing the residual soil moisture for germination and early growth. This practice is commonly used in rainfed, lowland rice-growing areas to optimize the land use, reduce fallow periods, and enhance productivity without additional irrigation. Common utera crops include lentil, chickpea, linseed, lathyrus, and mustard, which are well-suited to the residual soil moisture conditions in rice fields.

7 Interventions for intensification of rice-fallow areas

7.1 Cultivation of short-duration rice varieties

Farmers should adopt short-duration rice varieties with quicker maturity periods to enable the timely sowing of subsequent crops. This approach reduces the risk of terminal drought and enhances overall crop productivity.

7.2 Improvement in farm mechanization

Encouraging the adoption of the modern farm machinery and equipment can significantly boost productivity in rice-fallow farming. Mechanization accelerates essential agricultural tasks such as land preparation, planting, and harvesting, reducing labor requirements and improving the overall farm efficiency.

7.3 Adoption of soil conservation measures

Implementing soil conservation practices such as contour plowing, terracing, and bunding can effectively reduce soil erosion and enhance soil health. These techniques help retain moisture, mitigate the effects of drought, and ultimately improve crop performance.

7.4 Creation of water harvesting structures

Constructing water harvesting systems such as ponds and check dams helps capture and store the rainwater. This stored water can be utilized for irrigation during dry-periods, ensuring a steady water supply even when rainfall is insufficient.

7.5 Development of irrigation facilities

Investing in irrigation infrastructure, including canals, tube wells, and drip irrigation systems, can provide a reliable water source for rice-fallow areas. These facilities help overcome the constraints of variable rainfall and sustain optimal moisture levels for crop growth.

7.6 Supply of quality seeds and inputs

Ensuring access to high-quality seeds and essential agricultural inputs such as fertilizers and pesticides is crucial for enhancing crop yields. Farmers should be provided with certified seeds and recommended inputs to maximize their production potential.

7.7 Use of drought-tolerant, climate-resilient crops and varieties

Encouraging the cultivation of drought-tolerant, climate-resilient crops can help in mitigate the challenges posed by water scarcity during fallow period. Farmers should consider alternative crops that require less water and can withstand the dry conditions, fostering a more sustainable and productive farming systems.

8 Potential for cultivating oilseeds and pulses in rice-fallow areas

Rainfed regions in India plays a vital role in food production and rural economy but are often fragile and prone to distress. Approximately 11.65 million hectares of land remain uncultivated after rice harvesting, with 82% of this area located in eastern India, while remaining portion is distributed across Tamil Nadu, Karnataka, and Andhra Pradesh. These regions offer significant opportunities for growing upland pulses such as lentil, chickpea, lathyrus, mung and urd bean, which require minimal inputs and water (Figure 6). However, depleted soil moisture post-harvest can delay sowing and reduce crop yields. Limited moisture further affects plant growth, making supplementary irrigation essential during critical growth stages.

Conservation agriculture practices including crop residue retention, zero tillage (ZT), and appropriate crop rotation show great potential for improving pulse yields in rice-fallow areas. Both crop rotation and relay/paira cropping of pulses in standing rice fields could become widely adopted solutions. However, a thorough understanding of local ecology and constraints is necessary to address the challenges effectively. Techniques such as using suitable pulse varieties, zero tillage, retaining crop residues, seed priming, foliar nutrition, and mulching can significantly enhance pulse productivity.

Pulses and oilseeds have several advantages, including short growth cycles, climate resilience, and low input requirements, making efficient use of residual soil moisture. Despite India producing around 17–18 million tonnes of pulses annually on an area of 24–26 million hectares, demand still exceeds supply, necessitating imports. Integrating pulses into rice-fallow systems can help bridge this gap, enhance sustainability, and improve farmers' incomes by expanding cultivation areas and boosting crop productivity.

