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REVIEW ARTICLE

Diversified legume-based crop rotation strategies for enhancing crop yield - A comprehensive review

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Abstract

Crop rotation is a cornerstone practice in sustainable agriculture, it plays a crucial role in enhancing soil fertility, pest and disease management and overall crop productivity. This review is to optimize crop rotation strategies for improving the yield and sustainability of black gram (*Vigna mungo* L.), a pulse crop highly responsive to rotational practices. By synthesizing recent research, the study examines the effects of crop sequences, intercropping systems and legume-non-legume integrations on both crop productivity and soil health. Methodologically, it adopts a critical evaluation of existing literature to analyze the mechanisms underlying synergistic and antagonistic crop interactions, while also considering modern approaches such as precision agriculture and agroecological principles for refining crop rotation. The key conclusions highlight that crop rotation not only enhances soil fertility and productivity but also plays a pivotal role in pest and disease management. Furthermore, intercropping and integration with non-leguminous crops significantly improve black gram growth and yield while sustaining soil quality. The review emphasizes that precision-driven and ecologically grounded strategies present promising opportunities for fine-tuning rotations and future research to further adapt and refine these approaches for sustainable legume production.

Keywords: crop rotation; crop rotation strategies; intercropping; soil fertility; soil health; sustainability

Introduction

Crop rotation is the practice of growing different crop species on the same piece of land according to their respective seasons (1, 2). This contrasts with intercropping, which is the practice of growing two or more crops simultaneously on the same piece of land (3), or continuous monoculture, which is the practice of growing a single variety repeatedly on the same piece of land. Crop rotations have been repeatedly shown to be effective method of minimizing soil erosion, improving water use efficiency (WUE) and maintaining high yields (4, 5). The benefits of involving legumes in crop rotation shows in Fig. 1.

Crop rotation prevents the depletion of specific nutrients in the soil. For example, legumes improve soil fertility through the symbiotic association with microorganisms, such as rhizobia, which fix the atmospheric nitrogen and make nitrogen available to the host and benefits subsequent crops by a process known as biological nitrogen fixation (6). It also reduces the build-up of pest and diseases associated with monoculture, as different crops attract different pests (7-9). Monoculturing leads to an increase in pests and diseases which target that specific crop. By rotating crops, farmers can disrupt pest and disease cycles, reduces the need for chemical pesticides and fungicides (10, 11). Crop rotation, which involves cultivating various crops during different seasons within the same field, stands out as one of the most efficient methods for managing soil-borne plant diseases (12).

Rotating legumes and non-legumes optimize the nutrient use, with legumes fix nitrogen and non-legumes utilizing it efficiently (13). Combined rotations enhance the soil structure and organic matter, thereby improves long-term soil fertility. Diversifying crops in rotation reduces risk, stabilizes yield and supports sustainable agricultural practices (9).

Rotating different crops diminishes disease inoculum due to the unavailability of hosts or by other effects such as organic residues that can influence pathogens or antagonistic organisms (14). Allelopathic effect of certain crops can suppress weed growth better than others. Rotating crops with different growth habits and weed competitiveness can help manage weed populations naturally, reducing much reliance on herbicides, which all together ultimately increases yield (15-17). Crop rotation can help optimize water usage by alternating between crops with

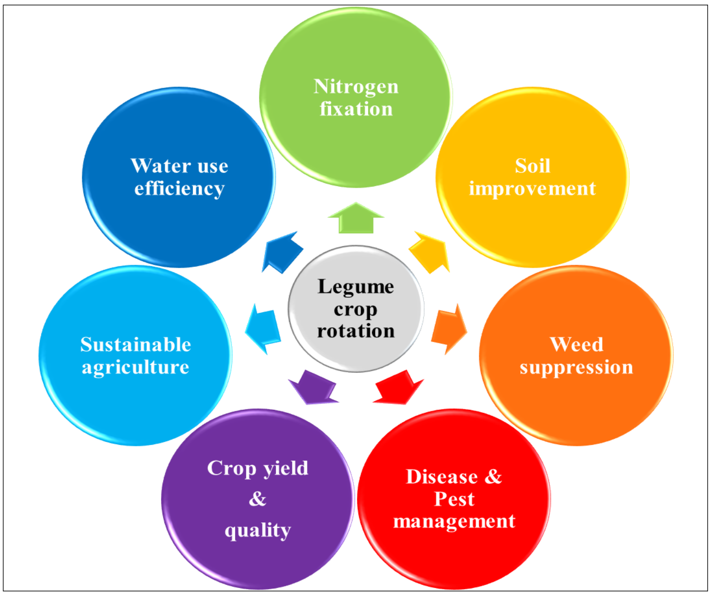

Fig. 1. The benefits of involving legumes in crop rotation.

shallow and deep root systems, thereby reducing irrigation needs and minimizing water wastage (18-20). Crop rotation enhances both yield and profit while facilitating sustainable production. Integrating legumes into the rotation, improves not only the cropping intensity, also increases the overall food availability and net profits from sales (9). Incorporating a legume cover into crop rotation could add a significant quantity of nitrogen in the soil for succeeding crop. The residual plant parts of legumes serve as a green manure benefited the succeeding crop through nutrient enhancement in the soil.

