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Beans with Benefits—The Role of Mungbean (*Vigna radiata*) in a Changing Environment

Lisa Pataczek[1], Zahir Ahmad Zahir[2], Maqshoof Ahmad[3], Saima Rani[4], Ramakrishnan Nair[5], Roland Schafleitner[6], Georg Cadisch[1], Thomas Hilger[1]

[1]Institute of Agricultural Sciences in the Tropics, Agronomy in the Tropics and Subtropics (490e), University of Hohenheim, Stuttgart, Germany
[2]Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan
[3]University College of Agriculture and Environmental Sciences, The Islamia University of Bahawalpur, Bahawalpur, Pakistan
[4]Agricultural Economics Research Institute, PARC National Agricultural Research Center, Islamabad, Pakistan
[5]The World Vegetable Center South Asia, Hyderabad, India
[6]Biotechnology and Molecular Breeding, The World Vegetable Center, Taiwan
Email: lisa.pataczek@uni-hohenheim.de

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Abstract

Dryland areas are experiencing low agricultural yields due to severe water shortages and salinity, leading to food scarcity. Mungbean (*Vigna radiata*) is gaining attention as a short-season crop that can tolerate dryland conditions, and fix atmospheric nitrogen, decreasing soil nutrient depletion. It is a source of high-quality protein for human consumption and can serve as a multipurpose crop, if harvest residues are used as fodder or green manure. However, little of this legume's potential has been explored. This review aims to underline the importance of mungbean as an agricultural crop by reviewing relevant literature on the potential contribution of mungbean to food security and a balanced diet as well as the effect of mungbean cultivation on farm income and gender equality. The challenges of climate change in plant production are discussed, and how progress in mungbean breeding and the application of improved cultivation techniques, such as regulated deficit irrigation, conservation agriculture, and inoculation with plant growth promoting rhizobacteria can overcome them.

Keywords

Adaption Strategies, PGPR, Food Security, Residual Effects, Conservation Agriculture

1. Introduction

A multi-country analysis revealed that 71% of households worldwide experienced food insecurity and climate shocks in the last five years. The periods of food insecurity ranged from less than one month in India to more than six months in Ethiopia [1]. This indicates that climate change has become a major challenge for food security. The pressure on natural resources is likely to rise and make both people and ecosystems more vulnerable, particularly where agriculture plays a major role in the country's economy. However, agricultural production has to increase by 70% in 2050 [2] to feed a still growing world population and to achieve the United Nations' first sustainable development goal, a world without hunger. In addition, the demand for freshwater is expected to exceed the renewable water supply by 40% in 2030 [3], while the world will need more than one-third more of energy by 2035 [4].

Currently, the global food supply is based on 30 crops, supplying 95% of our daily caloric intake, 60% of which is provided by just four crops, *i.e.* rice, wheat, maize and potatoes. Nonetheless, minor crops are still important at a local, regional and national level. In many cases, these minor crops are staples, contributing to food supply in certain periods and to a nutritionally balanced diet. Minor crops are sometimes also well-adapted to marginal conditions [5]. This also applies to landraces or wild relatives of major crops, making them a valuable genetic resource. Biodiversity can help farmers manage risks from new pests and diseases, and lessen the effects of sudden natural disasters or the impacts of soil degradation. Likewise, it allows production systems to adapt to environmental variations, which is vital to mitigate the risk of crop loss in the face of climate change. Finally, biodiversity contributes to productive and healthy farms [6]. The water-energy-food security nexus threatens many people worldwide and calls for action. Globally, food insecurity affects about 815 million people. Almost two thirds of them live in sub-Saharan Africa and South Asia [7], whereby 50% of them are smallholders and livestock keepers [8] [9]. Smallholder farmers in dryland areas, or areas with erratic rainfall usually lack technologies to diversify their production, making them particularly vulnerable.

