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Legumes in conservation agriculture: A sustainable approach in rice-based ecology of the Eastern Indo-Gangetic Plain of South Asia – an overview

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Abstract

Legumes in Conservation Agriculture (CA) have the potential to increase crop productivity and sustainability of the rice-based system. However, there is limited information available on the importance of legume crops in CA in the rice-based system of the Eastern Indo-Gangetic Plain (EIGP). Rice-based cropping is the mainstay of the people in Bangladesh, on the EIGP. These systems are the major food supplier to the region. In addition, they provide income and employment opportunities to the majority of people in the region. However, the system is facing unprecedented challenges and increased risk due to water, energy, labour and capital scarcity, which are exaggerated due to the effects of climate change. This could be further aggravated by deteriorating soil health, depleting underground water, and reduced land and water productivity which ultimately threaten sustainable food production and food security of the EIGP. Hence, sustainable crop intensification is essential, but increasing cropping intensity has reduced the yield of single crops by degrading soil properties. To address these constraints, Conservation Agriculture (CA), with a minimum tillage system, residue retention and crop diversification with legumes, could be an effective approach for improving crop productivity while sustaining the natural resources in intensive rice-based systems of EIGP. The addition of legumes in crop rotation is a suitable technique for crop diversification due to its multiple benefits related to soil health and natural resources. Diverse legume crops involving rice-based cropping exist at different agro-ecological zones in Bangladesh, and their rotation definitely could act a major role in promoting the CA in rice-based systems. Legume-based rotation offers multiple benefits, such as biological nitrogen fixation, improves soil pores through the deep root system, P-availability, soil fertility and enhanced nutrient cycling, and reducing the use of external input and thereby minimizing greenhouse gas emission and groundwater pollution, improving water productivity, and minimizes diseases and pest incidence. As a result, crop rotation with legumes has a high potential for CA and sustainable rice-based cropping systems in Bangladesh. The gaps between legume and non-legume crops in CA for each parameter suggest a noteworthy possibility for the improvement of rice-based systems in EIGP. This review suggests further sustainability improvements can be achieved through future field research focused on the inclusion of legume crops in the diverse rice-based systems under CA.

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Introduction

The current rice-based cropping systems are the backbone for the food security of the burgeoning population of the Eastern Indo-Gangetic Plain (EIGP) in South Asia[1]. The major cropping systems (rice-rice - 6.51 M ha; rice-wheat - 6.22 M ha, rice-maize - 1.0 M ha and rice-lentil - 0.7 M ha) are mostly dominated by rice (*Oryza sativa* L.) crop in the eastern IGP[2]. In this region, three different rice crops, i.e., aus (pre-monsoon rice), Aman (monsoon rice), and boro (dry season rice) rice are grown in three different seasons throughout the year, hence the cropping systems are generally referred to as rice-based cropping systems. The systems play a vital role in achieving food security and contribute to a major share of the national food basket. The system also provides income and employment opportunities for millions of people in the IGP. The rice-based system involving cereal-cereal rotation (rice-wheat) is highly productive but its high productivity is at the detriment of over-lifting of water and soil nutrients with increasing air pollution[3]. Moreover, the system is facing unprecedented challenges and risks due to climate change. The present challenges and risks are expected to become more widespread in the coming decades and pose a serious threat to sustainable crop production and food security of the IGP[4]. The falling water table, and degradation of natural resources and soil are the major factors responsible for unsustainable crop production in the IGP[5]. Hence, sustainable crop intensification is necessary to produce more food from less land. Increasing cropping intensity may diminish the yield of crops by degrading soil properties[6−8].

In rice-based systems, puddling of soil is generally used to grow rice while intensive tillage and limited return of crop residues are being used for the non-rice crop. Although puddling is beneficial for controlling weeds, transplanting seedlings and reducing deep percolation of the standing water[9], and puddle double rice under submerged conditions is a better niche for SOC sequestration[10,11], but it is difficult to establish the next dryland crop due to the degradation in the soils physical health[12]. In addition, it is well documented that the negative impacts of puddling on the soil environment, especially on beneficial microorganisms and soil aggregation[13,14]. Increasing labour scarcity and cost poses a threat to the sustainability of the system. With a falling water table, constant cultivation of high water-demanding rice crops leads to the deterioration of overall system productivity and input-use-efficiency[5,15]. The land preparation for the succeeding upland crop is hindered owing to the drying of the soil and the development of cracking soil blocks[16]. Thus, intensive tillage and irrigation are required to make a good seedbed for the next crop after rice, which causes late planting and eventually results in a lower yield of the dryland crop after rice[17]. In conventional farming systems (CT), intensive tillage along with residue removal are being used for growing the upland crop which also causes physicochemical and biological degradation[18].

In intensive rice-based systems, the continuous practice of cereal–cereal rotations over many years, to meet the food demand for the burgeoning population, has resulted in a decline in crop productivity and degradation in soil health in the IGP[19]. The reduction of soil organic carbon (SOC) was identified as one of the foremost causes of yield decline in cereal–cereal systems[20]. In addition, the imbalance of nutrient use and depletion of soil fertility[8], poor soil physical condition[21], and lack of micronutrients were the major causes of yield decline in cereal–cereal cropping systems[22]. The detrimental effects of exploitative crop production practices have given momentum to pursue alternative crop management practices and cropping systems, which can improve soil health and sustain productivity in the long run.

Concerning the challenges raised in continuous cereal-based rotations under conventional cultivation techniques, crop diversification with legumes in conservation agriculture (CA) may be an efficient strategy to increase crop productivity while protecting soil and the environment. The diversification of cereal-based rotations with legume crops improves crop and system productivity in the long run[23]. Further, the diversification of cereal-based rotations with low input demanding legume crops are being promoted to control the overutilization of groundwater, and minimize the cost of production and greenhouse gas emissions in the IGP[24]. Hence, the inclusion of legumes in CA offer potential benefits such as improved soil health and soil aggregation[25], which would lead to their residual effects on the subsequent crops.

Conservation agriculture relies on the three key principles — minimal soil disturbance, crop residue retention and crop diversification, preferably with legume crops, and has been shown to successfully reverse the process of soil degradation in large-scale commercial agriculture[6]. Further, CA is applicable in diverse agro-ecological zones and has been advocated for ensuring food security for millions of smallholders in the developing world[26]. In recent decades, many advantages are claimed for CA such as increased crop yield[27−30], improved soil organic matter and fertility, improved nutrient cycling and plant uptake[31], improved soil moisture[28,32], reduced production cost while maintaining, or increasing, crop yields[33]. Compared to the conventional farming system, CA practices generally resulted in improved SOC[34], controlled erosion, increased water-stable aggregates and infiltration, and microbial biomass carbon. Thus, legumes in CA are a vital approach to reverse the detrimental effect of conventional rice-based systems and contribute to achieving the twin goals of enhancing crop productivity and sustainability of rice-based systems in Bangladesh and the IGP in general. Therefore, the present paper deals with the role of legumes in CA in improving crop productivity while sustaining the existing rice-based cropping systems in EIGP.