Crop rotation strategies for legume yield enhancement

Monoculture versus crop rotation

Monoculture, while straightforward in its execution, can have several drawbacks when applied to legume cultivation. Growing gram exclusively in monoculture can also deplete specific nutrients from the soil (21). Without the benefits of crop rotation, the same crop continuously extracts the same nutrients year after year, leading to imbalances in soil fertility (22). Over time, this could result in reduced yields and necessitate increased fertilizer inputs to maintain the productivity. Crop rotation facilitates nutrient cycling in the soil, as different crops have varying nutrient requirements and contribute different amounts of organic matter when residues are incorporated into the soil. This improves the nutrient availability and balances soil fertility, supporting optimal gram growth and development (23). The constraints of monoculture and prospectus of crop rotation shown in Fig. 2 and 3, respectively.

Monoculturing legumes provides a continuous habitat for pests and diseases specific to a legume crop (24). Without the natural breaks introduced by crop rotation, these pests and diseases can thrive, increasing the risk of crop damage and yield losses. Crop rotation disrupts pest and disease cycles by alternating between different crops with varying susceptibility to specific pests and diseases (25). By introducing non-host crops into the rotation, farmers can reduce the build-up of pest and disease pressure on legumes, resulting in healthier plants and higher yields (26).

In legume monoculture systems, the same weeds that thrive in legume fields can establish and spread without interruption (24). This could result in increased weed pressure, as weeds compete with crop for resources such as water, sunlight and nutrients. Over time, the unchecked weed growth could reduce legume yields and increase the cost of production related to weed control measures (27). Rotating legumes with crops of different growth habits and canopy structures suppress the weed growth and reduce weed pressure (28). The natural weed management strategy minimizes the competition for resources and reduces the requirement for herbicides, contributing to cost savings, improves soil health, environmental sustainability and yield improvement (29, 30).

Monoculture can contribute to soil degradation, including compaction, erosion and loss of soil structure and fertility (31, 32). Without the rotational benefits of different crops, the soil becomes less resilient and more prone to erosion and nutrient loss. Soil degradation can negatively impact legumes

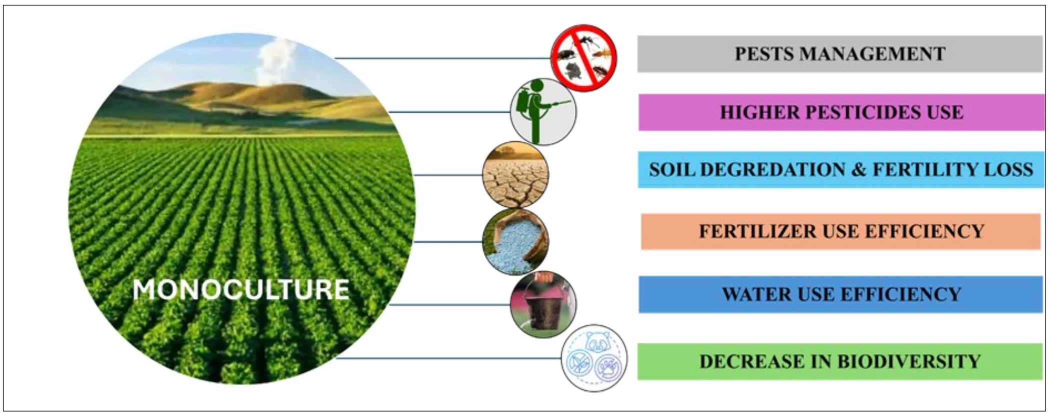

Fig. 2. Constraints of monoculture.