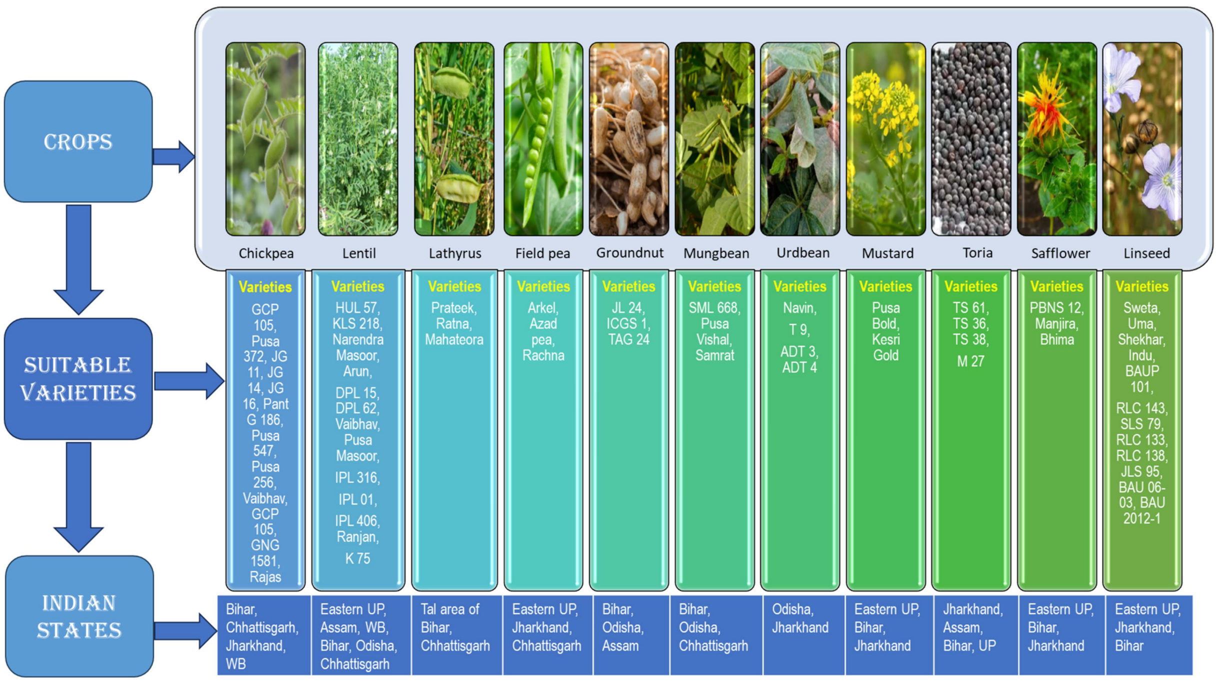

FIGURE 6
Appropriate pulse and oilseed crops and varieties for rice fallow region in eastern India.

The development and implementation of the research and development (R&D) programs, supported by government schemes and interventions, have significantly advanced the utilization of rice-fallow lands for pulse and oilseed cultivation. In India, nearly one-third of agricultural land remains fallow after paddy harvesting, representing a substantial opportunity for conversion into productive farmland. With appropriate policy measures, an additional 3.0 million hectares could be brought under the pulse cultivation and 1.0 million hectares under oilseed production. The promotion of crops such as lentil, lathyrus, and chickpea in rice-fallow areas, supported by initiatives like the National Food Security Mission (NFSM) has shown the positive results.

However, the impact of such programs on pulses and oilseeds cultivation has been limited due to restricted implementation areas and frequent changes in beneficiaries.

To overcome these challenges, more innovative and targeted strategies are required to enhance the effectiveness of rice-based cropping systems. This involves focusing on region-specific characteristics to optimize the utilization of fallow lands and benefit resource-poor farmers. Despite the potential of short-duration pulse and oilseed crops, efforts to expand their cultivation have been insufficient. All India Coordinated Research Project on mung bean, Lathyrus, Lentil, Rajmash, and Pea (AICRP-MuLLaRP) has not effectively promoted high-yielding varieties in the region. However, projects funded by the Department of Science and Technology (DST) and National Fund for Basic, Strategic, and Frontier Application Research in Agriculture (NFBSRA) have made progress in mitigating abiotic stress and improving resource efficiency in pulse production.

Consortium Research Platform on Conservation Agriculture (CRP on CA), established by Indian Council of Agricultural Research (ICAR), has identified soil and water management as critical factors limiting crop production in fallow areas. A comprehensive approach to soil and crop management is an essential to unlock the potential of rice-fallow lands for short-duration crops.

