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Pulse Crops for Sustainable Agriculture and Their Contributions to Soil Health, Nutrient Management and Resource Use Efficiency: A Review

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ABSTRACT

Pulse crops are an important part of sustainable agriculture, as they help to enrich the soil with nutrients, promote natural resource management, and boost its fertility. Pulses are crucial sources of dietary protein and are also valuable for their ecological value in terms of biological nitrogen fixation, addition of organic matter, and enhancing soil biological activity. The review aims to highlight the potential use of pulse crops in sustainable agriculture systems with specific reference to soil health, soil nutrient management, resource-use efficiency and long-term productivity. The 60 research papers were reviewed under the following six main themes: biological nitrogen fixation, soil organic carbon, soil fertility improvement, nutrient availability, residue management, water-use efficiency, nutrient-use efficiency, and weed management. The findings of the reviewed shows that rotation and the use of pulse crops in conservation tillage production systems can enhance soil structure, organic carbon, water infiltration, water-holding capacity, and the availability of essential nutrients. Pulse crops can also fix their own nitrogen, especially when associated with Rhizobium, which can help to lower the need for synthetic nitrogen fertilisers and increase the nitrogen available to the following crop. Crop residues also play an important role in nutrient recycling, building soil organic matter, mitigating erosion and sustaining soil biological activity. Pulses may also help to address the challenges posed by climate change and soil degradation as they optimise use of resources and productivity of cropping systems as a whole. Therefore, pulse crops can be effectively used as a means to sustain soil health, optimise nutrient cycles, improve resource-use efficiency and ensure resilient and sustainable agricultural production in response to changing climatic conditions in diversified and conservation agriculture systems.

Keywords: *Pulse Crops; Integrated Nutrient Management; Sustainable Agriculture; Climate Resilience.*

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1. Introduction

Climate change, soil fertility decline, land degradation, water scarcity, high production costs and inefficient utilisation of agricultural inputs are increasingly creating challenges for agricultural production. These difficulties

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pose risks to future productivity and sustainability of agricultural systems and have increased the need for resource-efficient and environmentally friendly agricultural production. Pulse crops play an important role in this context through their contributions to food and nutritional security, soil fertility improvement, biodiversity conservation and efficient utilisation of natural resources. They can also contribute to sustainable intensification of cropping systems through nutrient cycling, reduced dependence on external inputs and enhanced resilience of agricultural ecosystems (Choudhary et al., 2020; FAO, 2016; Kumar et al., 2023). Pulse crops are an important group of leguminous crops grown in tropical, subtropical and temperate regions. Major pulses include chickpea, pigeonpea, lentil, field pea, mungbean, blackgram, cowpea and other grain legumes. Besides being important sources of dietary protein, dietary fibre, vitamins and minerals, pulses provide important ecological services within agricultural systems. They form symbiotic associations with rhizobia and other beneficial microorganisms, enabling biological nitrogen fixation, through which atmospheric nitrogen is converted into forms that can be utilised by plants. Consequently, pulses can contribute to the nitrogen economy of cropping systems and potentially reduce dependence on synthetic nitrogen fertilisers when appropriately managed (FAO, 2016, 2018; Buernor et al., 2022).