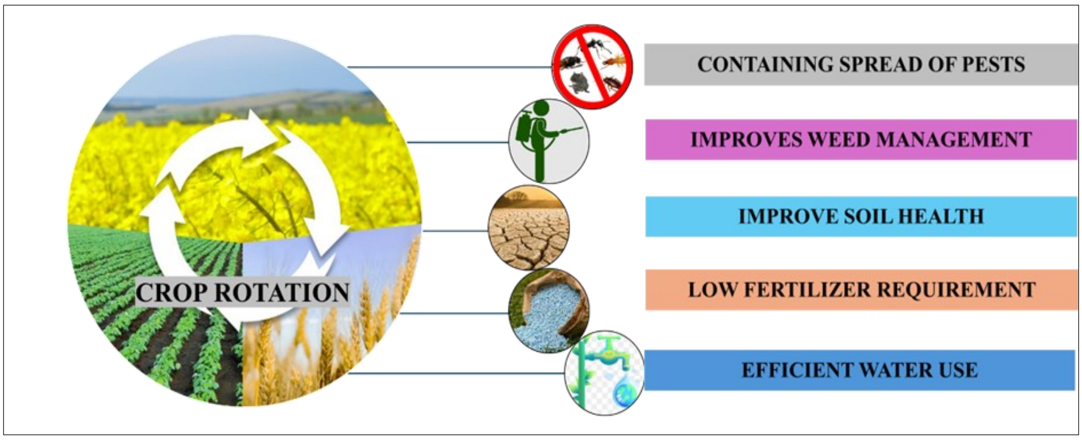

Fig. 3. Prospectus of crop rotation.

productivity and long-term soil health, posing significant challenges for sustainable agriculture (23, 33). Crop rotation improves the soil conditions by diversified crop species and cropping patterns (28). Incorporation of leguminous crops such as soybeans or cowpeas into rotation adds organic matter into the soil, fixes atmospheric nitrogen and enhances microbial activity. These benefits could promote the soil fertility, enhance the soil structure and increase the nutrient availability for improving the subsequent legumes productivity (34, 35).

Impact of different crop sequences on productivity of legumes

Different crop sequences have a complex effect on legume production that includes elements of soil health, nutrient availability, managing pests and diseases and overall agricultural sustainability (36). Effective crop sequencing strategies, such as crop rotation, legume intercropping and polyculture systems, enhance legume yield by promoting the soil fertility through nitrogen fixation, improving the resource utilization and mitigating the pest and diseases and reduce weed competition (37). Different crop sequences and their impact on legume yield is shown in Table 1.

Intercropping systems and their influence on legumes productivity

Intercropping system which allows more efficient use of resources such as sunlight, water and nutrients. Legumes and complementary crops with varying resource needs could be paired to maximize resource use and leading to increased overall productivity (38). For example, crops with shallow root systems intercropped with legumes, which has a deeper root system, allowing for better soil exploration and nutrient uptake (39). Intercropping helps to manage pests and diseases by disrupting their host plants and reducing their spread. By planting black gram alongside crops that are less susceptible to the same pests and diseases, damage to their black gram crop could be minimized. Additionally, some intercropping combinations may attract beneficial insects or repel pests, further enhancing pest management efforts (40). When Faba bean + Field pea intercropping with 25:75 ratio, the obtained total grain yield was 4040 kg ha^{-1} (1050 + 2990 grain yield kg ha^{-1}) with 1.14 LER (Land Equivalent Ratio) which is when compared to solo crop (41). Table 2 showing intercropping systems and its effect on legumes productivity.

Intercropping effectively suppress the weeds by creating a dense canopy that shades the soil and inhibits weed growth. Pairing legumes with crops that have vigorous canopy development smother weeds and reduce competition for resources, leading to improved weed control and higher legume yields (42). This system could enhance soil health by increasing the organic matter inputs, improving the soil structure and promoting the microbial activity. Leguminous intercrops, such as cowpeas or pigeon peas, fixes atmospheric nitrogen, enriching the soil with nutrients and benefiting subsequent crops.

Intercropping leads to improved soil fertility and better overall growing conditions for legumes (43). Intercropping systems enhance climate resilience by providing a buffer against environmental stresses such as drought, heat or pest outbreaks. Diverse cropping systems are less susceptible to total crop failure, as the different crops may respond differently to adverse

Table 1. Impact of different crop sequences on legumes yield

Crop sequences	Impact on legumes yield	References
Cereal-legume rotations		
Rice-black gram	This is a common rotation where rice is followed by black gram. The stubbles from rice could provide organic matter, but nitrogen availability might need to be supplemented for optimal black gram growth	(96)
Wheat-black gram	This sequence could be beneficial as wheat stubble adds organic matter and wheat has a different root structure that could improve soil porosity for the subsequent black gram crop	(99)
Legume-legume rotations		
Soybean-black gram	Enhances soil nitrogen levels significantly, but care must be taken to manage potential pest and disease, weeds build-up due to the similar host range	(100)
Chickpea-black gram	Both crops being legumes can fix nitrogen, but similar attention is needed to pest and disease management, weed management and nutrient requirement	(101)
Other rotations		
Maize-black gram	Maize added substantial organic residue, improved the soil structure. However, maize being a heavy feeder may require additional soil fertility management for subsequent black gram planting	(98)
Vegetable-black gram	Rotations with vegetables like potatoes or leafy greens could be beneficial for pest and disease management, but nutrient management needs to be closely monitored due to varying nutrient requirements	(97)