Production constraints of conventional rice-based systems in eastern Indo-Gangetic plains

Several constraints hinder crop production of rice-based systems in the IGP. Mismanagement of natural resources is one of the major constraints causing stagnating or decreasing crop yield of rice-based systems in IGP[3]. Some of the key constraints, causes, consequences and possible solutions are summarized in Table 1.

Opportunities for conservation agriculture in rice-based systems

The current population of Bangladesh is about 161 million and is likely to be 186 million in 2030 and 202 million in 2050[56], with arable land being lost by 1 % every year. Hence, there is no alternative except crop intensification to meet the food demand for a growing population. Although the intensive rice-based systems are the major food supplier, the sustainability of the system is being hampered by degrading soil health, polluting environments, high input requirements[39], high production cost and low farm profits[57], stagnating or declining yield and productivity[58−60], degrading soil and water resources[61], declining soil carbon and total nitrogen, and delays in sowing[62]. Nevertheless, the CA production system is one of the effective approaches for increasing crop productivity, and profitability and ensuring food security while sustaining the natural resources in IGP[13,33]. There are several opportunities available for CA in rice-based systems, which are shown in Fig. 1.

Available Conservation Agriculture planters for small-size farms

Conservation agriculture-based on 4-wheel tractors (4-WT) has been practised for many years in developed countries. However, 4-WT is generally not compatible with mechanization

Table 1. Production constraints of conventional rice-based systems in Indo-Gangetic Plains.

Constraint	Cropping system	Cause	Consequence	Solution	References
Stagnation or decline in crop yield	Rice-wheat	Continuous cereal–cereal rotations	The decline in soil physical and chemical quality	Inclusion of legumes in rice-based system	[35]
Unsustainable production system	Rice-wheat; maize-wheat	Continuous cereal–cereal rotations	Crop productivity decline	Inclusion of legumes in rice-based system	[23]
The decline in soil organic carbon, total productivity	Rice-wheat	Continuous cultivation of rice-wheat cropping system	Decline in sustainability	Inclusion of pulses and organic nutrient management practices	[19]
Unsustainable production system	Rice-wheat	Low yield and farm income; environmental constraints and weather variability	Declined crop yield, profitability and resource use efficiency, and increased global warming potential	Adaptation of CA-based systems	[13, 36–40]
Decreasing crop productivity	Rice-wheat;Cotton-wheat	Degradation of soil physical properties	The decline in crop productivity	Application of CA-based management system - minimum or no tillage along with crop residue retention	[41]
Soil organic carbon depletion	Rice-wheat	Intensive tillage and removal of crop residue	Reducesproductivity and causes environmentaldegradation	Residue retention and ZT system	[42, 43]
				ZT and residue retention	[44–46]
	Rice-wheat/lentil-mungbean; rice-mustard-Jute	Intensive tillage and removal of crop residue	Depletion of SOC and soil N, and causes environmentaldegradation	Strip planting system and residue retention	[47–50]
Stagnation of crop yield, greenhouse gas emissions	Rice-wheat	Excess use of agricultural inputs	Increased the emission of greenhouse gases	Changes transplanted rice to direct-seeded/non-puddled rice, reduce the use of organic sources	[51–54]
Yield reduction	Rice-wheat	Heavy weed infestation	Declined yield as a result of heavy weed infestation	Incorporation of legumes in the rotation and cultivation of allelopathic crops	[52]
Input intensive deteriorates soil health and is less profitable	Rice-maize	Puddling in rice and complete residue removal	Negative impact on soil physical status for maize	ZTDSR followed by ZTM (zero tillage maize)	[55]

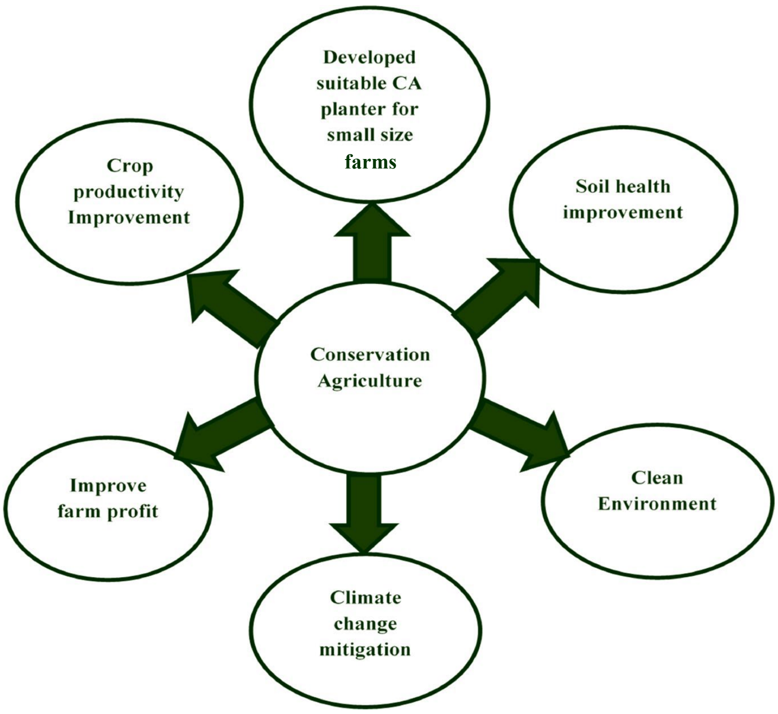

Fig. 1 Opportunities of Conservation Agriculture (CA) in intensive rice-based system.

in Bangladesh due to small and scattered fields[63,64]. A two-wheel tractor (2-WT) based machine, Versatile Multi-crop Planter (VMP) has been manufactured for crop production under the CA system in small holder farms with several planting modes of diverse crops[65]. To date, the available 2-WT and power tiller numbers are 700,000 in Bangladesh, 9,123 in Nepal and 117,200 in India, and the numbers are gradually increasing for cultivating small holder land[66]. Added to that, there are now many experienced operators of 2WTs who can provide training to new local service providers[33].

Minimize turn-around time and yield penalty due to delayed planting

In intensive rice-based cropping, limited optimum sowing time is available between the harvesting of the present and planting of the following crop. In a conventional rice-based system, rice is grown on puddled soil and ponding of water; and repeated dry tillage is followed by the broadcasting of seeds used for growing subsequent cool dry season crops. All these practices for growing diverse crops in a rice-based system lead to delays in seeding by more than a week. The short growing period and late planting, grain filling or podding stage coincide with high temperature which results in a plentiful yield of cool dry season crops. However, mechanized CA planting opens up options for reducing the turnaround time and offering sowing in time; thus, enabling crop intensification and increasing crop productivity[6,67,68].

Crop diversification opportunities

Conservation Agriculture promotes crop diversification through practicing different crop rotations and associations involving diverse crop species in a year[69]. The adoption of CA systems has several opportunities for growing different crops under crop diversification. Several crops like rice, jute, mustard, chickpea, lentil, wheat, maize, mungbean etc. could be well adapted to the new mechanized CA planting systems[67]. In CA systems, a suitable crop rotation is one of the three key principles. Crop diversification through an appropriate crop rotation reduces the soil degradation, soil salinity, infestation of insects-pests and weeds, increases crop productivity and farm profit, improves soil health, carbon sequestration and mitigate the climate change effects[34,70].