The contribution of pulses to soil health extends beyond biological nitrogen fixation. Pulse crops contribute root biomass, residues and rhizodeposits that can provide organic matter and substrates for soil microorganisms. These inputs can influence soil aggregation, nutrient cycling, microbial activity and other soil biological processes. Legume inclusion in crop rotations can also influence soil organic carbon and nutrient availability, although the magnitude of these effects depends on crop species, residue return, soil conditions and the duration of the cropping system (Li et al., 2023; Liu et al., 2022; Kumar et al., 2023). Pulse-based cropping systems can therefore contribute to improved soil fertility and productivity of subsequent crops when appropriately integrated into diversified production systems (Kaur et al., 2018; Zhao et al., 2022). Nutrient management is an important component of sustainable pulse production. Although biological nitrogen fixation can supply a substantial proportion of the nitrogen requirement of legumes, balanced application of essential nutrients is still required for optimum crop growth and productivity. Imbalanced or excessive use of chemical fertilisers may increase nutrient losses, production costs and environmental impacts. Integrated nutrient management (INM), involving appropriate combinations of inorganic fertilisers, organic manures and beneficial microorganisms, provides an approach for maintaining crop productivity while improving nutrient-use efficiency and soil quality (Wu & Ma, 2015; Paramesh et al., 2023). Studies on mungbean and other pulses have demonstrated beneficial effects of integrated nutrient management on crop growth, yield and nutrient uptake (Kumar et al., 2024; Lakshman et al., 2023; Meena et al., 2020).

A further important component of pulse-based sustainable agriculture is resource-use efficiency. Pulses can contribute to efficient use of nutrients, water and other agricultural resources through biological nitrogen fixation, crop diversification, nutrient recycling and beneficial effects on succeeding crops. Inclusion of legumes in crop rotations has been associated with improvements in the productivity and resource-use efficiency of subsequent crops. A global systematic review and meta-analysis reported yield advantages of legume-based rotations and identified several agronomic and ecological factors responsible for these benefits (Zhao et al., 2022). Pulse-based cropping systems can also contribute to restoration of soil health and resource conservation, particularly in rainfed agroecosystems (Kumar et al., 2023). Pulse crops are well suited to conservation and diversified agricultural systems. Conservation agriculture generally involves reduced soil disturbance, maintenance of soil cover and crop diversification. The incorporation of pulses into such systems can provide biological nitrogen inputs, nutrient-rich residues and diversified root systems, while contributing to soil biological activity and nutrient cycling. Research from the Indo-Gangetic Plains has indicated that conservation agriculture and crop diversification can improve soil properties, productivity and resource-use efficiency (Alekhya et al., 2024; Kumar et al., 2024). Global meta-analyses have further demonstrated that conservation-agriculture components can influence soil carbon and nitrogen storage and carbon mineralisation (He et al., 2023; N'Dri Bohoussou et al., 2022).

Pulse crops provide nutritional, agronomic, ecological and economic benefits that can contribute to sustainable agricultural production. Their role in biological nitrogen fixation, nutrient recycling, soil organic matter dynamics, microbial activity, biodiversity and resource conservation makes them an important component of diversified cropping systems (Rubiales & Mikic, 2015; Kumar et al., 2023). Pulses are also recognised for their nutritional value and potential contribution to environmentally sustainable food systems (Drewnowski & Conrad, 2024). However, pulse production is constrained by low and variable productivity, nutrient deficiencies, moisture stress, pests and diseases, weed competition, poor access to quality seed and other production and marketing constraints. Therefore, integrated production strategies involving suitable varieties, balanced nutrient management, organic amendments, biofertilisers and improved crop management are required to increase productivity while maintaining soil health and resource-use efficiency (Choudhary et al., 2020; Gupta et al., 2024). Therefore, pulse crops have considerable potential to contribute to sustainable farming while simultaneously supporting food and nutritional security, soil health, efficient nutrient management, resource conservation and environmental sustainability.

This narrative review critically analyses scientific literature concerning the role of pulses and integrated nutrient management in improving soil fertility, nutrient cycling, resource-use efficiency, crop productivity, profitability and sustainability of agricultural production systems and identifies important areas for future research gaps.