As highlighted by Mohapatra et al. (2022), efficient natural resource management and integrated crop management (ICM) practices are crucial for sustainable cropping intensification in rice-fallow systems. Addressing the multifaceted challenges of rice-fallow management requires coordinated efforts across research, policy development, infrastructure improvement, and community engagement. Programs like "Targeting Rice-Fallow Areas in Eastern India for the Promotion and Production of Pulses & Oilseeds" under Rashtriya Krishi Vikas Yojana (RKVY), along with advocacy by Commission for Agricultural Costs and Prices (CACP), are steps in the right direction. However, tackling the complexities of fallow land intensification requires the precise assessments, identification of the constraints, and development of tailored crop plans to enhance the farm incomes, reduce poverty, and ensure the food security.

9 Strategies for converting mono-cropped areas into double-cropped systems in rice-fallow production

To enhance pulses and oilseeds cultivation in rice-fallow areas, several key interventions are necessary. A cluster-based approach for demonstrating improved production technologies, along with increasing the availability of quality seeds, is a crucial. Seed priming, along with Rhizobium or fungicide treatments, can enhance seed performance. Effective agronomic measures such as micronutrient application, pest management, and supplemental irrigation further improve productivity. Resource conservation technologies (RCTs) help conserve soil moisture and increase farm efficiency. Additionally, increasing cropping intensity can alleviate winter fodder shortages. Simple interventions such as seed priming and applying urea/DAP and micronutrients at critical growth stages have significantly improved crop yields for resource-poor farmers (Kumar et al., 2018a,b). Implementing these strategies can foster the sustainable and profitable pulse and oilseed farming while addressing the agronomic challenges. The following integrated strategies can significantly boost the system productivity of rice-fallow areas in India.

9.1 Water harvesting and storage

Moisture scarcity during winter remains a significant constraint for second-season cropping in rice-fallow areas, despite ample monsoon rainfall. Studies suggest that rainwater harvesting and small-scale irrigation infrastructure can enhance water availability during dry months (Das et al., 2014). The construction of ponds and reservoirs, supported by government initiatives, has proven effective in several regions for ensuring life-saving irrigation (Richards et al., 2021). Research indicates that harvesting excess rainwater—often lost as runoff—can supplement winter water supplies, reducing the dependency on erratic rainfall patterns (Velasco-Muñoz et al., 2019). Field trials in high-rainfall regions demonstrate that integrating water conservation measures with improved agronomic practices mitigates abiotic stresses, such as waterlogging in valleys and rapid soil moisture depletion in uplands (Manik et al., 2019). These strategies collectively enhance agricultural resilience, promoting sustainable intensification of rice-fallow areas.

9.2 Utilization of RCT

Zero-tillage (ZT) and residue retention significantly enhance soil moisture conservation and crop productivity in rice-fallow systems. Reduced tillage (RT) techniques have been shown to increase pulses yield by 33–44% as compared to conventional tillage (CT), particularly for chickpea, lentil, and black gram (Kar and Kumar, 2009). Retaining 30% of rice residue and using ZT-practices, such as those involving Happy Seeder, have resulted in substantial yield improvements for lentil, chickpea, and safflower (Ghosh et al., 2016). Utera cropping system, a specific form of ZT, allows for early sowing and optimal moisture utilization, benefiting crops like lathyrus, linseed, and lentil (Mishra et al., 2016).

9.3 Systematic crop production approach

Replacing the long-duration rice varieties with short-to medium-duration alternatives facilitates early harvesting and timely sowing of subsequent crops. For relay cropping (paira/utera), proper field leveling ensures the uniform soil moisture and improved seed germination. Mechanized or line transplanting of rice enhances yield potential in fallow-based cropping systems (Mishra and Kumar, 2018). The challenge of limited quality seed availability for late-season sowing can be addressed through community-based seed multiplication programs and enhanced distribution channels supported by the National/State Seed Corporations (NSC).

9.4 Ensuring access to high-quality seeds

Community-based seed multiplication programs and improved storage and distribution systems are essential for sustaining the productivity in rice-fallow systems. National and State Seed Corporations (NSC) should ensure the timely availability of certified seeds. Short-duration pulse and oilseed crop varieties with terminal drought resistance, such as Pusa Masoor 5 (lentil), C 235 (chickpea), Uma (linseed), and Ratan (grasspea), have demonstrated high yield potential (Kumar et al., 2021). Seed priming that involves soaking seeds in water or nutrient solutions before sowing-enhances the germination and early seedling growth, and improving overall yield potential (Ali et al., 2005).