Decrease production cost and improve farm profit

Reducing the cost of production is one of the major driving factors for shifting mechanized CA planting options from conventional farming practices[71]. In CA-based planting, a mechanized single pass is applied for the sowing of seed and fertilizer simultaneously into rows that minimize production costs as compared to the conventional farming system[49,67]. Adoption of CA implies less labour, irrigation water, and other expenditures; thus improved farm profitability under CA in rice-based systems[6,33,72].

Improved crop productivity

The mechanized CA planting technique increased the crop yield and productivity of different crops in the rice-based system. The findings of several types of research conducted in eastern IGP demonstrated that CA techniques maintained equal or higher crop yields in intensive rice-based systems[14,33,48].

Environmental benefits

Conservation agriculture involving minimum tillage, surface residue cover and diversified crop rotations with legume crops offers multiple ways to minimize greenhouse gases. First, recycling crop residue by eliminating the burning of crop residues and excessive tillage reduces a huge amount of greenhouse gases emission and thereby, global warming potential[53,73].

Resilience and adaptation to climate change

The surface seeding as a result of shallow tillage under conventional cultivation techniques makes rainfed crops more vulnerable to drought[74]. However, the average seeding depth in a mechanized CA planting system is about 3–5 cm[67]. The deeper seed placement in the mechanized CA planting system makes rainfed crops more drought tolerant. The decreased soil disturbance for a longer-term period improves soil structure and infiltration rate, hence, soil water remains at the deeper soil profile; and enables plant roots to source available water from the deeper soil profile. Thus, the plant becomes more drought tolerant, increases the resilence and adapted to climate change under the CA system[75,76].

Concept of conservation agriculture

Conservation agriculture (CA) is a complete concept designed to adjust crop yields and incomes while conserving a balance of farming, economic and ecological benefits[77]. According to the FAO guideline, 'CA' is an approach to managing agroecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment[78]. Conservation agriculture has been planned on the principles of combined management of soil, water and other agricultural capitals in achieving sustainable agricultural production. The CA as a production system is underpinned by a set of three interlinked principles - minimum or no mechanical soil disturbance, permanent soil cover with residue retention, and legume-based crop rotations. Although CA can apply to all sizes of farms, its adoption is important in the areas of degrading soil, high labour and energy scarcity[79]. The details of CA-related technologies are described in Fig. 2.

Components of Conservation Agriculture

A few common terms used to describe conservation tillage, are explained as follows.

Minimum soil disturbance

The minimum tillage is one of the key principles of CA (Fig. 3). Minimum tillage (MT) involves the minimum soil disturbance required for seed and fertilizer sowing in the soil. Minimizing multiple passes of tillage and thus the reduction in soil compaction may improve soil structure and stability, soil organic matter (SOM) and soil water content, microbes and buffer soil temperature as well as avert some weeds[6]. Various methods of minimum tillage are described as follows:

No-tillage/Zero-tillage

The no-tillage system eliminates all pre-planting soil disturbance to prepare the seedbed without the opening of a 2–3 cm wide strip or small strip in the ground for seed placement to ensure adequate seed/soil contact[80]. Another term for no-tillage is direct drilling or zero tillage in which seeds are sown

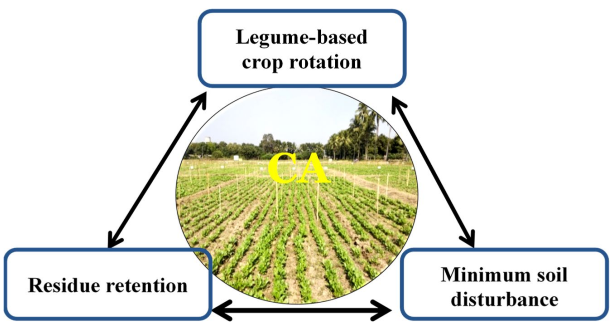

Fig. 2 Three interlinked key components of CA.

Fig. 3 Soybean in zero-till system.

without any prior soil tillage allowing only less soil disturbance (< 5 cm) by the soil tillage[81]. In no-tillage, 85 –100 % of the surface area leftovers are covered with crop residues (Fig. 3).

Strip planting system

A strip-planting system is a mode of conservation tillage. In the strip planting system, the seedbed is separated into a seeding area and an untilled tillage area (Fig. 4). The seeding area (strip width is about 4–5 cm and seeding depth is 5–7 cm) is tilled to adjust the soil and micro-climate environment for crop establishment. The inter-row zone (~20 cm, which is equivalent to 80%–85% area of the seedbed) is leftover undisturbed and protected by at least 30% retention of previous crop residue[48]. Hence, there is a potential benefit of combining conventional tillage and no-tillage by disturbing the seeding zone while leaving the inter-row undisturbed with residue cover.

Permanent raised bed planting

The permanent raised bed (PRB) system of planting is agronomic management where crops are sown on top of the raised beds. Although it can be considered as reduced tillage, there is considerable soil disturbance while forming new beds. Raised beds are developed by moving soil from the furrows[82]. There are two parts in a PRB system e.g. bed top and bed furrow (Fig. 5).

In the bed planting system, irrigation channels drain and traffic lanes are used through furrows of the bed. Usually, on the top of the bed, two to six rows are planted[83]. For a permanent bed, once developed, the bed is not demolished or displaced but is only revamped in cropping of each season[84]. With soil conditions, field slope, available machinery, crop type and irrigation technique the dimension of raised beds may vary. The bed planting system is beneficial for growing legumes and other crops in both water-logged and drought-prone regions.

Crop residue retention

Crop residue retention is one of the key components of CA, which can protect the soil from sunlight and direct raindrop impact[85]. It also guards the soil surface against erosion, while retaining C at the topsoil. According to Graham et al.[86], the threshold levels of crop residue removal must be established based on the amount of residue needed to (i) preserve soil and water, (ii) equal or increase crop production, (iii) improve SOM pools, (iv) decrease net GHG emissions, and (v) reduce non-point source pollution. With the emergence of a range of planters for 2-WT, there is a need to estimate the ideal residue retention for CA in rice-based cropping systems.

Crop diversification involving legume crops in rotation

Crop rotation involves growing diverse crops in a given period on the same field and it is one of the major principles of CA (Fig. 2). However, the choice of suitable crops and cropping systems is an important factor for maintaining soil health, crop productivity and profitability. Appropriate crop and variety selection in the system is vital for a CA system to be successful[87]. The choice of a short-duration legume crop could be a viable option to fill the gap between the cool dry season and monsoon season rice in Bangladesh.

Role of legumes in CA in rice-based systems

Continuous cultivation of rice and cereal crops for longer periods has created several problems, notably a decline of soil fertility[88,89], deterioration of soil physical properties[90], decrease in the water table, and disease and pest outbursts etc, resulting in a threat to the sustainability of the system in IGP[88]. Further, cereal crops are heavy feeders of nutrients[91] and constant cereal cultivation is the cause of the depletion of soil organic matter and nutrients, and degradation of soil physical properties, which are also key reasons for yield decline in intensive rice-based cropping systems of EIGP[62,92]. Hence, effective crop diversification is needed to sustain the agricultural production system. Some major crop rotations involving legume crops are shown in Table 2.