2. METHODOLOGY

2.1 Literature Search Strategy

A narrative review of approximately 60 scientific papers and other relevant sources was conducted to gather information on the role of pulse crops in sustainable agriculture, particularly their contributions to soil health, nutrient management and resource-use efficiency. The literature search included peer-reviewed research articles, review papers, book chapters and institutional publications from recognised agricultural and international organisations. The search focused on major themes including soil fertility, soil organic carbon, soil microbial activity, nutrient cycling, phosphorus availability, residue management, conservation agriculture, water-use efficiency, nutrient-use efficiency, crop diversification, climate resilience and sustainable intensification (Wu & Ma, 2015; Kumar et al., 2023; Paramesh et al., 2023). The relevance of pulses to sustainable agriculture was given particular attention because of their symbiotic association with nitrogen-fixing microorganisms and their potential contribution to nitrogen cycling and soil fertility. Literature concerning biological nitrogen fixation, rhizobial inoculation and phosphorus nutrition was therefore included because nutrient availability and microbial associations strongly influence legume productivity and biological nitrogen fixation (Divito & Sadras, 2014; Buernor et al., 2022).

The major search terms included *pulse crops*, *pulses*, *legume crops*, *sustainable agriculture*, *soil health*, *soil fertility*, *biological nitrogen fixation*, *nutrient management*, *nutrient-use efficiency*, *resource-use efficiency*, *soil organic carbon*, *nutrient cycling*, *crop rotation*, *conservation agriculture*, *water-use efficiency*, *residue management*, *climate resilience* and *sustainable intensification*. Special emphasis was placed on pulse-based cropping systems and their effects on soil properties, resource conservation and agricultural sustainability. Recent research has demonstrated that pulses can contribute to soil health restoration, resource conservation, carbon and nitrogen cycling and resilience in rainfed agroecosystems (Kumar et al., 2023; Zhao et al., 2022).

1.2 Literature Selection and Eligibility Criteria

The identified literature was screened according to its relevance to the objectives and themes of the review. Studies were included when they provided information or experimental evidence concerning one or more of the following aspects: pulse production, biological nitrogen fixation, soil fertility, soil organic carbon, soil microbial activity, nutrient availability, nutrient cycling, residue management, conservation agriculture, water- and nutrient-use efficiency, climate resilience, environmental sustainability and crop diversification. Peer-reviewed research articles and scientifically established publications were given priority, particularly recent studies providing experimental or synthesis-based evidence concerning sustainable pulse production. Earlier studies and authoritative institutional publications were also considered when they provided fundamental information on biological nitrogen fixation, soil fertility, pulse-based cropping systems or resource conservation (FAO, 2016, 2018; Rubiales & Mikic, 2015). Studies unrelated to pulse crops, soil health, nutrient management, resource-use efficiency or agricultural sustainability were excluded. Publications lacking sufficient scientific information or falling outside the objectives of the review were also excluded. Following screening and assessment of relevance, approximately 60 research papers and scientific sources were selected for detailed examination and thematic synthesis.

AI, Machine Learning and Remote Sensing in Pulse Systems

The integration of artificial intelligence, machine learning and remote sensing into pulse production can assist in yield prediction, crop monitoring, stress detection and disease identification. These technologies can combine soil, weather, crop, satellite and UAV data to support more site-specific nutrient and water management. Such approaches have potential to improve resource-use efficiency, productivity and sustainability of pulse-based production systems. However, the reliability of these technologies depends on data quality, model validation under local conditions and appropriate agronomic expertise.

1.3 Data Extraction and Thematic Synthesis

The selected literature was systematically examined and synthesised according to major themes related to the role of pulses in sustainable agriculture. These themes included pulse production and sustainable agriculture, nutritional and agricultural importance of pulses, soil health and soil organic carbon, biological nitrogen fixation and nutrient cycling, integrated nutrient management, residue management and nutrient recycling, conservation agriculture, resource-use efficiency, climate resilience, environmental and economic benefits, and constraints and future research priorities.The table below shows that globally, pulses are important food and agricultural crops, with production concentrated in several countries. During 2011–2013, India was reported as the largest producer of

pulses, accounting for approximately 24.3% of global pulse production, followed by Myanmar (7.3%), Canada (7.0%), China (6.3%), Nigeria (4.6%), Brazil 4.2%), Australia (4.2%), the Russian Federation (3.2%), Ethiopia (2.9%) and the United States (2.8%) (FAO, 2016). These data provide historical context for the global importance of pulses and should not be interpreted as current production statistics.