Table 2. Intercropping systems and its effect on legumes productivity

Intercropping systems	Base crop	Intercrop	Effect	Reference
Legume/Legume intercropping system	Pigeon pea	Groundnut	Groundnut makes rapid canopy coverage of the ground and uses the resources more efficiently	(43)
	Pigeon pea	Green gram (grain)	117.5 kg N ha^{-1} added to the soil which is available for succeeding crop	
	Pigeon pea	Black gram (grain)	85.1 kg N ha^{-1} added to the soil which is available for succeeding crop	
	Field pea	Faba bean	The ratio of 75:25 shown improvement in grain yield when compared to solo crop	(41)
Legume/Cereal intercropping system	Maize	Green gram or Mung	It was observed that the highest utilization of P occurred when P was banded near each mung row	(97)
	Sorghum	Pigeon pea	Intercropping sorghum + pigeon pea with 2:2 row ratio on raised bed planting had the highest pigeon pea equivalent yield, net returns and benefit: cost ratio	(102)

conditions. This resilience helps to mitigate the impacts of climate variability on legumes productivity (44).

Legume-non-legume rotations

Legumes, through their symbiotic relationship with *Rhizobium* bacteria, fix atmospheric nitrogen into the soil and thereby enhances the soil fertility and reduces the need for synthetic fertilizers. Legumes improve soil structure and organic matter content, which enhances soil aeration and water retention. Legumes are rich in protein, fiber, vitamins and minerals, providing essential nutrients for human and animal diets. Legumes offer diverse uses and market opportunities, from fresh vegetables to processed products like tofu and soy milk (45). Non-legumes, including cereals, fruits, vegetables and tubers, are staple foods worldwide, providing essential carbohydrates and nutrients. Non-legumes like cover crops prevent soil erosion, enhance water retention and add organic matter to the soil. Major non-legume crops like rice, wheat and maize are critical for global food supply and economic stability. Non-legumes contribute essential vitamins, minerals and dietary variety, supporting balanced and healthy diets (46). A two-crop rotation, such as corn (*Zea mays*) and soybean (*Glycine max*) or corn and alfalfa (*Medicago sativa*) in alternate years, uses the legume to provide complementary inorganic nitrogen in the soil for the succeeding crops. For a long time, legumes have been known as the soil building crops because the biological, physical and chemical properties of the soil are significantly improved when legumes are grown on it. It therefore makes good sense agriculturally to alternate them with cereals and other crops that require large amounts of nitrogen. Rotate legumes with non-leguminous crops such as cereals (rice, wheat, maize) or oilseeds (sesame, groundnut) (43). Legumes like black gram fix atmospheric nitrogen, enriching the soil with this essential nutrient. Non-leguminous crops utilize the nitrogen, which is fixed by leguminous crop in soil, contributing to their growth without the need for additional fertilizers (47). This rotation helps maintain soil fertility, prevents nitrogen depletion and reduces reliance on external nitrogen inputs (48). Rotate black gram with deep-rooted crops like maize, sorghum or pearl millet. Deep-rooted crops penetrate deeper soil layers, improving soil structure and accessing nutrients beyond the reach of shallow-rooted crops (16). Black gram benefits from the improved soil structure, enhanced nutrient availability and reduced soil compaction following the deep-rooted crops which ultimately increases yield (49). According to experiment conducted (50) on average, when wheat was the preceding crop, all legumes except faba bean for seed, produced higher canola and barley yields. The legumes had little negative effect on canola oil or barley protein concentration. The results indicate that growing legumes for seed before hybrid canola can improve canola and subsequent barley yield without negatively affecting canola oil or malting barley protein.

However, despite these benefits, some challenges remain, Continuous or poorly managed legume-legume rotations can lead to pest and disease carry-over, particularly nematodes, wilt pathogens and pod borers, which reduce yields in subsequent cycles. Excessive reliance on legumes may also deplete certain non-nitrogen nutrients such as phosphorus and potassium if not supplemented through fertilization or residue management. In some regions, water stress during legume growth limits their nitrogen-fixation efficiency, reducing benefits for following crops. Additionally, labour and input costs for managing diversified rotations may be higher for smallholder farmers. Addressing these challenges through integrated pest management, balanced nutrient supplementation and site-specific rotation planning is essential to fully realize the benefits of legume-non-legume rotations.