9.5 Weed management

Integrated weed management (IWM) strategies, including residue mulching, ZT sowing, and post-emergence herbicides like quizalofop (50 g/ha) applied 15–20 days after sowing (DAS), effectively control weeds (Kumar et al., 2016). In legumes such as groundnut and mung bean, application of Imazethapyr (100 g/ha) has been successful in controlling the narrow-leaved weeds.

9.6 Timely plant protection

Seed treatments with fungicides such as carbendazim and biological agents like *Trichoderma viride* (8–10 g/kg seed) have been widely recommended to prevent seed rot and early seedling diseases, enhancing crop establishment and yield (Nazir et al., 2022). Studies have demonstrated that integrating these treatments with proper agronomic practices reduces disease incidence and improves seedling vigor, particularly in pulse crops grown under the moisture-limited conditions (Kumar et al., 2021).

9.7 Soil moisture conservation

Conservation agriculture (CA) practices, including raised bed planting, play a crucial role in soil moisture management and thereby enhancing productivity in rice-fallow systems (Kumar et al., 2022a). Raised bed planting effectively conserves moisture, increases the soil organic carbon (SOC), and improves soil properties. This method has been shown to increase the pulses yield-such as lathyrus, lentil, and chickpea by 33–44% as compared to the conventional tillage (CT), outperforming no-till (NT) and relay cropping systems in moisture conservation (Kar et al., 2004; Gangwar et al., 2006). Zero tillage (ZT) also contributes to reducing the moisture loss and allows for earlier planting of post-rainy season crops by 7–10 days (Mishra et al., 2016). To optimize residual soil moisture, pulses and oilseeds should be sown immediately after rice harvesting. Multi-location trials conducted in Kanpur, Kalyani, and Raipur have demonstrated that practices such as rice stubble retention, mulching, and no-till sowing significantly enhance productivity by conserving soil moisture in rice-fallow areas (Ali et al., 2005). These conservation practices are vital for mitigating the moisture stress and terminal drought, ultimately improving crop yield sustainability in rice-fallow systems (Kumar et al., 2022b).

9.8 Crop establishment options

Research by Mishra et al. (2016) demonstrated that zero tillage (ZT) combined with mulching significantly boosts crop yield of winter pulses such as chickpea (JG-14), lathyrus (Ratna), and lentil (HUL-57). Similarly, Kumar et al. (2018a,b) observed that ZT consistently improved crop productivity of subsequent winter crops. Increasing stubble height in conventional tillage (CT) production systems enhances the soil moisture conservation, benefiting winter crop yields in rice-fallow areas. Kar and Kumar (2009) reported that raised bed planting (RT) following rice harvest resulted in higher pulses yield. Retaining crop residue enhances soil quality by reducing erosion, evaporation, and weed growth while improving the nutrient availability and resource management. In no-till (NT) production systems, residue retention prevents the soil sealing and crust formation. Small-scale farmers in the developing regions often prioritize crop residues for biofuel or livestock feed. However, maintaining a portion of residues improves the long-term soil quality. Retaining crop residues and employing techniques such as utera cropping help mitigate terminal drought by preserving the soil moistures and reducing evaporation, making these practices highly effective for cultivating pulses and oilseeds.

9.9 Ensuring timely availability of essential inputs

In rice-fallow areas, post-rainy season crops predominantly rely on residual soil moisture, often facing nutrient deficiencies due to the limited application of fertilizers, biofertilizers, and agrochemicals. Studies have shown that optimizing agronomic practices, including timely sowing, appropriate plant spacing, and moisture conservation techniques, significantly improves the crop establishment and yields in such moisture-limited conditions (Kumar et al., 2020). Ensuring the timely availability of quality seeds, fertilizers, and plant protection chemicals is critical for enhancing productivity. Research indicates that use of improved seed varieties with better drought tolerance and early maturity can substantially increase crop yields in rice-fallow systems (Kumar et al., 2014). Additionally, integrating biofertilizers such as Rhizobium and phosphate solubilizing bacteria has been found to enhance nutrient uptake and soil fertility, leading to better crop performance (Shome et al., 2022). These evidence-based interventions collectively contribute to the sustainable intensification of rice-fallow systems.