Table 1. Major pulse-producing countries in the world

Rank	Country	Approx. pulse production	Share/world production	Importance
1	**India**	~17.5 million tonnes	**24.30%**	World's largest pulse producer; major crops include chickpea, pigeon pea, lentil, mung bean and black gram. Important for food and nutritional security and soil fertility.
2	**Myanmar**	~5.3 million tonnes	**7.30%**	Major producer and exporter of mung bean, black gram and pigeon pea; pulses are important for farmers' income and international trade.
3	**Canada**	~5.0 million tonnes	**7.00%**	Major producer/exporter of lentil, field pea and chickpea; highly important in international pulse trade.
4	**China**	~4.5 million tonnes	**6.30%**	Produces a wide range of pulses and legumes; pulses contribute to food diversity and agricultural sustainability.
5	**Nigeria**	~3.3 million tonnes	**4.60%**	One of Africa's major pulse producers, particularly important for cowpea production, food security and smallholder livelihoods.
6	**Brazil**	~3.0 million tonnes	**4.20%**	Major producer of common beans and other legumes; pulses are important in the national diet and farming systems.
7	**Australia**	~3.0 million tonnes	**4.20%**	Important producer and exporter of chickpea, lentil and field pea; pulses contribute to crop diversification and soil fertility.
8	**Russian Federation**	~2.3 million tonnes	**3.20%**	Important producer of peas, lentils and chickpeas; pulse production is expanding as part of diversified cropping systems.
9	**Ethiopia**	~2.1 million tonnes	**2.90%**	Major African producer of faba bean, chickpea and field pea; pulses are important for protein supply and soil fertility.
10	**United States**	~2.0 million tonnes	**2.80%**	Produces dry beans, peas, lentils and chickpeas; pulses contribute to food, feed, trade and diversified agricultural systems.

Source: FAO (2016). The production figures and shares refer specifically to the 2011–2013 period.

The results of the reviewed studies were synthesised under the following major themes:

1. Pulse crops and sustainable agricultural production.
2. Nutritional and agricultural importance of pulses.
3. Soil health, soil organic carbon and soil biological activity.
4. Biological nitrogen fixation, nutrient cycling and nutrient management.
5. Crop residues, nutrient recycling and soil fertility enhancement.
6. Conservation agriculture and resource-use efficiency.
7. Water-use efficiency, crop diversification and climate resilience.
8. Environmental, economic and ecosystem benefits, constraints and future research priorities.

The results of the reviewed studies were compared to identify major trends, supporting evidence, limitations and research gaps. Particular attention was given to the effects of pulses on soil fertility, biological nitrogen fixation, soil organic carbon, microbial activity, nutrient availability and efficient use of water and nutrients. Evidence from pulse-based rotations and diversified cropping systems was also considered because crop diversification can influence soil properties, productivity and resource-use efficiency (Li et al., 2024; Zhao et al., 2022).

1.4 The Review's limitations are as follows:

The review has several limitations. The selected studies differed considerably in pulse species and varieties, soil types, agro-climatic conditions, cropping systems, tillage practices, nutrient-management systems, rainfall patterns and experimental duration. Such variation makes direct comparison of results difficult. Biological nitrogen fixation is particularly variable and is influenced by crop species and cultivar, soil fertility, climate, rhizobial effectiveness, nutrient management and cropping sequence (Divito & Sadras, 2014; Buernor et al., 2022). Long-term field experiments are required to better quantify the effects of pulse-based systems on soil organic carbon, carbon sequestration, nutrient cycling, soil microbial functions, productivity and greenhouse-gas emissions. Meta-analyses have demonstrated that crop diversification, conservation agriculture and legume incorporation can affect soil carbon and soil functions, but the magnitude of these effects varies among environments and management systems (He et al., 2023; Li et al., 2023; Tadiello et al., 2023).