Mungbean [*Vigna radiata* (L.) Wilczek] is such a minor crop that dryland smallholder farmers can use to break the downward spiral, and increase the profitability and sustainability of their farms. It is a nutritious warm season legume crop. The grains are rich in protein, minerals, and vitamins. Mungbean is widely grown in Asia, but also in parts of Africa and Australia. Nowadays, almost 90% of the mungbean production is found in Asia, where India, China, Pakistan and Thailand are among the most important producers [10]. Integration of mungbean in cropping systems, particularly in Central and South Asia, may increase the sustainability of dryland production systems. Diversification of local production systems through inclusion of mungbean as a catch crop provides additional income to farmers and has potential to improve soil fertility.

The World Vegetable Center (WorldVeg) in Taiwan holds more than 7000 accessions, a valuable resource that could yield traits useful for breeding improved mungbean varieties, maximizing their potential and to foster the livelihoods of resource-poor farmers. However, little of this potential is still explored.

Therefore, this review aims to summarise the current knowledge on mungbean resistance breeding, its potential contribution to food security, and in general its use as a multi-purpose crop that could increase farmer's income and livelihoods, feed animals and possibly enhance soil fertility over time. This review covers mungbean adaption strategies, nutritional values for human and animal consumption, the concepts of regulated deficit irrigation (RDI) and conservation agriculture (CA), the economic potential, the opportunity for women to participate in agriculture by the cultivation of mungbean and the positive effects of bacterial inoculation of mungbean seeds under adverse growing conditions.

2. Crop Improvement

2.1. Adaption Strategies and Breeding Progress

Environmental stress, pests and diseases are limiting productivity and cultivation of a range of crops. Mungbean is adapted to tropical and subtropical low-lands and relatively tolerant to abiotic stresses, like drought and heat, but soil salinity affects mungbean more heavily than other crops [11]. Salt stress interferes not only with the plant, but also with symbiotic microorganisms such as *Rhizobium* sp. essential for biological N fixation (BNF), resulting in growth retardation and reduced yields [12]. Salt tolerant *Vigna* species found on ocean beaches under strongly saline conditions, such as *V. marina,* cannot be crossed with mungbean, and thus are not available for breeding salt tolerant varieties [11]. Some degree of salt tolerance has been found in the mungbean germplasm, but tolerance at germination and at the seedling stage may appear in different accessions. Combining these traits by breeding is complex, as many genes are implicated with tolerance.

Mungbean yellow mosaic disease (MYMD) is the most significant factor limiting cultivation. Different begomovirus species infecting mungbean have been identified [13]. Moderate resistance against MYMD has been found in the mungbean genepool, but was not sufficient for generating resistant varieties. Mutation breeding using moderately resistant accessions and hybrids derived from them resulted in several lines with high levels of resistance against MYMD [14]. The line NM94, the result of a cross between a line derived from mutation breeding and a high yielding cultivar, is now registered as a MYMD resistant line in various countries. However, in regions where MYMD-Urd bean strain is predominant, susceptibility of NM94 has been reported [15]. Breeding programs in Pakistan and India resulted in several stable MYMD resistant lines. ML1628 was developed by the Punjab Agricultural University, Ludhiana, India, and resists to multiple species/strains of the virus causing MYMD [15].

Bruchids (*Callosobruchus* sp.) are a major storage pest of mungbean. The beetles lay their eggs on pods in the field. Larvae hatch during storage and develop in a single bean to adulthood, and then lay their eggs on the beans. In a few months storage time, bruchids can destroy all stored mungbean grains [16].

Genetic resistance against this pest has been found in mungbean and has been used to breed resistant varieties in China, Korea and at the WorldVeg [17] [18] [19]. Bruchid resistance of different sources were genetically mapped and markers for selection of resistant lines in breeding programs are available [19] [20].

Marker-assisted selection is becoming important in mungbean breeding. The availability of the entire genome sequence and affordable high-performance genotyping tools, such as genotyping by sequencing facilitate mapping of breeder desired traits, and marker development for breeding [21] [22]. Genome-wide association genetics is clearing the way for mapping agronomically important traits, but the low funds put into minor crops, such as mungbean, limits the population size for phenotyping and ultimately confines these efforts mainly to simple oligogenic or monogenic traits, and mapping bi-parental populations. Examples of traits recently mapped in mungbean are drought tolerance [23], seed starch content [24], high iron and zinc [25], salt tolerance [11] and resistance to powdery mildew [26], MYMD [27], and, as mentioned above, bruchid resistance [19] [20]. For most mapped loci, validation of their value for breeding is still lacking.