Cover crops and their role in productivity

Cover crops play a vital role in enhancing black gram yields and promoting sustainable agricultural practices. When strategically planted between cash crop cycles, they provide multiple benefits such as soil enrichment, weed suppression, moisture conservation, nutrient cycling, pest and disease regulation, erosion control and improved crop rotation dynamics (51). Leguminous cover crops such as cowpea and sun hemp contribute to biological nitrogen fixation, enriching the soil with readily available nitrogen that directly supports the nutrient needs of black gram in subsequent rotations. Non-leguminous cover crops like sorghum and pearl millet are particularly effective for weed suppression and soil structure improvement, as their dense canopy reduces weed competition and their extensive root systems prevent compaction, thereby improving the rooting environment for black gram (52). Similarly, brassica species such as mustard act as biofumigants, releasing natural compounds that help suppress soil-borne pathogens and pests, which would otherwise limit black gram productivity. Grasses like rye and oats serve as erosion-preventing and moisture-conserving cover crops, protecting the soil surface and retaining water for the following black gram crop. By combining these functional roles, cover crops not only enhance soil health and fertility but also create favourable ecological conditions that directly improve the growth, resilience and yield of black gram in rotation systems (53).

Complimentary impacts of cover crops

Moreover, certain cover crops, particularly leguminous species like cowpea or clover, have the unique ability to fix atmospheric nitrogen through symbiotic relationships with nitrogen-fixing bacteria in their root nodules (54, 55). This nitrogen fixation process results in the accumulation of nitrogen-rich biomass, which when incorporated into the soil, releases nitrogen, benefiting subsequent crops such as legumes by reducing the need for synthetic nitrogen fertilizers and supporting healthy plant growth (56). Integrate leguminous cover crops such as cowpea, sun hemp or green gram into the rotation with black gram (57). Table 3 shows the list of different legume cover crops and their benefits in crop rotation.

Leguminous cover crops add nitrogen to the soil through biological nitrogen fixation, enriching soil fertility (58). In addition to soil health benefits, cover crops play a crucial role in weed management. By shading the soil surface and competing for resources like water, nutrients and sunlight, cover crops suppress weed growth, thereby minimizing weed pressure on subsequent cash crops like black gram.

Weed suppression

Natural weed suppression reduces the reliance on herbicides and promotes ecological balance within agroecosystems (59).

Table 3. Cover crops and their benefits in crop rotation

Legume cover crop	Type	Role	Benefits in crop rotation	References
Berseem Clover (*Trifolium alexandrinum*)	Summer annual or winter annual legume	Suppress weeds Prevent erosion Green manure Chopped forage	•Planted with oats or annual ryegrass, berseem clover suppresses weeds well during establishment and regrowth after oat harvest •Can be used as a nurse crop for alfalfa	
Cowpea (*Vigna unguiculata*)	Summer annual legume	Suppress weeds N source Build soil Prevent erosion Forage	•Cowpea plantings quickly shade the soil to block out weeds •Quick green manure •Companion crop •Attracts beneficial insects	(61)
Crimson Clover (*Trifolium incarnatum*)	Winter annual or summer annual legume	N source Soil builder Erosion prevention Inter-row ground cover Forage	•Crimson clover adds to the soil organic N pool by scavenging mineralized N and by normal legume N fixation	
Field Peas (*Pisum sativum* subsp. *Arvense*)	Summer annual and winter annual legume	N source Weed suppressor Forage	•Rich nitrogen source •Pulse crops (grain legumes such as field peas, fava beans and lentils) improved sustainability of dryland crop rotations by providing disease suppression, better tilth and other enhancements to soil quality	
Hairy Vetch (*Vicia villosa*)	Winter annual or summer annual legume	N source Weed suppressor Topsoil conditioner Reduce erosion	•It can provide sufficient N for many vegetable crops, partially replace N fertilizer for corn or cotton and increase cash crop N efficiency for higher yield •Widely adapted •Phosphorus scavenger	(61, 103)
Medics (*Medicago* spp.)	Winter annual or summer annual legume	N source Soil quality builder Weed suppressor Erosion fighter	•Medics earn a place in dryland crop rotations because they provide N while conserving moisture comparable to bare ground fallow •Fight with weeds •Boosts organic matter •Widely acclimated	(61, 104, 105)
Red Clover (*Trifolium pratense*)	Short-lived perennial, biennial or winter annual legume	N source Soil builder Weed suppressor Insectary crop Forage	•Widely adopted •Many economic uses •excellent soil conditioner, with an extensive root system that permeates the topsoil •Attracts beneficial insects	
Sweet Clovers (*Melilotus officinalis*)	Biennial, summer annual or winter annual legume	Soil builder Fertility source Subsoil aerator Weed suppressor Erosion preventer	•Have a greater ability to extract potassium, phosphorus and other soil nutrients from insoluble minerals •Soil structure builder •Most drought tolerant of all clover crops that produce as much biomass	(61)
White Clover (*Trifolium repens*)	Long-lived perennial or winter annual legume	Erosion protection Green manure	•Value added forage •Premier living mulch •Beneficial insect attraction	
Woollypod Vetch (*Vicia villosa* ssp. *dasycarpa*)	Cool-season annual legume	N source Weed suppressor Erosion preventer Add organic matter attract bees	•Attracts many pollinators and beneficial insects •Adda plenty of soil building organic matter	