Further research is also required on precision agriculture, remote sensing, digital technologies, site-specific nutrient management, life-cycle assessment, economic evaluation and farmer-level adoption of sustainable pulse production practices. Despite these limitations, the available evidence indicates that pulses can contribute to soil health, nutrient cycling, resource-use efficiency, climate resilience and sustainable agricultural production (Kumar et al., 2023; Zhao et al., 2022).

2. RESULT

3.1 Pulse Crops and Their Importance in Sustainable Agriculture

Pulse crops are an important group of grain legumes belonging mainly to the family Fabaceae and include chickpea, lentil, field pea, pigeonpea, mungbean, blackgram and cowpea. They play an important role in sustainable agricultural systems because of their nutritional, biological, ecological and agronomic functions. Their capacity to establish symbiotic associations with nitrogen-fixing microorganisms, contribute to nutrient cycling and diversify cereal-based cropping systems makes them particularly valuable in sustainable production systems (FAO, 2016; Rubiales & Mikic, 2015; Kumar et al., 2023). Pulse crops can be incorporated into crop rotations, intercropping systems and conservation-agriculture practices. Their relatively short growing periods can also permit their inclusion in intensified cropping systems. Legume-based rotations have demonstrated benefits for subsequent crop productivity and resource-use efficiency. A global systematic review and meta-analysis found that legume-based rotations can provide yield advantages and identified soil, climatic and management factors influencing these benefits (Zhao et al., 2022).

2.2 Nutritional and Agricultural Importance of Pulse Crops

Pulses are important sources of plant protein, carbohydrates, dietary fibre, minerals and other nutrients. Chickpea, lentil, pea, mungbean, blackgram, pigeonpea and cowpea contribute to dietary diversity and nutritional security. Recent research has highlighted the nutritional density and relatively favourable environmental characteristics of pulse crops, reinforcing their importance in sustainable food systems (Drewnowski & Conrad, 2024). In addition to their nutritional value, pulses provide important agronomic services. They contribute to the nitrogen economy of cropping systems through biological nitrogen fixation and can improve the productivity of subsequent crops when incorporated into rotations. However, the quantity of nitrogen fixed and the amount subsequently available to following crops depend on crop species, cultivar, soil conditions, rhizobial effectiveness, nutrient availability and management practices (Divito & Sadras, 2014; Buernor et al., 2022).

2.3 Contribution of Pulse Crops to Soil Health

Biological nitrogen fixation, organic matter inputs, root activity, residue decomposition and interactions with soil microorganisms are among the principal mechanisms through which pulses can contribute to soil health. Legume roots form nodules in association with rhizobia, enabling atmospheric nitrogen to be converted into biologically useful forms. This process represents an important nitrogen input into agricultural ecosystems and can reduce dependence on external nitrogen inputs under suitable conditions (FAO, 2016, 2018; Divito & Sadras, 2014). Pulse crops also contribute roots, residues and rhizodeposits to the soil. These materials can provide substrates for microbial activity and contribute to soil organic matter and nutrient cycling. Legume incorporation can influence soil organic carbon fractions, aggregation and other soil properties, although the magnitude and direction of these changes depend on environmental conditions, cropping history and management practices (Li et al., 2023; Li et al., 2024; Liu et al., 2022).

Pulse-based rotations have also been associated with improvements in subsequent crop productivity and resource-use efficiency. However, changes in soil organic carbon may require longer periods to become detectable, and short-term experiments may therefore underestimate the potential soil-carbon benefits of diversified pulse-based systems (Li et al., 2023; Tadiello et al., 2023).