9.10 Credit facilities and marketing infrastructure

Economically poor farmers often face challenges in accessing quality agricultural inputs and financial resources, limiting their ability to adopt second-season cropping. Studies have shown that targeted financial interventions, such as subsidies on seeds and fertilizers, access to institutional credit, and crop insurance schemes, can significantly enhance the smallholder participation in diversified cropping systems (Di Bene et al., 2022). Government-backed initiatives like interest-free agricultural loans and weather-based crop insurance have been instrumental in reducing the financial risks and promoting crop intensification in resource-constrained regions (Kumar and Babu, 2021). Strengthening the rural marketing infrastructure is another key factor in incentivizing the farmers to cultivate high-value crops. Research indicates that well-developed supply chains, including the farmer-producer organizations (FPOs), contract farming, and direct market linkages, improve the price realization and reduce post-harvest losses. These evidence-based strategies collectively contribute to the sustainable intensification of rice-fallow systems.

9.11 Safeguarding against stray cattle

Stray cattle, including *Neelgai* (blue bulls), pose a significant threat to crops in fallow areas, discouraging cultivation. Implementing effective policies, such as community fencing, controlled grazing, or alternative fodder management strategies, can help in mitigate the impact of stray cattle, protect the standing crops, and promote second cropping systems.

9.12 Introducing short-duration, high-yielding, climate-resilient pulse varieties

Short-duration pulse varieties are essential for overcoming the terminal moisture stress and heat stress in rice-fallow areas. Successful breeding programs should prioritize traits that enhance the drought tolerance and rapid growth. Providing high-quality seeds with more than 90% germination rates and selecting genotypes with broad canopies can help in reducing soil evaporation and improve crop yields.

9.13 Introducing water-efficient/smart genotypes

Pulse crops can be screened for water efficiency, with their water needs decreasing in the following order: pea > chickpea > lentil > lathyrus. Summer mung bean and urd bean require more water than peas, making them less suitable for drought-prone conditions. Selecting and promoting water-efficient genotypes is a crucial for optimizing crop productivity in the moisture-limited environments.

9.14 Seed pelleting

Seed pelleting with agrochemicals such as superphosphate, *rhizobium* culture, and plant protection chemicals has been shown to improve crop establishment and yields in various trials. Evaluating its cost-effectiveness and performance in rice-fallow conditions is necessary, as it may enhance seed survival and crop growth under the moisture stress conditions.

9.15 Foliar nutrition

In relay cropping systems, where conventional fertilizer application is challenging, seed pelleting and foliar feeding serve as an effective alternatives. Field trials have demonstrated that foliar spraying with 2% urea during flowering and pod formation stages boosts mung bean, urd bean, chickpea, and lentil yields by enhancing the leaf nitrogen concentration and photosynthesis (Anonymous, 2008; Ali and Kumar, 2009). Additionally, seed pelleting with micronutrients such as zinc is beneficial. Addressing widespread molybdenum (Mo) deficiency in Central India caused by insufficient nutrient replenishment can involve soil application of ammonium molybdate (1–1.25 kg/ha), foliar application of 0.1% Mo, or seed inoculation with 1.0 g Mo/kg.

9.16 Timely planting

In rice-fallow areas, delay in planting pulses can be avoided by broadcasting seeds 2–5 days before rice harvesting. Alternatively, zero-tillage drills post-harvesting ensure the sufficient soil moisture for optimal pulse productivity. Timely planting with the adequate soil moisture is a crucial for maximizing the pulse productivity, as it allows crops to efficiently utilize the residual moisture and develop strong root systems to withstand late-season moisture stress.

9.17 Timely plant protection

Low soil moisture in rice-fallow areas limits the effectiveness of post-emergence herbicides, while hard soil conditions make inter-cultivation challenging. Hand weeding should be done early in crop growth stage. Effective pest and disease management includes seed treatment with fungicides such as carbendazim and applying *Trichoderma viride* at 8–10 g/kg of seed to prevent seed rot and protect the young seedlings (Kumar et al., 2022c).