Fig. 4 Lentil in Conservation Agriculture practices (strip planting system and high residue retention).

Fig. 5 Lentil sowing using a raised bed planting system.

Table 2. Major crop rotations involving legume crops in Bangladesh. Source: Rahman[93].

Cropping pattern	Region (land type)
T. Aman rice – Chickpea – Fallow	High Barind Tract (drought-prone)
Sesbania (green manure) – Chickpea	
T. Aman rice – Wheat – Mung bean	High-land (plain)
Fallow – Legumes – Jute	
T. Aman rice – Maize – Mung bean	Medium land (plain)
T. Aman rice – Mung bean – T. Aus rice	Saline and non-saline areas
T. Aman rice – Soybean – Fallow	

The addition of leguminous crops in a crop rotation could be a strong case for crop diversification as it reverses the degradation process, improves the yield of component crops, and soil fertility through atmospheric nitrogen (N) fixation and supplies residual N to the following crop[19,94]. In addition, the system can lessen different input requirements as compared to cereal-based systems. Further, legume crops adsorbed less soil water and leave unused soil water in the deeper depth of the soil profile which might be beneficial for deep rooting crops after legume crops[95]. Legume-dominated cropping pattern can sequester soil organic carbon (SOC), increase soil N content, and improve soil aggregate stability as a result of symbiotic N fixation, return of leaf litter and N-rich roots to the soil[19,25], which principals to residual benefits for the succeeding crops. Also, legume crops can add 20 to 60 kg N per hectare to the following crop[96]. In addition, the nitrate losses can be reduced by cultivating pulse crops after monsoon rice. Further, the addition of pulse crops in the cropping pattern increased rice equivalent yield and profits[39], improved soil C sequestration and plays a critical role to alleviate climate change[97]. However, all of these benefits of legumes are reported for conventional rice-based farming. But the impact of legumes in conservation agriculture is yet to be fully evaluated in rice-based systems of IGP. Further, the legumes inclusion in rice-based cropping sequence under CA are needed to be examined at contrasting soil environments of IGP. It is anticipated that legume inclusion in the rotation under CA might be vital for ensuring the sustainability of rice-based cropping systems in Bangladesh of IGP.

Economics of legumes in CA

Growing crops in the rice-based system of IGP is largely dependent on monsoon rain and the productivity is, therefore, inconsistant every year. However, economic sustainability is crucial to ensure farmers' sustainable income. Hence, constant efforts need to be made to research different aspects of crop production to increase the productivity of various crops in the rice-based system. The inclusion of legumes in the rice-based system has enabled an increase in overall productivity without deteriorating natural resources. There is every possibility of saving resources following the rice-legume system in crop production. Hence, the rice-legume is a relatively profitable system as the legume crop requires less fertilizer and other inputs. Being of short-duration, legume crops can easily fit into the window between two main crops in a year. It minimizes the use of fertilizer input for itself as well as for the succeeding crop by 25%–30%[98]. Moreover, less input, less crop management practices, less labour and less time are required to grow legume crops. As a result, the cost of cultivation of leguminous crops is lower when compared to cereal crops.

Legumes for soil health improvement

Legume crops improved soil health in the rice-based system by improving the soils physical, chemical and biological properties. A detailed description is given below:

Legume impact on soil physical properties

Preserving soil physical health at a desirable level is challenging in the rice-based cropping system[35]. Soil with better physical health improves crop performance as well as minimizes environmental degradation[99]. The inclusion of legumes improved the soil physical environment by virtue of increasing concentrations of microbial biomass, carbon sequestration, BNF and phosphorus solubilization and mycorrhizal association in the intensive rice-based system[35,100]. The soil bulk density was significantly reduced through the retention of legume residues in the soil in cereal–legume cropping systems[101]. Legumes have deep and taproot systems and exposed pathways deep into the soil profile which improve the soil physical condition. Some legume crops having a deep root system break the hard pan that opens pathways deep into the soil and improves soil physical properties[102]. The legume-based crop rotations are favourable to soil physical properties especially improved soil aggregate and soil structure. A glycoprotein released from the roots of legumes called 'glomalin', is a gluey substance that entangles soil minerals, organic matter, and debris and forms stable soil aggregates. Therefore, the microbial activity of the rhizosphere improved soil structure in legume-based rotations (Fig. 6).

In a long-term rotational experiment, Meena et al.[104] recorded a higher portion of soil aggregates above 250 μm where the previous crop was legumes. The glomalin of legumes works as 'glue' that binds soil together into stable aggregates. This aggregate stability increases pore space and tilth, reducing both soil erodibility and crusting. These aggregate formations due to legume crops improved the infiltration of soil water[105]. Further, the leguminous crop also protects the soil from nutrient loss and erosion. Further, N-rich legume residues stimulate earthworms to make burrows. The root channels of deep-rooted legume and earthworm holes improve the soil porosity, aeration and water percolation at the deeper soil profile.

Legume impact on soil chemical properties

The legume crops influence soil chemical properties like soil pH, nutrient availability, cation exchange capacity, etc, (Fig. 6). Legumes could acidify their rhizosphere by absorbing more cations than anions from the soil solution and increase the relationship between plants, soil and microbes on soils for optimum crop growth and development[106,107]. The legume crop meets a significant portion of their N demand from the atmosphere as diatomic N instead of NO_3 from the soil. As a result, their net effect lowers the soil pH of the alkaline soil[106,108]. Legume crops are rich in both nitrogen and carbon. Besides, a substantial portion of nutrient-rich residues is added through legume crops to the soil as root biomass and leaf litter[109]. The root biomass and leaf litter being rich in N facilitate the rapid decomposition of crop biomass in soil and increase microbial activity. The microorganisms in the soil need both carbon and nitrogen. The nitrogen of the legumes crops allows the decomposition of crop residues and their conversion to soil building the organic matter[106]. Further, the legume crop residues may change unavailable P to the available form

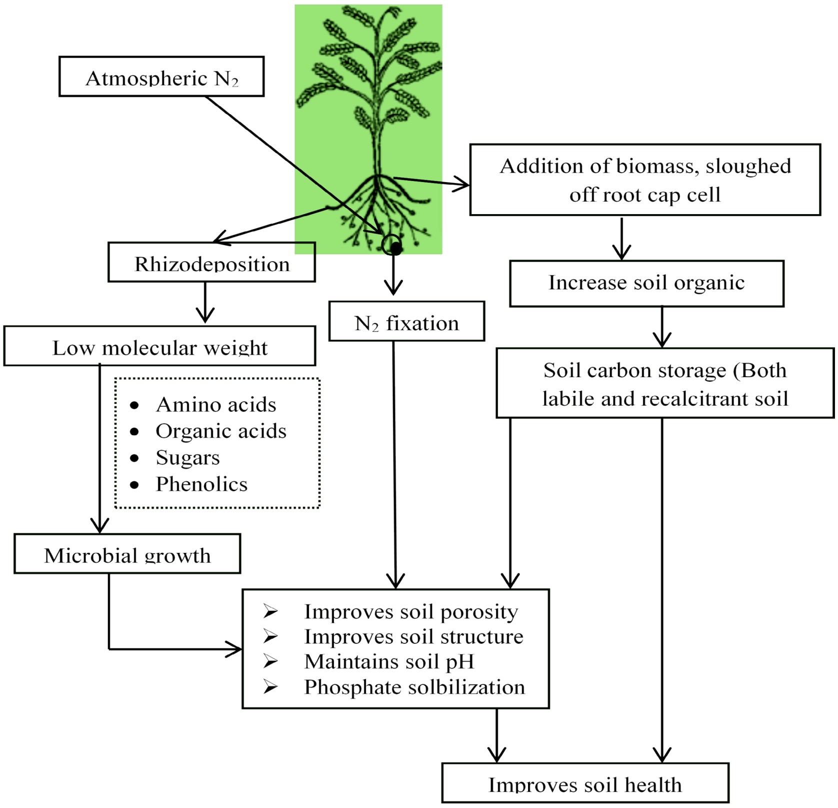

Fig. 6 Impact of legumes on soil health. Modified from Gogoi et al.[103].