2.4 Pulse Crops in Nutrient Management and Integrated Nutrient Management

Pulse crops are important components of integrated nutrient management because of their ability to obtain nitrogen through biological nitrogen fixation and their compatibility with mineral fertilisers, organic manures and microbial inoculants. Appropriate combinations of inorganic nutrients, organic amendments and beneficial microorganisms can improve nutrient availability, crop growth and productivity while maintaining soil quality (Wu & Ma, 2015; Paramesh et al., 2023). Balanced nutrient management is particularly important for effective biological nitrogen fixation. Phosphorus, potassium and sulphur influence root development, nodulation and nitrogen-fixation processes in legumes. A meta-analysis demonstrated that phosphorus, potassium and sulphur nutrition can significantly influence plant growth and biological nitrogen fixation in crop and pasture legumes (Divito & Sadras, 2014). Similarly, studies involving rhizobial inoculation and phosphorus supplementation have reported positive responses in several grain legumes (Buernor et al., 2022).

Integrated nutrient management has also demonstrated benefits in mungbean. Studies have reported improvements in growth, yield and nutrient uptake following combinations of organic and inorganic nutrient sources and microbial inoculants (Kumar et al., 2024; Lakshman et al., 2023; Meena et al., 2020). Such findings support the integration of balanced mineral nutrition, organic amendments and microbial inoculants in sustainable pulse production.

Table 3.4. Summary of nutrient-management and bio-inoculant studies in pulse crops

S/N	Species	Region	Practice/nutrient management	Main outcome	Effect size	Source
1	**Mungbean (Vigna radiata)**	Kashmir, India	5 t FYM ha^{-1} + 30:50:30 kg NPK ha^{-1} + Rhizobium + PSB	Improved growth, nodulation, yield and test weight	**918 kg grain ha^{-1}; 72.22% higher** than control (518 kg ha^{-1})	Pir et al. (2009)
2	**Blackgram (Vigna mungo)**	Eastern Uttar Pradesh, India	Soil-test-based NPK + 10 t FYM ha^{-1} + Rhizobium + 30 kg S ha^{-1} + Mo	Increased grain, stover and biological yield and nutrient uptake	**959 kg grain, 2,479 kg stover and 3,438 kg biological yield ha^{-1}**	Chaudhary et al. (2016)
3	**Soybean (Glycine max)**	Ghana / international	Rhizobium inoculation + P supplementation	Combined biological and mineral inputs improved yield	Rhizobium + P response: **92.6%**	Meta-synthesis (2022)
4	**Cowpea (Vigna unguiculata)**	Ghana / international	Rhizobium inoculation + P supplementation	Combined biological and mineral inputs improved yield	Rhizobium + P response: **133.3%**	Meta-synthesis (2022)
5	**Groundnut (Arachis hypogaea)**	Ghana / international	Rhizobium inoculation + P supplementation	Combined biological and mineral inputs improved yield	Rhizobium + P response: **43.1%**	Meta-synthesis (2022)
6	**Common bean (Phaseolus vulgaris)**	Global	Rhizobia + plant-growth-promoting rhizobacteria co-inoculation	Improved plant growth and productivity	Yield increase of approximately **34%**	Global meta-analysis
7	**Chickpea (Cicer arietinum)**	Global	Rhizobia + plant-growth-promoting rhizobacteria co-inoculation	Improved plant growth and productivity	Yield increase of approximately **19%**	Global meta-analysis

3.4 Strengthens

The available evidence indicates that nutrient management in pulse crops can benefit from appropriate combinations of mineral nutrients, organic amendments and beneficial microorganisms. Phosphorus, potassium and sulphur are particularly important because deficiencies can affect root growth, nodulation and biological nitrogen fixation (Divito & Sadras, 2014). Field studies in mungbean have also demonstrated positive responses to integrated nutrient management involving phosphorus, organic manure and microbial inoculants (Pir et al., 2009).
There is evidence of complementary effects between rhizobial inoculation and phosphorus supplementation in grain legumes. A meta-synthesis found positive yield responses to rhizobial inoculation and phosphorus supplementation

in several grain legumes, although the magnitude of response differed among crops and environments (Buernor et al., 2022). Therefore, the combination of balanced mineral nutrition, organic sources and microbial inoculants may provide an effective strategy for improving nutrient-use efficiency and sustaining pulse productivity.