9.18 Supplementary and life-saving irrigation

To manage the limited water resources effectively, implementing supplementary or life-saving irrigation during post-rainy season can help mitigate the moisture stress and sustain the crop productivity. Utilizing farm ponds or natural reservoirs with precision irrigation methods such as drip and sprinkler systems optimizes water use by delivering precise amounts of water and fertilizer at critical crop growth stages (Praharaj et al., 2016a). Technologies such as precision land leveling, zero-tillage, furrow-irrigated raised-bed planting, and residue management are also valuable in reducing water use while improving water productivity and efficiency (Praharaj et al., 2016b). Given the uncertainties of rainfall and climate change, improving resource-use efficiency (RUE) is essential for enhancing pulse crops productivity. Strategic water management in pulses supports sustainable intensification of food production in India, particularly in regions facing natural resource degradation and climatic risks. In rice-fallow areas, intercropping pulses with crops such as linseed or sesame can maximize land utilization and farm income. Planting one or two rows of short-duration pulses between wider rows of strip crops can enhance the biological nitrogen fixation (BNF), while minimizing the competition for resources.

9.19 Research and development (R&D)

Strategic research and development (R&D) have significantly improved rice productivity in fallow areas. For instance, high-yielding, disease-resistant urd and mung bean varieties have been successfully developed for coastal peninsula. Further targeted research is needed to address disease hotspots and improve seed availability and agronomic management practices. Expanding pulse cultivation to 3.0 million hectares of rice fallow land could yield an additional 1.5–2.0 million metric tons of pulses, as estimated by the Ministry of Agriculture (Anonymous, 2009).

9.20 Actual mapping of rice-fallow areas

A coordinated approach involving all the relevant stakeholders is crucial for mapping and effectively utilizing rice-fallow areas. Satellite image and remote sensing tools are an essential for accurate approach for identifying and updating fallow land records, enabling better planning and intervention strategies.

9.21 Merging all R&D actions on rice-fallows

Consolidating research and development efforts at different levels from farm to state is critical for ensuring the effective implementation of future action plans. Integrating R&D results from various sources will create a cohesive approach to advancing agricultural practices and optimizing the fallow land utilization.

9.22 Implementing model pilot projects

Model pilot projects conducted directly on the farmers' fields are essential for demonstrating and promoting the recently developed technologies. These projects should be implemented in a mission-driven manner to showcase their effectiveness and encourage the widespread adoption among the farming communities.

9.23 Continual addressing of constraints in rice-fallow systems

Assessing and addressing constraints on-site enables faster adoption and dissemination of the proven technologies. Immediate resolution of issues facilitates effective implementation of innovations, and accelerating their acceptance among farmers.

9.24 System-mode approach and tools

Adopting agroecology-based farming systems that integrate the multiple enterprises has been widely recognized as a sustainable approach to enhancing the farm incomes and resilience. Research indicates that diversified farming systems, including crop-livestock integration, improve resource-use efficiency, soil health, and overall farm productivity (Fatima et al., 2023). Studies have demonstrated that integrating animal husbandry with crop production contributes to long-term sustainability by optimizing nutrient recycling, reducing input costs, and providing an additional income source for smallholder farmers (Fatima et al., 2023). Utilizing rice-fallow lands for strategic residue management further enhances the resource use efficiency. Field experiments suggest that conserving at least 30% of crop residues for animal feed not only supports livestock nutrition but also prevents excessive residue burning, thereby reducing greenhouse gas emissions and improving the soil organic matters (Kumar et al., 2018a,b). These evidence-based strategies contribute to the sustainable intensification of rice-fallow production systems, fostering both the environmental and economic benefits.

9.25 Broad-scale mechanization

Mechanization is a critical driver of farm efficiency, reducing labor dependency and enhancing productivity in rice-fallow systems. Studies have shown that adoption of appropriate mechanization strategies can significantly improve land preparation, sowing, and harvesting efficiency, particularly in the regions with labor shortages. While large-scale machinery is beneficial for consolidated farmlands, research highlights the necessity of small, locally operated equipment for undulating terrains and fragmented smallholder farms (Sims and Kienzle, 2017).

9.26 Scaling-up and scaling-out crop management practices

Innovative technologies and best management practices (BMPs), once tested and refined on the farms, should be scaled up and widely adopted. Expanding these successful interventions will help in increase the production efficiency and total agricultural output by reaching more farmers and extending crop coverage, ultimately enhancing the overall agricultural productivity.