Another important direction in research of adaptation strategies by mungbean to stressful environments, are wide crosses that aim to introgress traits from related wild species. One example is the introgression of MYMD immunity from *V. mungo* [28]. Crossing barriers are affecting this approach, but several *Vigna* species are cross fertile [29].

2.2. Nutritional Aspects for Human and Animal Consumption

Mungbean is an important grain legume in South, East and Southeast Asia, which produce up to three million metric tons of seed consumed directly as *dhal*, porridge and bean sprouts, or processed into high value noodles [30]. To meet global mungbean demand and to address widespread malnutrition, it is imperative to improve the current average global productivity as well as to expand its reach into new regions, including Central Asia and Africa [31]. Mungbean is a substantive source of dietary protein (24% - 28%) and carbohydrates (59% - 65%) on a dry weight basis, and provides about 3400 kJ energy/kg grain [32]. In comparison to other legumes, such as chickpea (*Cicer arietinum*), pigeon pea (*Cajanus cajan*), and lentils (*Lens culinaris*), mungbean starch is easier to digest [33]. Mungbean also induces less flatulence and is well tolerated by children [34]. In addition, mungbean is lower in phytic acid (72% of the total phosphorus content) than pigeon pea, soybean (*Glycine max*) [35], and cereals. Phytic acid is commonly found in cereal and legume crops and has a negative impact on iron and zinc bioavailability in plant-based human diets. Owing to its palatable taste and nutritional quality, mungbean has been used as an iron-rich whole food source for baby food [36].

The seeds and sprouts of mungbean contain abundant nutrients with biological activities. The review by Tang *et al.* [37] provides insights into the nutritional value of mungbeans. Constituents that have been isolated in the past few decades, such as flavonoids, phenolic acids, organic acids, amino acids, carbohydrates, and lipids have been discussed. In addition, dynamic changes in metabolites during the sprouting process and related biological activities, including antioxidant, and health promoting effects, are evidence of its use as a medicine.

Previous studies have examined the nutrient profile of several mungbean lines/varieties. These studies have shown limited variation for most of the nutrients studied. Ebert *et al.* [38] found that relatively old mungbean accessions were superior in protein, calcium, iron, zinc, carotenoid and vitamin C content, compared to improved mungbean lines at maturity. WorldVeg recently developed a mini-core collection of 296 accessions [39]. However, they are yet to be examined for their nutritional merit, which could be a potential source for different nutrients. The effect of the surrounding environment on the concentration of minerals in mungbean lines was observed by Nair *et al.* [40], highlighting the importance of multi-locational testing.

Mungbean can also be used as livestock feed, e.g. the raw or processed seeds and the straw or hay of the whole plant [41]. Raw seeds contain anti-nutrients, limiting their use as feed [10] [41]. Using the beans as feed is controversial because it competes with human consumption. This review, therefore, will focus on mungbean as forage, mainly hay and straw.

In most cases mungbean could be grazed two times during the crop cycle. There are early maturing varieties, which are particularly appreciated as early forage, as they develop faster compared to other summer legumes, like cowpea (*Vigna unguiculata*) [10]. The forage yield ranges from 0.64 t ha^{-1} to about 1.8 t ha^{-1} [42]. Fresh mungbean forage has a protein content of 13% - 21% on a dry matter basis, whereas mungbean straw has a protein content of 9% - 12%, which is higher than the protein content in cereal straw [42].