of P for the succeeding crops. Natural P in the tissues of legume crops residue provides a labile sort of P on decay to the following crops. Soil microorganisms play a significant role in nutrient recycling through decomposition of organic carbon and nutrients. Inclusion of legume in the rotation helps in minimizing N requirement as well as efficient utilization of native P due to secretion of certain acids that help in solubilization of several forms of P. The increased availability of P a result of P acquisition from insoluble phosphates through root exudates. Further, long-term growing of mungbean in rice-wheat system improved SOC more than other systems (Table 3).

Legume impact on soil biological properties

The nodule of legumes captures the atmospheric N as diatomic N with the help of the enzyme nitrogenase rather than nitrate from the soil and their effect is to decrease the soil pH. Both soil microbial activities, as well as plant growth

Table 3. Effect of cropping pattern and nutrient management on soil fertility.

Treatments	Soil organic C (%)	Avail. N (kg/ha)	Avail. P_2O_5 (kg/ha)	Avail. K_2O (kg/ha)
Rice-wheat	0.35c	258.9c	18.1c	222.9c
Rice-chickpea	0.38b	272.5b	20.7ab	237.9b
Rice-wheat-rice-chickpea	0.37bc	266.6b	19.2b	238.0b
Rice-wheat-mungbean	0.42a	286.3a	21.1a	262.2a

Adapted from Nadarajan & Kumar[102].

significantly, increase at favourable pH (Fig. 6). In addition to the nitrogen stored in proteins, it has a further coating for storing glycoprotein in the leaf cells[110]. Besides, phosphorus (P) is the second most important component after N for growing crops. However, these essential nutrients become unavailable to plants as a result of bounding complexes with different nutrients even though the soil may contain a huge amount of P[111]. However, growing legume crops can improve the P uptake. For example, there are several organic acids secreted by the roots of legume crops (malate, citrate, oxalate, tartrate, and acetate) that reduce the soil pH in the rhizosphere and help in the conversion of inaccessible P to available forms[103,112]. In addition, legume crops secret enzyme phosphatase from their roots which helps in breaking down P-containing organic complex[113].

Legume crops increase microbial density and diversity of soil microbes that leads to better stability in the total life of the soil as compared to cereals or fallow[114]. It also provides increased biomass in the soil by adding extra N from their root and shoot, and BNF. Soil microbes use the additional N to decompose carbon-rich residues of cereal crops. The soil microbial biomass carbon (SMBC) is regarded as one of the major soil biological properties of soil. Legume-based crop rotation increased the SMBC over cereal-based rotation[115]. The bacterial growth serves to increase the legume rhizosphere because of the hydrogen gas during BNF[103]. The microbial activities are enhanced by the nodule-rhizosphere interaction of the leguminous crops. Also, growing leguminous crops in rotation significantly influences soil biological agents and increased the diversity of microbes[116]. The leguminous rhizospheric microorganism captures atmospheric N and thereafter improved root exudation and increased C:N ratio[117]. The exudation of the lectins of legumes influences the movement of rhizobacteria and improves root colonization and phyto-beneficial activity[118]. Legume crops form a tripartite symbiotic association (mycorrhiza-legume-Rhizobium)[119] and are accountable for the colonization of specific arbuscular mycorrhizal (AM) fungi because of their distinctive nutritional necessities linked with their nodule activity[120]. The hyphae of the mycorrhizae absorb and transport a huge amount of low-diffusing P to their host plant and help in nodule development[121]. The compatibility of different interactions of AM fungal strains is important to fix N and uptake nutrients and water by the pulse crops[122]. The AM colonization is promoted by legume crops under the low-input situation.

Legumes release hydrogen (H_2) gas into soil during nitrogen fixation (N_2 + 8H+ + 8e− + 16 Mg-ATP → $2NH_3$ + H_2 + 16Mg-ADP + 16 P)[123]. The H_2 released from nodules is oxidized by the soil in the rhizosphere. However, several legume nodules release a large amount of H_2 due to the absence of a hydrogenase uptake enzyme system (HUP-) or low activity of the HUP system within the strain of rhizobia[124]. For example, N-fixing HUP-legume crop can produce approximately 5,000 L of H_2 per day per hectare during peak growth, which is an energy equivalent of 5%–6%[125]. The soil microorganisms oxidized H2 and used it as an energy source to multiply rapidly around HUP-root nodules[126]. The growth plant increased in legume-based cropping systems due to increased bacterial populations adjacent to H_2-releasing nodules[127].

Legumes can provide high soil biological biodiversity, which is helpful to improve resistance and resilience against various stresses[128]. Legumes also increase the total root biomass in the soil by supplying extra N of their root and shoot biomass. Soil microorganisms break down carbon-rich residues of crops using the extra N[106]. Soil biodiversity, soil C and N are important for improving soil health and ensuring food and nutrition security.

Various nutrients and microbes are important factors for plant growth and development, and microbial association with legume crops. Several constraints affect crop production such as parent material, particle size, humus, soil water content, soil pH, temperature, aeration, root zone, the rhizo-flora, and advances in mycorrhiza. In addition, nutrient stress is another major limitation in crop production as an imbalance in nutrient concentration impedes the metabolism process of plants[129]. Generally, nutrient stress means either the presence of lower concentrations or excessive concentrations of the element. A deficit of nutrients improves the accumulation of reactive oxygen species, reduces nodulation, nitrogen fixation, photosynthesis, and chlorophyll content and results in hormonal imbalance[130]. In this case, endophytes are beneficial microbes, which could be an alternative eco-friendly approach to chemical fertilizers for crop production and reduce nutrient stress for plants[131]. Legume crops in association with microbes enable them to survive under hostile conditions and help to tackle the adverse effects of environmental stresses[132]. Legume crops and microbes are involved by a mechanism to cope up with the hostile environment and microbes in leguminous crops solubilize the nutrients and make them absorbable to crops. Microbes integrated with crops provide biotic and abiotic stress tolerance in crops without causing any detrimental effects (Fig. 7). Hence, nutrient use efficiency as well as stress tolerance in crops can be improved by using microbes, which is an eco-friendly approach.