Furthermore, leguminous cover crops contribute to moisture conservation by reducing soil evaporation, improving water infiltration and retention and minimizing runoff. This is particularly beneficial for legumes cultivation in regions with erratic rainfall patterns or limited irrigation resources, as it ensures adequate soil moisture levels for optimal crop growth and yield (60). Cover crops also serve as a valuable tool for pest and disease management. Some cover crops like Berseem clover (Table 3) suppress weeds (61). Some cover crops possess allelopathic properties, which inhibit the growth of certain weeds, pests and pathogens, thereby reducing the incidence of pests and diseases in subsequent crops like black gram (62). Additionally, leguminous cover crops provide habitat and food sources for beneficial insects and microorganisms that contribute to natural pest control and disease suppression, further enhancing crop health, resilience and productivity (63, 64).

Soil health in cropping systems

Soil health and nutrient depletion are critical factors influencing the productivity and sustainability of black gram cropping systems. Black gram, also known as urad bean or black lentil, is an important pulse crop cultivated extensively in various regions worldwide, particularly in Asia. However, continuous cultivation of black gram without proper management practices can lead to soil degradation, nutrient imbalances and reduced crop yields over time (65).

Black gram is a leguminous crop that belongs to the family Fabaceae, capable of fixing atmospheric nitrogen through symbiotic association with nitrogen-fixing bacteria (66). While this ability contributes to soil fertility to some extent, black gram cultivation still relies on soil nutrients for optimal growth and yield (67). Continuous mono-cropping of black gram can lead to the depletion of key nutrients such as nitrogen, phosphorus, potassium and micronutrients, which are crucial for plant growth and development (68). Influence of legume incorporation on soil physical, chemical and biological properties are shown in the Fig. 4 (106).

Physical properties

The physical characteristics of soil are mostly unaffected by crop husbandry techniques; however, there are significant factors related to aeration, erosion, runoff, infiltration rate and the soil's ability to retain moisture and nutrients (69). As a result, optimal tillage, root development, ground water recharge and extended soil moisture availability all depend on healthy soil, whereas poor soil physical condition can make farm operations more challenging (29, 69, 70). Inclusion of legumes in soil acts as soil conditioner and improves soil physical properties significantly (71).

Chemical properties

Crop production is influenced by nutrient dynamics, which are largely determined by the chemical characteristics of the soil and the concentration of nutrients (70). By contributing organic matter and facilitating biological nitrogen fixation (BNF), which maintains soil fertility and maximizes overall productivity, legume crops have a substantial impact on the chemical characteristics of soil (72). It is well recognized that legumes have a beneficial impact on the pH, organic carbon stock and accessible nutrients. By releasing organic acids, they change the pH of the soil, which may improve the availability of phosphorus (33) and increase soil microbial activity (73), both of which have a significant impact on nutrient dynamics. Incorporating legumes into soil improves its nitrogen content while also adding significant amounts of organic matter, vital nutrients and carbon dioxide sequestration (74-76).

Biological properties

Incorporating legumes into cropping systems significantly improves soil biological properties by enhancing nitrogen fixation and phosphorous availability, thereby boosting soil fertility and microbial activity. Nitrogen is limiting macro-nutrient in most of the agricultural soil and the requirement of nitrogen in plant is also higher than other mineral nutrients (77, 78). Rhizobia in association with legume synthesize nitrogenase enzyme which help in atmospheric nitrogen fixation. Biological nitrogen fixation assimilates as protein and glycoproteins in plant biomass (79, 80). Legume inclusion in cropping system help in