3. Economic Importance

3.1. Market Opportunities and Additional Income

Currently, the world production area of mungbean is about six million hectares per year, out of which 90% is in Asia, with an average yield of 400 $kg{\cdot}ha^{-1}$ [31]. The productivity of mungbean is still low, but the demand might increase in future due to its high dietary quality [43] [44]. Mungbean provides significant amounts of protein, carbohydrates and a range of micronutrients to human diets. They contain the essential amino acid lysine, which is lacking in cereals, but are relatively poor in methionine, an essential amino acid that is present in cereals. In addition the beans contain high levels of antioxidant activity, which scavenge free radicals [45]. These beneficial dietary properties of mungbean can be also correlated to an improved state of health of women in several Asian countries between 1984 and 2006, when mungbean consumption increased, resulting in an estimated economic benefit of up to US$ 4 million (per country) [46].

Mungbean sprouts are popular, since they are a source of minerals and vitamins, require little cultivation area and resources and can be harvested after a short time period [47] [48]. They are marketed fresh, canned, or processed [49]. In the past five years, the total import of mungbean into Europe, most of it for sprout production, was between 21 Mt and 27 Mt [50]. The main origins of these imports were Myanmar (in 2017: 14.4 Mt) and China (in 2017: 3.8 Mt). Australia is the largest developed country supplying mungbean (in 2017: 1.8 Mt). The United Kingdom imports the highest quantity of mungbean in Europe, probably due to a large Indian and Pakistani population that use mungbean in their traditional recipes.

Mungbean production cannot only increase a farmer's income through the sale of beans, but also through the reduction of farm inputs after cultivation. When grown between wheat and rice in India, it left 33 - 37 kg nitrogen (N) ha^{-1} for the succeeding crop [51]. Doughton and McKenzie [52] observed increasing sorghum yields by 70% after mungbean cultivation. This corresponds to an N application of 68 $kg \cdot ha^{-1}$.

3.2. Regulated Deficit Irrigation—Potential for Saving Water in Mungbean Cropping

Mungbean is generally considered to be able to tolerate dryland conditions well as compared to higher yielding crops, but regions suffering from severe water scarcity could make use of RDI, a conservation agriculture practice highly practical in dryland regions. Crops are irrigated with an amount of water just below the requirement for optimal plant growth [53]. The overall goal is to influence stomatal conductance and plant water use to potentially improve biomass production, if certain drought adaption strategies exist within a crop, such as the allocation of assimilates towards grain filling [54] [55]. The degree of deficit, and growth stages in which RDI should be applied are regulated by crop-specific intrinsic drought resistance mechanisms, but if applied correctly during non-critical growth stages, RDI has been shown to improve water use efficiency and yields while utilizing less irrigation water [53] [56] [57].

Bourgault *et al.* [58] investigated the effects of various levels of RDI on mungbean production and crop development in Uzbekistan in 2003 and 2004. Mungbean yields were highest at the moderate water stress level (65% of soil available water capacity) in 2003 and in 2004 at the severe stress level (80% of available water capacity). Their results showed that water deficit affects the translocation of resources to seeds and that mungbean is able to maintain its harvest index under severe stress. Based on these results, RDI might be a good strategy for high yields, using less water.

3.3. Role of Women in Mungbean Production

It is widely recognized that rural women play an important role in agriculture, depending on social and cultural norms. Luqman *et al.* [59] indicated that women's contribution to agricultural labor force in developed countries amounts to 36.7%, whereas it is about 43.6% in developing countries. In agro-based economies, women play a significant role in crop and poultry production, livestock management, and cottage industries. According to ESCAP [60] and Jamali [61], they often spend two-thirds of their time on fulfilling these tasks as compared to men who spend only half of it. Tibbo *et al.* [62] reported that they are involved in almost every agricultural field of activity, but women's sole participation is more prevalent in weeding and harvesting, followed by seed cleaning, drying, storage and binding of crops, respectively. Off-farm activities such as marketing and transport, as well as handling of agricultural machinery are dominated by men. Female participation is notably higher in food storage and processing [59].