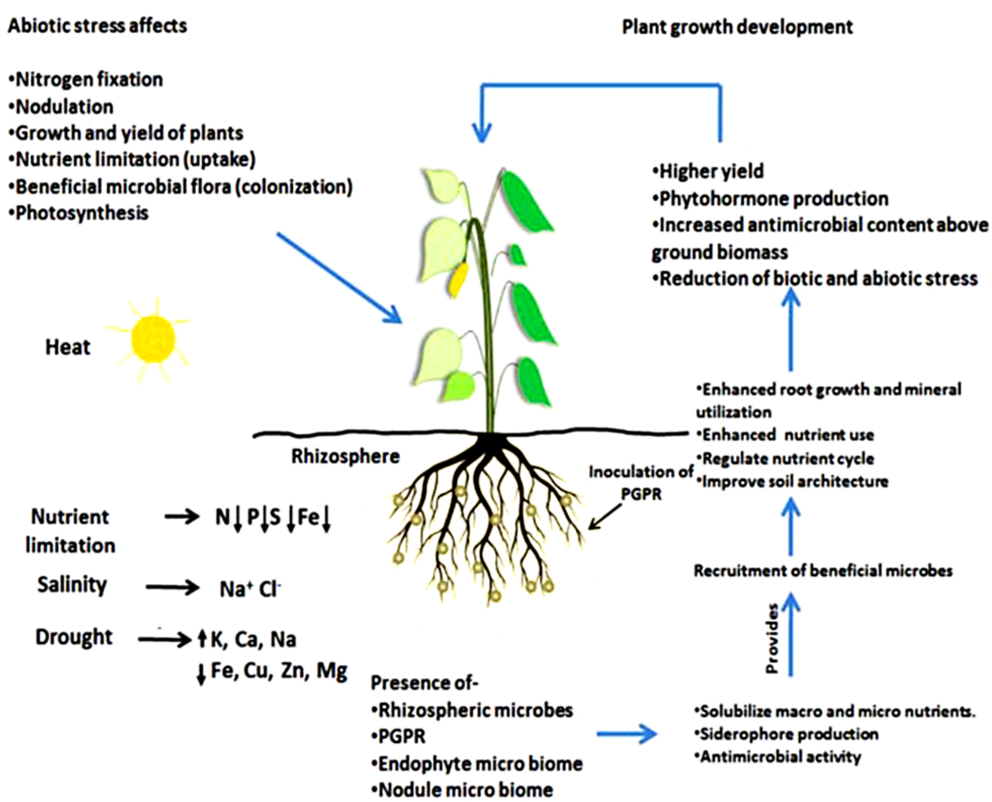

Fig. 7 Abiotic and nutrient stress tolerance in plants through endophytic microbes. Adapted from Kirchof et al.[12].

Water consumption of legumes in CA

Legume crops can be successfully cultivated through conservation agriculture, which is known as water-saving technology. In addition, the water requirement of legume crops is much less than cereal crops. Due to distinctive features, legume crops are more proficient in uptake water-efficient than other crops. Legume crops can uptake soil water from deeper soil profiles due to their deep root system, thereby having the ability to thrive well under drought situations. The legume crops need only 150–250 mm whereas rice needs 1,000–2,200 mm, wheat 300–400 mm and sugarcane 1,500–2,500 mm of water (Table 4). In general, winter legumes need no irrigation or one irrigation after rice crop whereas wheat crop needs 5–6 irrigations (3–4 cm of each irrigation) in Indo-Gangetic Plains. Consequently, the problem of groundwater depletion is commonly found in rice-wheat regions of EIGP. This situation can be reversed by substituting one of the cereal crops with legume crops.

Ecological benefits of legumes in CA

In the last decades, groundwater pollution in the rice-based system through nitrate leaching is a rising concern in IGP. Hence, suitable cropping systems involving crops that require a low rate of nitrogenous fertilizer and better agronomic practices are required to minimize nitrate leaching and improve N-use efficiency. The addition of pulse crops in the rice-based system is one of the best agronomic practice that can minimize nitrate leaching as well as improves N-use efficiency. Legumes can capture atmospheric N in symbiosis with certain types of bacteria present in the root nodules of the leguminous crops (Table 5). By fixing atmospheric nitrogen legumes can supplement 20 to 60 kg N to the following crop[134]. The efficiency of nitrogenous fertilizer to succeeding crop was reported up to 40–80 kg/ha[135].

Table 4. Water requirement of potential legume crops of the rice-based system in IGP. Adapted from Kumar & Yadav[133].

Sl No.	Legume crops	Water requirement (cm)
Winter legumes		
1	Chickpea	12–21
2	Lentil	10–12
3	Field pea	12–14
4	Rajmash	20–25
5	Lathyrus	10–12
Kharif/summer legumes		
1	Black gram (summer)	22–30
2	Mungbean (summer)	20–35
3	Black gram (Kharif)	6–12
4	Mungbean (Kharif)	12–15
5	Pigeonpea	16–22.5

Table 5. Nitrogen fixation and release into the soil of different legume crops.

Crop	N-fixation (kg/ha)	N release into the soil (kg/ha)	References
Lentil	35-100	32.8	[136]
Mungbean	50–55	34.5	[136]
Chickpea	26–63	–	[136]
Cowpea	53–85	50.3	[136]
Pigeonpea	68–200	–	[136]
Field pea	46	59.4	[136]
Black gram (Urdbean)	50–60	38.3	[136]
Lathyrus	85%–91% Ndfa	36–48	[137]

Success stories of legume inclusion in rice-based cropping system in CA

Including legumes in crop rotations have multiple benefits such as improved soil health, increased crop productivity and farm profitability. In addition, it helps to develop sustainable production systems by fixing atmospheric nitrogen. The fixed nitrogen is used by the legume crop and the subsequent crops[135]. Furthermore, the inclusion of legumes in the rotation improves soil aggregation, and soil carbon content, reduce greenhouse gas emission and thereby protects the environment. Therefore, there are plenty of success stories across the globe. Some of them are summarized in Table 6.

Way forward

Conservation agriculture is promoted, and the fixed nitrogen of legume crops meets the requirement of nitrogen for their own as well as for the succeeding crops. Hence, the demand for total fertilizer requirement is less with the co-benefits of increasing yields in the legume-based system over the cereal-cereal system. In addition, legumes significantly reduced GHGs emissions as BNF is a less-emissive form of N input to the soil than fertilizer N[144]. As a result, reduced fertilizer demand and less-emissive N contributes to the global nitrogen cycle, reduces GHG emission, and minimizes global warming, and water contamination. In addition, intercropping of legumes in cereals grown with wider rows also minimizes nitrate leaching.

The use of suitable crop rotations can be enhanced and increase the SOC[145]. Fine tilth for growing legumes in the rice-based system is not essential. Even legumes perform better or equally well both under conservation tillage and farmers' practices though conservation tillage sequesters more C than conventional tillage methods. In addition, roots, litter falls and plant biomass of legumes improves soil organic matter. The legume-based rotation also increased the availability of N and enhanced biomass C. Further, it promotes the release of C through root exudation into the rhizospheric zone[146]. The fixed N by legume crops also accelerates the C sequestration in the rotation due to an increase in microbial activities and biomass production. The legume-based rotation also enhances the nutrient use efficiency and thus resulted in higher belowground biomass and C inputs in soil. Also, short-duration legumes can easily be fitted in fallow in between two main crops and reduce C-loss and enhance C-sequestration in the rice-based system. Growing legumes under minimum tillage in the rice-based rotation also reduced the consumption of fossil fuels. Consequently, the legume-based system reduced CO_2 emission which is a major driver of climate change. Thus, legume crops are grown mitigate global warming and climate change effects through increasing soil C-sequestration and minimizing CO_2 emission. The legume-based system also reduces the emission of nitrous oxide (N_2O) as compared to other systems that are greatly dependent on nitrogenous fertilizer.