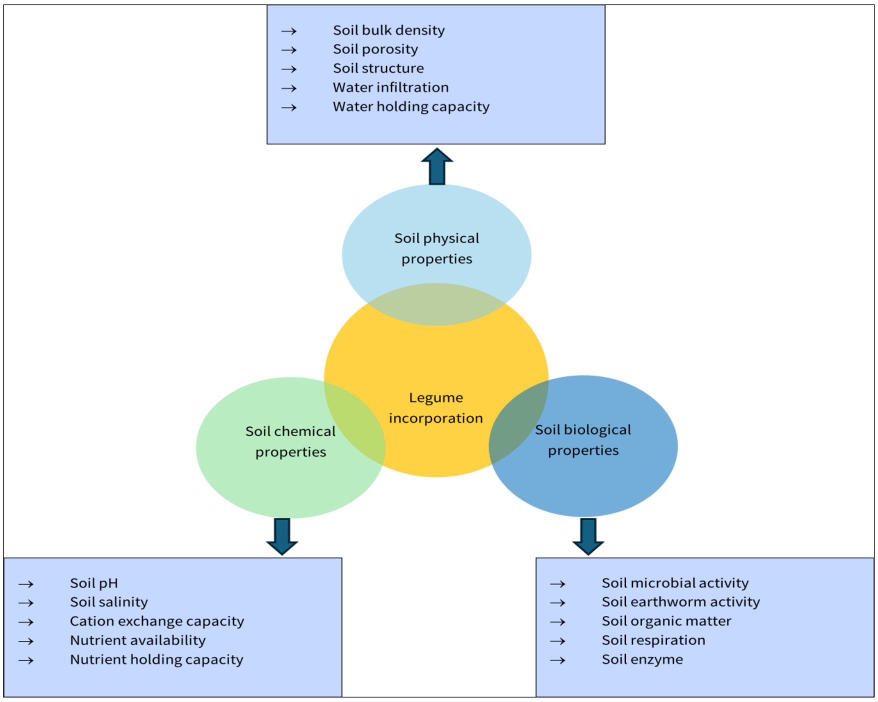

Fig. 4. Influence of legume incorporation on soil physical, chemical and biological properties.

releasing several acids in the form of root exudates (81, 82) and enhancing phosphatase enzyme activity (83). Hydrogen gas is released as byproduct during biological nitrogen fixation which encourage microbial activity, microbial carbon and microbial nitrogen in root zone. Inclusion of legumes in cropping system enhances the soil microbial activity (84).

Pulses play a crucial role in the nitrogen and phosphorus cycles, contributing significantly to climate change mitigation and the pursuit of sustainable development objectives. Legume crops aid in soil erosion reduction and mitigate global warming, thus fostering agricultural sustainability through enhanced nutrient retention (85). Plant biomass plays a crucial role in building up the soil organic carbon reservoir. Legumes stand out by storing 30 % more soil organic carbon compared to other plants due to their nitrogen-fixing capability (86). Mechanisms of legume contribution to soil fertility and crop productivity is shown in Fig. 5.

The capacity for carbon sequestration is primarily influenced by factors such as the type of legume species, its characteristics, agro-climatic conditions, the cropping system employed and the technologies utilized throughout the crop growth phase (87). Adding leguminous crop residues to the soil leads to the release of organic compounds such as organic acids, sugars, amino acids, vitamins and mucilage (88). These substances affect soil particle aggregation, leading to improved hydraulic conductivity, enhanced water infiltration and increased water holding capacity of the soil.

Moreover, the incorporation process supplies carbon and energy to soil microbes, which are essential for decomposing organic matter and facilitating nutrient recycling (89). Nitrate leaching from fields treated with legume and non-legume manure varied between 6 % to 48 % and 29 % to 94 %, respectively. Additionally, phosphorus availability increased in rice crops through green manuring when supplemented with rock phosphate mineral fertilizer. Consequently, integrating legume green manure crops with mineral fertilizers enhanced soil organic carbon levels, nutrient availability, uptake and retention, minimized nutrient leaching and weed growth, mitigated the negative impacts of agrochemicals and soil-borne pathogens and ultimately boosted rice-wheat cropping system yields (90).

Optimizing climate resilience through legume crop rotation strategies

Adaptation strategies

In contemporary climate change scenarios, soil moisture levels are fluctuating due to the variability in climate factors. These fluctuations in soil moisture content are a consequence of the changing climate variables. Variability in precipitation, temperature and land use types leads to rapid fluctuations in soil moisture levels, as the response time typically occurs within a few hours (91). Adopting site-specific crop varieties, tailored technologies and tools, diversifying crops, integrating forecasting tools and managing resources at the community level are some effective strategies for cultivating climate-resilient agriculture (92).