Mungbean is the major summer crop in Pakistan, but average yield is low in comparison to other countries [63]. As a result, Pakistan imports large quantities of pulses to meet its increasing domestic demand [64]. Unavailability of quality seed, pests and diseases, heat and drought, as well as labor shortages are the main reasons for low productivity. According to Schreinemachers *et al.* [63], farmers spent on average 129 hours per hectare in mungbean growing areas. Harvesting, threshing and cleaning of the seeds accounted for 60% of total working time. These tasks are laborious and are mostly performed by women and children [63].

The labor-intensive manual work carried out by farmers and their families is hard and time-consuming, which is an additional constraint to increased production of mungbean [65]. The whole farmer's family contributes to the production of pulses, especially women and children. Women are actively involved in every production stage, except ploughing [66]. Therefore, mungbean are recognized as women's crops in many smallholder farming communities [67]. The cash flow they generate is marginal, but plays a significant role in meeting household needs and improving health and education [68].

As reported by Agarwal [69], in some farm operations like processing and storage, male workers are becoming numerically insignificant. Singh *et al.* [70] indicated that female farmers are involved in clearing the fields and grading of the seeds, weeding and harvesting of mungbean, post-harvest management at household level and livestock breeding in mungbean production areas in Pakistan. These activities require less physical strength, but are less prestigious [71]. Women need to perform these tasks in addition to housekeeping, child and elderly care, and livestock management [72]. Sisei [65] and Satyavathi *et al.* [71] concluded that women work physically harder and longer than most men, and their activities are more diverse. Many studies showed that increasing workload does not enhance women's ability to produce food, earn income, and care for family members. Sah *et al.* [73] indicated that the situation has led to changes in cooking habits and the preparation of fewer, less nutritious meals. Moreover, traditional systems are limiting women's access to resources and imposing a gendered division of labor that allocates the most labor-intensive and poorly rewarded work to women [74]. The mechanization in mungbean could benefit women in particular, as it frees up time for other productive work, such as self-employment, value addition, income earning, and family care. It could also foster and intensify mungbean production and improve incomes. This may lead to more land being brought under cultivation to meet an increased market demand [75].

4. Soil Health and Environmental Impact

4.1. Residual Effects in Crop Rotations

Legumes in a rotation with cereals can in most cases increase cereal yield [76] [77] [78], due to residual N from the decomposition of their residues [79]. This release can contribute to a net increase of soil N when the biological N fixation rate is high [80]. It is reported that the cereal yield after legume cultivation can increase by 30% - 350%, when compared to cereal monocropping systems [81]. Sharma *et al*. [82] reported that the wheat yield following mungbean, without residue incorporation and N fertilizer application, was around 0.45 Mg ha^{-1} higher than the yield of wheat following sorghum, corresponding to 36 - 52 kg urea-N ha^{-1}. With residue incorporation, the fertilizer equivalence was 74 - 94 kg urea-N ha^{-1}. Previous studies showed that grain legumes are unable to maintain soil fertility because of their high N harvest index [83]. An overview of the latest publications on residual effects of mungbean in crop rotations is summarized in **Table 1**.

The net soil-N balance after mungbean cultivation can be either positive (5 - 64 kg N ha^{-1}), or negative, when the above-ground material is removed at harvest [84] [85] [86]. Nevertheless, these calculations do not consider N from decomposing below-ground residues [87] [88] and underestimate the total N supplied from grain legume residues [89] [90]. Below-ground nitrogen (BGN) in roots, nodules and rhizodeposits represents an important source of N and needs to be considered for the prediction of N pools in legume-based cropping systems [91]. However, it is important to better estimate the amount of plant available N and the mechanisms of soil N turnover [92] [93].

McNeill and Fillery [94] found after a legume-wheat season 32% - 55% of legume derived BGN in the soil. This finding is also in line with a study conducted in China by Zang *et al.* [95], which measured N derived from rhizodeposition of mungbean and its uptake by intercropped oat. The majority of N from rhizodeposition remained in the soil, whereas the specific form and the turnover time are not known. A slow turn overtime might not be useful for plant nutrition, but could be important for soil organic matter build-up. In any case, this indicates a contribution of mungbean rhizodeposition to the soil N pool for subsequent crops, and can ultimately help to improve soil fertility.