Weed suppression of legumes in CA

Weeds are one of the main constraints of the CA system in the Eastern Indo-Gangetic Plain. The choice of a suitable crop is

Table 6. Success stories of legume inclusion in rice-based cropping system under the CA system.

Cropping pattern		Findings	Locations	References
Legume-based cropping patterns	Non-legume-based cropping patterns			
Wheat-mungbean-rice, wheat-blackgram-rice, wheat-sesbania-rice	wheat-fallow-rice	The adoption of legumes in the wheat–rice cropping sequence increased the productivity and improved soil SOM, total N, available P and available Zn	Rajshahi, Bangladesh	[138]
Monsoonal rice-lentil/*Lathyrus*-rain-fed rice	monsoonal rice-fallow-rain-fed rice	The inclusion of relay-sown legume for fallow in the existing cropping pattern can intensify and diversify the rice-based cropping	EIGP and Bangladesh	[71]
Rice-wheat-mung bean, maize-wheat-mung bean, rice-chickpea	Rice-wheat, maize-wheat	Legume-based rotation increased soil organic carbon and available nitrogen and phosphorus, and system productivity and net return	Kanpur, India	[23]
Maize-chickpea, rice-chickpea	Maize-wheat, rice-wheat	Inclusion of chickpea in the cereal-cereal rotations improved SOC pools over time	Kanpur, India	[139]
Rice-chickpea, rice-wheat-mung bean, rice-wheat-rice-chickpea	Rice-wheat, maize-wheat	Inclusion of legume in rice-based rotation improved soil aggregation, carbon concentration in aggregates, and soil carbon pools	Kanpur, India	[140]
Rice-wheat-mung bean, rice-wheat-cowpea, rice-maize-mung bean, rice-wheat-mung bean, rice-maize/cowpea, rice-maize/mung bean, rice-lentil-maize	Rice-maize-fallow, rice-fallow-maize, rice-wheat-fallow	Inclusion of legumes in the fallow between two cereal crops could improve soil health and farmers' income	Nepal	[141]
Rice-wheat-green gram, rice-mustard-green gram, Rice-red gram+turmeric-green gram, maize-wheat-blackgram, maize+blackgram-chickpea-sesbania, blackgram-maize+vegetable pea-sesbania	Rice-wheat, maize-cole crops-sesame,	Including legume crops is a viable option for enhancing productivity, profitability and soil health in the rice-based system of EIGP.	Bihar, India	[142]
Legume based rotation	Non-legume based rotation	The inclusion of legumes enhanced the soil's organic carbon content	Global-scale meta-analysis (513 pairwise data from 167 studies)	[143]

important for crop diversification to reduce weed invasion. Growing legumes in crop rotation could be an important consideration for minimizing weed populations below the threshold level. Multispecies crop rotation with crops having different growing behaviours may decrease chances for weed germination and growth, and renaissance through resource competition and niche interference. Switching one cereal crop in the rice-based system with a legume crop may help in diminishing the weed seed bank in the soil. For example, Hazra et al.[147] found from a long-term experiment in India that legume crops can diminish the pervasion of *Phalaris minor* in winter crops. In addition, some legume crops with a fast-growing habit such as mungbean and black gram can compete with the weeds and can suppress weed growth. In addition, a legume with a better canopy cover was more effective than other non-legume crops with a narrow canopy cover in weed control. Mung bean or cowpea inhibited the weed development and showed as effective as two-hand weeding, and mungbean was shown to be effective at the initial stage, while cowpea at later growth stages[148]. The intercropping of legumes with other crops is also a viable option to suppress rising weeds. Intercropping of short duration, fast and early developing legume crop with longer growth habits cover and suppress rising weeds satisfactorily.

The application of legume residue in CA can influence seed germination of weeds due to changes in soil properties in the seed zone of the soil layer. The applied legume residue on the soil surface is the barrier of sunlight interception and protection to the soil surface. The soil surface protection by residue cover influences soil temperature and soil water at the surface soil[149]. In addition, the surface residue cover can control weeds by delaying the germination of weed seed and thereby, decreasing the population and growth of weeds. Thus, residue retention of legume crops minimizes yield loss due to weeds[108]. Moreover, weed are more vulnerable to the phytotoxic effects of crop residues, and the allelopathic effect of crop residue influences the soil chemical properties at the weed seed zone and may cause germination failure of weeds[150]. There are several legume crops like lentils and cowpea that suppress and decrease numerous weeds due to the allelopathic effect of weeds[108]. Hence, the use of legume residue can be used to control weeds and minimize the dependency on herbicides.

Legume crops require less fertilizer and irrigation compared to cereal crops for their growth and development. The use of less fertilizer and irrigation enhances weed germination as compared to cereal crops. Thus, legume crop minimizes weed invasion.

Insect-pest cycles disruption by legumes in CA

Legume crops are an excellent chance in a continuous cereal-based crop rotation and decrease the weed, insects, and diseases problems. In this case, a three year interval between the same type of crops is sufficient to reduce the weed, insect, and disease infestation. The addition of legume crops in the rotation improves soil structure as well as reduces insect and disease incidence while promoting mycorrhizal colonization[151]. The increased level of N-fertilization and irrigation considerably improved the incidence of diseases, insect pests and weeds, and resulted in severe yield loss in the rice-wheat cropping system[152]. The addition of legume crops in the rice-wheat cropping system greatly reduced *Phalaris minor* population and the incidence of diseases and pests in a long-term experiment at Kanpur[108].

Diversified benefits of legumes for sustainable crop production

Crop diversification with legume crops adapted and gained popularity in many countries in recent decades due to its sustainable outcomes[153]. Diversification and intensification of rice-based systems under CA in IGP through short-duration legume varieties will be the key to sustainability. However, the following research strategies are needed to attain sustainable crop production in rice-based systems:

Management options

Generally, manual hand weeding is performed to control weeds for legume crops in all seasons, which is costly and time-consuming. Hence, research efforts should be taken to identify post-emergence herbicides of legume crops for weed control. In addition, it is needed to develop genotypes tolerant to post-emergence herbicides in Bangladesh. Already post-harvest herbicide-tolerant varieties have been developed using genetic diversity or mutagenesis in many crops in developed countries. For example, Sharma et al.[130] developed imazethapyr tolerance five lentil genotypes (LL699, LL1397, IPL406, EC78452 and LL1203) and suggested that there are genotypic variations for herbicide tolerance in legumes that can be used for identifying herbicide-tolerant varieties. These herbicide-tolerant varieties are necessary options for controlling weed with post-emergence herbicides which can control weeds properly and increase crop yield.