Modelling tools

Simulation models offer a convenient means to assess various

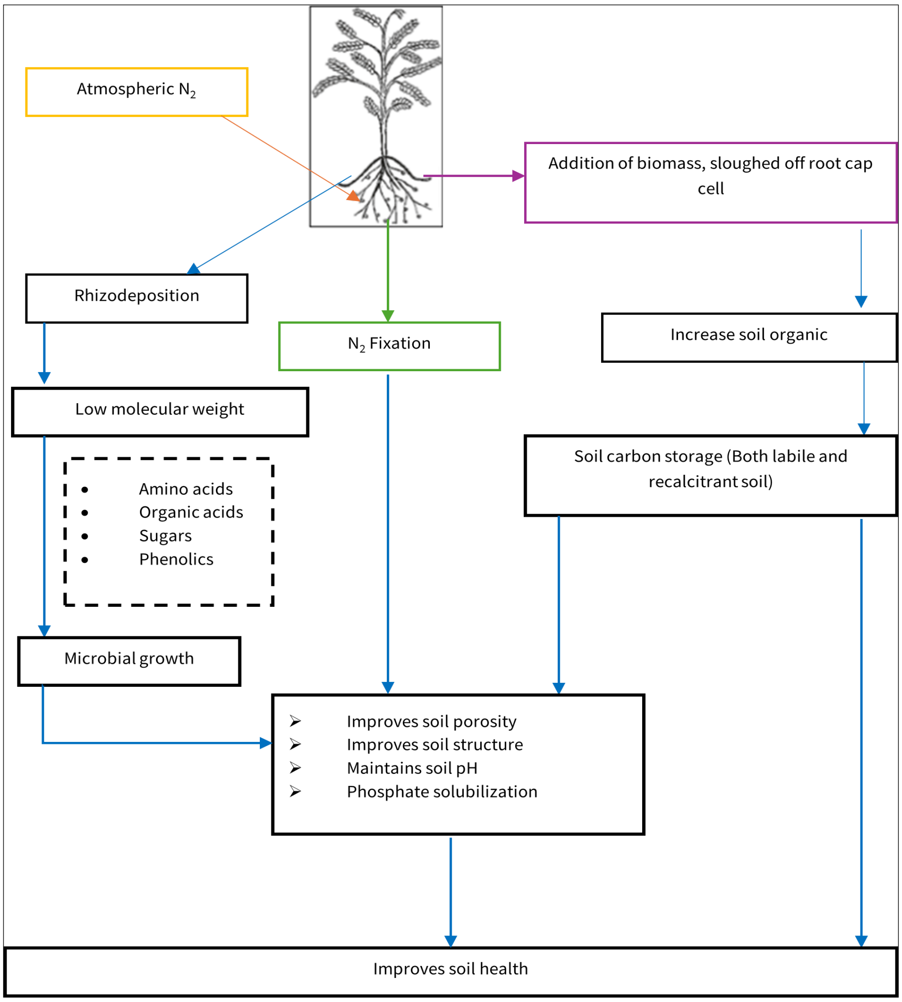

Fig. 5. Mechanisms of legume contribution to soil fertility and crop productivity.

crop management strategies, allowing for the exploration of technological adaptations to climate change (93). These options encompass enhancements in crop varieties, alterations in suggested planting schedules and densities, innovative cropping sequences, adjustments in the duration of fallow periods necessary for rainfed systems to recharge soil water and the introduction of alternative or novel crops.

Field applications

The planting date emerged as the most commonly adjusted variable. To identify an optimal planting date amidst fluctuating climates, assessments were conducted, which monitored daily soil temperature or moisture levels to a certain suitable condition for sowing (91). Irrigation scheduling is recognized as the key method for enhancing water use efficiency, boosting crop yields, augmenting water resource availability and positively impacting soil and groundwater quality (94). For each crop, three adaptation strategies were evaluated: advancing planting dates, adjusting irrigation schedules and assessing the combined impact of advancing planting dates and modifying irrigation schedules (95).

Conclusion

Integrate legumes into crop sequences to enhance soil fertility through nitrogen fixation and improve overall yield. Diversify cropping patterns and manage residues to strengthen nutrient cycling, pest control and long-term soil health. Adapt rotation strategies to local agroecological conditions for better resilience against climate variability. Leverage collaborative efforts among farmers, researchers and policymakers to design and implement context-specific rotation practices. Prioritize sustainability-focused rotations that balance productivity with environmental protection for long-term food security.

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Authors' contributions

AS contributed to the conceptualization, literature collection, manuscript drafting, editing, refinement and critical revision; KS and SE participated in the literature review, data analysis and manuscript editing; PA, TS and RA conducted the methodology review, provided technical guidance and performed proofreading, while NU and AK were involved in manuscript review and supervision. All authors read and approved the final manuscript.

Compliance with ethical standards

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Ethical issues: None

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