3.5 Pulse Crops and Nutrient Cycling

Pulses contribute to nutrient cycling through biological nitrogen fixation, root turnover, residue decomposition and interactions with soil microorganisms. Nitrogen fixed by legumes is incorporated into plant tissues, and a portion may subsequently enter the soil through root turnover and residue decomposition. The amount of nitrogen transferred to subsequent crops depends on residue quantity and quality, decomposition conditions, crop management and environmental factors (FAO, 2016; Kumar et al., 2023). Pulse-based systems also interact with phosphorus and other nutrient cycles. Rhizobia, phosphate-solubilising microorganisms and other beneficial rhizosphere organisms can contribute to nutrient mobilisation and microbial activity. Phosphorus nutrition is particularly important because adequate P availability can support root development, nodulation and biological nitrogen fixation in legumes (Divito & Sadras, 2014; Gupta et al., 2024).

3.6 Pulse Crops and Resource-Use Efficiency

Efficient utilisation of water, nutrients, energy and other agricultural resources is a fundamental principle of sustainable agriculture. Pulses can contribute to resource-use efficiency through biological nitrogen fixation, crop diversification, nutrient recycling and beneficial effects on subsequent crops. A global systematic review and meta-analysis demonstrated yield advantages associated with legume-based rotations and identified improvements in resource-use-related outcomes in several cropping systems (Zhao et al., 2022). Water is another critical resource in pulse production. Water productivity can vary substantially according to crop species, agro-climatic conditions, soil characteristics, irrigation practices and management. Research on mungbean has specifically examined water-use efficiency under controlled conditions, demonstrating the importance of water-management strategies in improving mungbean productivity (Zhong et al., 2024). More broadly, pulse-based cropping systems can contribute to efficient use of available resources when combined with appropriate agronomic management (Kumar et al., 2023).

3.7 Pulse Crops in Conservation Agriculture

Pulse crops can play an important role in conservation agriculture through crop rotation, reduced soil disturbance, residue retention and crop diversification. These practices can influence soil physical, chemical and biological properties and may improve nutrient cycling and water management. Meta-analyses have shown that conservation-agriculture components can affect soil organic carbon and total nitrogen storage and carbon mineralisation (He et al., 2023; N'Dri Bohoussou et al., 2022). In the Indo-Gangetic Plains, integration of pulses into diversified conservation-agriculture systems has been identified as an approach for improving soil health and crop productivity. Recent studies have highlighted the potential of diversified conservation agriculture to improve productivity and soil properties while reducing environmental impacts (Alekhya et al., 2024; Kumar et al., 2024).

3.8 Pulse Crops and Climate-Smart Sustainable Agriculture

Pulse crops can contribute to climate-smart agriculture through biological nitrogen fixation, crop diversification, nutrient cycling and potentially reduced dependence on synthetic nitrogen fertilisers. Improving nitrogen-use efficiency can also contribute to reducing environmental impacts associated with nitrogen fertiliser production and use. Crop diversification through the inclusion of legumes can improve the resilience and sustainability of cropping systems (Rubiales & Mikic, 2015; Zhao et al., 2022). Conservation agriculture and diversified cropping systems can additionally influence soil carbon dynamics and greenhouse-gas-related outcomes. Global analyses have shown that conservation-agriculture practices can affect carbon mineralisation and soil carbon and nitrogen storage (He et al., 2023; N'Dri Bohoussou et al., 2022). However, the magnitude of these benefits varies with soil type, climate, crop species, cultivar, nutrient availability and management practices. Therefore, location-specific research remains necessary for developing appropriate pulse-based management systems.