Imbalance application of nitrogenous fertilizer in the cropping system incurred more capital investment, energy budgeting and carbon footprint, which causes environmentally and economically unacceptable crop production systems. However, the inclusion of legumes in the cropping system reduces nitrogen losses, reduces pollution, increases N budgeting, and improves soil health, crop productivity and overall sustainability[148,154].

Concerted research efforts are required to evaluate proper pest and nutrient especially micronutrients management strategies of legume crops in CA in different agroecological zones in the rice-based system. Also, agronomic fortification strategies of legume crops are desirable to be assessed[131].

Legumes improve agroecosystems, crop productivity, soil SOC and N stocks, soil chemical and biological properties, BNF, reduced greenhouse gas emission and nitrate leaching[103]. However, these benefits of legumes are needed to be quantified in the rice-based system of Bangladesh, and their mechanisms are understood.

A life-cycle assessment of greenhouse gas emissions from legumes involving rice-based systems in CA is also essential to find alternative options to minimize greenhouse gas emissions over existing cropping and cultivation technique[132].

Genetic options

Research should be initiated to develop varieties appropriate for crop diversification in CA.

Legume varieties that have resistance to biotic stresses such as ascochyta blight, botrytis, fusarium wilt, viruses, pod borer, aphid, bruchids, cutworms and leaf miners need to be developed in Bangladesh.

Legume crop varieties that have high yield and are bold seeded suitable for machine sowing are desirable to promote CA in the rice-based system in Bangladesh.

Legume varieties that have the potential to increase SOC restoration are needed to be developed in Bangladesh.

Varieties with profuse root systems and early vigour/ground coverage need to be developed to cultivate under CA-technologies.

Super-early (< 95 d) lentil, pea, chickpea and grasspea varieties can be successfully grown in the fallow window in between monsoon-rice and boro-rice crops.

Promoting legumes in rice-fallows

Bangladesh has the potential to increase crop production areas by growing short-duration legume varieties in a large area of rice fallows. A large part of rice-fallow land can be targeted for growing legumes during the cool dry season after the monsoon rice crop. Pulses Research Centre of Bangladesh Agricultural Research Institue recently developed an extra early lentil variety, BARI Masur-9 (< 95 d) and BARI Chola-11 (100–106 d) that would be well substitute for 8 million ha of fallow areas between two rice crops in Eastern Indo-Gangetic Plain[155,156]. Growing short-duration varieties (e.g. BARI Mung-6, BARI Mung-7, BARI Mung-8 and Binamoog-8, BARI Mash-3) during the Kharif season (between early monsoon and cool dry season), by relay cropping, and intercropping, ensures further utilization of existing agricultural land which remains fallow in between two seasons. Replacement of upland rice crops with high yield and resistance to different disease and insect legume cultivars (e.g. BARI Masur-8, BARI Kesari-5, BARI Kesari-6, BARI Motor-3, BARI Chola-9, BARI Chola-10 and BARI Chola-11) is another worthwhile strategy that has the potential to offer higher farm profits.

Incorporation of legume crops in CA as relay cropping

One of the major methods of multiple cropping is relay cropping in which one crop is sown on a standing second crop before the second crop is harvested[155]. In relay cropping legume with rice, the legume crop is sown on the mature standing rice crop 10–15 d before the monsoon rice is harvested (Fig. 8). Relay cropping is considered as a totally non-tillage practice, a component of CA which can improve soil health and crop productivity[33]. Growing legume as relay cropping as a replacement for fallow in the rice-fallow-pre-monsoon rice cropping pattern could be an opportunity to intensify and diversify cropping. This was confirmed in practice in some of the northern districts of Bangladesh, Nepal and eastern India, following the on-farm trial of relay sowing[71]. Also, the addition of legumes as relay crops (Fig. 8) in crop rotation can intensify rice-based cropping and improve soil health and crop yield[71,157]. Often long duration rice cultivation leads to delayed sowing of legume crop after monsoon rice to reach optimal moisture conditions of the seed bed and results in yield depletion due to late sowing[158]. On the contrary, available soil moisture losses quickly at the time of harvesting of monsoonal rice crop are hard to establish the cool dry season legume crops after rice[109]. However, the yield reduction due to delay sowing can be addressed while the yield of cool season legume crops can be increased through extending life cycle by relay cropping legume into monsoonal rice[71]. In relay cropping, legume crops get more time for vegetative growth between two rice crops and increases yield. Among the legume crops, grass pea and lentil is generally sown as relay into monsoonal rice in EIGP (Fig. 8). Interestingly, this system can be considered as resource conservation technology

Fig. 8 Relay sowing lentil into standing monsoonal rice.

as it does not need any cost related activities and resources such as tillage, weeding, nutrient application and irrigation[109].

Abiotic stress tolerance

Abiotic stress (waterlogging, cold, heat, drought and salinity) tolerant legume varieties are needed to be developed and deployed to minimize the negative effects of climatic change.

Rhizobium

Further study is essential to increase N_2 fixation by developing effective rhizobium strains and inoculation methods. Since N fixation is influenced by fertilizer N, more tolerant cultures of rhizobium are needed. Moreover, a matching nutrient supply system is needed as N fixation by legumes alone may not fulfil the requirement of nutrients. Thus, the combination between mineral fertilizers and rhizobium needs further research as a way of achieving a better combination of nutrition systems. The magnitude to which legumes can fix atmospheric N and their contribution to the soil N economy needs to be measured. Besides, an improved supply system, as well as application procedure for rhizobium, are required to develop.

Mechanization

The present crop production technique under the conventional method in Bangladesh is poorly mechanized, which is costly, labour-intensive, time-consuming and unsustainable. Therefore, it is necessary to warrant affordable and manageable mechanization at all stages of crop production (sowing, intercultural operations and harvesting) to ensure timely farm operations, reduce the cost of production, improve the utilization efficiency of expensive inputs increase farm profit, reduce greenhouse gas emission and finally achieve sustainable crop production. The 2-WT machine can be used for sowing seed in line with minimum soil disturbance can minimize the production cost. Further, developing new legume varieties suitable for machine harvesting varieties can also attract farmers to the large-scale commercial cultivation of legumes instead of subsistence farming. In the case of variety choice, plants having a higher podding height from above the ground, erect and non-lodging growth habit, uniform maturity and top-bearing characteristics of legumes should be an obvious choice for mechanical harvesting without harvest loss.

Conclusions

Legumes are suitable crops for crop diversification in CA for sustainable crop production in rice-based cropping systems in the Eastern Indo-Gangetic Plain. Legumes can provide multiple benefits to human, animal and soil health improvement and maintain natural resources. As efficient protein producers and climate-hardy crops, legumes mitigate and adapt to climate change effects, improve health by supplying nutrition, and help to promote economic stability. Introducing different legume crops to fit into various rice-based cropping systems can be crucial to increase resilience to climate change and improving soil health, crop productivity and sustainability. Hence, the addition of legume crops in CA for the rice-based system may give the way for sustainable agriculture to combat hunger and ensure food and nutritional security.

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Conflict of interest

Akbar Hossain is the Editorial Board member of journal *Technology in Agronomy*. He was blinded from reviewing or making decisions on the manuscript. The article was subject to the journal's standard procedures, with peer-review handled independently of this Editorial Board member and his research group.

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