10 Future research and prospects

The effective utilization of rice-fallow lands presents a promising avenue for enhancing agricultural productivity and rural livelihoods. Future research should focus on developing the climate-resilient and short-duration pulses and oilseeds varieties that can thrive well under the residual soil moisture conditions. Emphasis should be placed on improving seed distribution systems, ensuring timely availability of high-quality seeds, and adopting precision agronomic management practices to optimize the crop establishment in these fallow lands. Expanding irrigation infrastructure and promoting efficient water management strategies will be crucial for enhancing the crop yields in these areas. Research should also explore sustainable cropping systems tailored to specific agroecological zones, incorporating conservation agriculture management practices to improve the soil health and long-term crop productivity. Integrating pulses into public food distribution programs and farmer support initiatives can incentivize their cultivation and contribute to the nutritional security.

Additionally, policy-driven interventions must be informed by data-driven research on economic viability, market linkages, and farmer adoption behavior. Strengthening extension services, digital advisory tools, and financial incentives for farmers transitioning to pulse cultivation will be vital for scaling up this transformation. By addressing these key challenges, rice-fallow areas can be effectively utilized to improve the overall farm incomes, enhance food security, and contribute to a more sustainable agricultural landscape.

11 Conclusion

Despite the identification of numerous technological, institutional, and market-based solutions, integration of evidence-based strategies in designing and implementing fallow land intensification pathways remains limited. Rice-fallow intensification, particularly in risk-prone areas, lacks a cohesive support systems, an active community of practice, and a well-established policy network at various levels, which hampers effective policy reforms.

Research on fallow land management must align with ongoing government schemes and adopt a collaborative approach, involving the multiple partners to assess the investment pathways and sequence interventions for effective winter fallow intensification. Coordination among various stakeholders-including agriculture, water resources, electricity, and public works departments-is essential for successful irrigation management and overall governance.

Rice-fallow systems present the significant opportunities for expanding pulses and oilseeds cultivation through advanced agro-technologies. Key strategies for success includes the soil moisture conservation and mitigating abiotic stress. Focused research is crucial to understand rice-fallow ecology and developing location-specific, short-duration, drought-tolerant cultivars. By addressing site-specific constraints and implementing well-planned cropping strategies, these unutilized lands can be transformed into productive agricultural areas, contributing to poverty reduction and improved nutrition.

Author contributions

RK (1st author): Conceptualization, Data curation, Formal analysis, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. AD: Supervision, Writing – original draft, Writing – review & editing. SM: Conceptualization, Data curation, Validation, Writing – original draft, Writing – review & editing. PU: Conceptualization, Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing. BB: Writing – original draft, Writing – review & editing. JM: Conceptualization, Data curation, Writing – original draft, Writing – review & editing. AS: Conceptualization, Validation, Writing – original draft, Writing – review & editing. JC: Conceptualization, Validation, Writing – original draft, Writing – review & editing. SanjK: Data curation, Writing – original draft, Writing – review & editing. PS: Conceptualization, Writing – original draft, Writing – review & editing. AB: Data curation, Writing – original draft, Writing – review & editing. SSR: Data curation, Writing – original draft, Writing – review & editing. RS: Validation, Writing – original draft, Writing – review & editing. PP: Validation, Writing – original draft, Writing – review & editing. DS: Data curation, Writing – original draft, Writing – review & editing. SantK: Data curation, Writing – original draft, Writing – review & editing. AA: Data curation, Writing – original draft, Writing – review & editing. KiS: Data curation, Writing – original draft, Writing – review & editing. KuS: Data curation, Writing – original draft, Writing – review & editing. AK: Conceptualization, Writing – original draft, Writing – review & editing. Manibhushan: Conceptualization, Writing – original draft, Writing – review & editing. PJ: Conceptualization, Writing – original draft, Writing – review & editing. VP: Conceptualization, Writing – original draft, Writing – review & editing. BJ: Conceptualization, Writing – original draft, Writing – review & editing. SN: Conceptualization, Writing – original draft, Writing – review & editing. SSM: Conceptualization, Writing – original draft, Writing – review & editing. RK (27th author): Writing – original draft, Writing – review & editing. SA: Writing – original draft, Writing – review & editing. VS: Writing – original draft, Writing – review & editing. DM: Writing – original draft, Writing – review & editing. MR: Writing – original draft, Writing – review & editing. AC: Data curation, Writing – original draft, Writing – review & editing. SR: Writing – original draft, Writing – review & editing. SC: Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

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