3.9 Constraints to Pulse Production and Sustainable Utilisation

Despite their potential contribution to sustainable agriculture, pulse crops face several biological, environmental and socioeconomic constraints. Important production constraints include insect pests, diseases, drought, heat stress, waterlogging, nutrient deficiencies, poor soil fertility and weed competition. Climate variability can affect crop

establishment, flowering, pod development and grain filling, thereby contributing to unstable productivity. Nutrient and management constraints are also important. The productivity response of legumes to phosphorus, potassium, sulphur and biological inoculants can vary according to soil and climatic conditions (Divito & Sadras, 2014; Buernor et al., 2022). Poor access to quality seed, improved varieties, extension services, mechanisation, markets and post-harvest facilities can further restrict the adoption and profitability of pulse production systems.
Therefore, sustainable pulse production requires an integrated approach involving improved cultivars, balanced nutrient management, appropriate organic amendments, effective biofertilisers, improved crop establishment, water management, weed and pest management and suitable cropping-system diversification (Choudhary et al., 2020; Gupta et al., 2024; Kumar et al., 2023). Such integrated approaches can help increase pulse productivity while maintaining soil health, resource-use efficiency and environmental sustainability.

Geographical Scope

The review covers the global research undertaken on pulse crops across different agro-climatic regions of the world. Pulses such as chickpea, lentil, pigeonpea, mungbean, blackgram and cowpea play an important role in sustainable agriculture through biological nitrogen fixation, nutrient cycling, improvement of soil biological activity and crop diversification. Research conducted in different countries has examined pulse production, integrated nutrient management, soil health, resource-use efficiency and sustainable production practices under diverse environmental conditions. The review also encompasses studies from major pulse-growing regions across Asia, Africa, Europe, the Americas and other parts of the world. Special attention is given to the influence of soil properties, climate, cropping systems and crop management practices on pulse productivity, soil fertility and sustainability. The geographical scope further includes research on balanced fertilisation, organic manures, biofertilizers, water management, residue recycling and other resource-conserving practices. Overall, the review provides a comprehensive global perspective on the role of pulse crops in developing productive, sustainable and resource-efficient agricultural systems in various geographical regions of the world.

Conclusions

The literature reviewed shows that pulse crops play an important role in Sustainable Agriculture with their ability to fix biological N, to cycle nutrients, to increase soil biological activity and also to diversify. Pulse-based cropping systems can also help to boost productivity of subsequent crops and increase N & W Use efficiency. Balanced fertilisers, organic manures, biofertilisers, water use efficiency, residue recycling and appropriate varieties can be used to further improve these benefits. However, the performance and benefits of pulse crops depend upon soil, climate, crop sequence and management. There is still a lack of key research on long-term effects on soil organic carbon, soil nutrient balance, soil biological activity, water productivity and greenhouse-gas emissions. Therefore, long-term, multi-location and location-specific studies are required to facilitate a better understanding and improvement of the contribution of pulse crops to sustainable agriculture.

Declaration of AI Use

The manuscript was prepared through the intellectual contribution and efforts of the author(s) in design, data analysis, interpretation, and scholarly content of the manuscript. Grammarly and ChatGPT have been used only to help with the revision of the manuscript, with regard to grammar and reference formatting. The author(s) accept full responsibility for the accuracy, integrity and final content of the manuscript.

Authorship contribution statement

Abdulrauf Mohd Hamisu: Conceptualisation, Methodology, Investigation, Data Curation, Formal Analysis, Visualisation, Writing - Original Draft, and Writing - Review & Editing; Shyam Datta Waghmare, Nitesh Samadhiya, Ado Muhammad, Bala Usman Mustapha and Mannir Abdulmumini Yawale: Methodology, Supervision, Validation, and Writing - Review & Editing; Surender Singh Siwach, Kabiru Hamisu and Bashir Ahmad Babaj (Author 3 & 4): Validation, Visualisation, and Writing - Review & Editing. All the remaining authors contributed to the grammatical checkup.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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