Table 1. Impact of mungbean cultivation and residue incorporation in a crop rotation on soil fertility parameters and yield of a following crop.

Country	Effect on following crop	Effect on soil parameters	Residues incorporation	Source
Cambodia	Rice yield increase by 15% to 20%. When phosphorous (P) applied to mungbean rice yield increase of 13% to 33%. Removal of above-ground plant material resulted in no effect on rice yield.	9 kg of biologically fixed N and 21 kg of biologically fixed N with P application.	Mungbean as green manure	[96]
China	Relative contributions of N to wheat grain from mungbean: 48.4% - 68.1%.	Accumulative N decomposition rate of the shoots for mungbean were 67%, of the roots 55% (higher than Huai bean and soybean). Mean total N input: 154 kg N ha^{-1} yr^{-1}.	Above-ground biomass was incorporated	[97]
Pakistan	Yield of maize increased compared to fallow.	-	Mungbean was harvested for grain and fodder purposes	[98]
	Wheat quality increased by increased levels of macronutrients (N, P, potassium, calcium, magnesium), sugar content, amino acid, proteins, and phytohormones, compared to fallow land. Wheat biomass increased, compared to wheat grown after fallow.	Soil organic matter, N%, nitrate, P (ppm), water content, organic carbon (C), potassium, iron, copper, manganese, zinc increased compared to fallow land.	Not stated	[99]
	-	Increase of soil microbial biomass-C in wheat-mungbean rotation compared to wheat-maize by 25.7% to 31.2%. Bacterial population increased with mungbean by 13.3% to 42.1%, as well as organic N by 14.7% to 31.8%.	Not stated	[100]
Vietnam	Cropping systems with mungbean improved rice grain and straw yield in subsequent season in contrast with rice monoculture.	Increased content of soil organic C and a labile C fraction compared with rice monoculture. Less pronounced improvements in electrical conductivity, cation exchange capacity and total acidity.	Not stated	[101]

4.2. Role of Bacterial Inoculation under Salinity, Drought, and Nutritional Stress

Mungbean is one of the important crops with the ability to improve soil fertility through N fixation by symbiotic association with rhizobia present in root nodules [102]. Despite of its high nutritional value and significant contribution to soil fertility improvement, mungbean is cultivated on marginal soils with low inputs [103]. Under such conditions, the nodulation in mungbean is low due to alkaline calcareous soils, high salt accumulation [104], water shortage, and low organic matter, particularly in arid and semiarid regions. The increase in rhizosphere salinity can decrease the osmotic potential of the soil solution in the root zone [105], resulting in a decrease of water availability to plants. This might be due to the unavailability of indigenous rhizobia, or lower efficiency under the existing climatic conditions. Mungbean is a salt sensitive crop with a threshold level of 1.8 dS m^{-1} [106]. Its germination is severely affected by salinity [107]. Salinity-induced osmotic stress limits absorption of water from the soil [108], increasing the concentration of toxic ions in plant cells, and leading to ionic stress.

There are some rhizobial strains which can survive under harsh conditions with low water availability, high salinity [109] [110] and have low nutrient requirements [31] due to morphological, metabolic and structural modifications. It has been well-established that *Rhizobium* strains isolated from salt affected fields are more tolerant to salinity and can improve growth of mungbean under salt-stressed conditions [111] [112] [113]. Inoculation with rhizobia enhances root proliferation and the number of primary roots under salinity stress, leading to improved growth and yield, through a number of mechanisms such as N_2 fixation, production of plant growth regulators, and disease suppression [114]. The biologically fixed N from symbiotic associations improves the fertility of soils, enabling plants to take up more nutrients from the nutrient rich niche of rhizosphere. Moreover, the effectiveness of these strains can be improved through co-inoculation with plant growth promoting rhizobacteria (PGPR) containing 1-aminocyclopropane-1-carboxylate (ACC) deaminase [110], or with plant growth regulators *i.e.* precursor-inoculum interaction [115].

The use of PGPR for inoculation of seedlings, seeds or soil helps in the mobilization of nutrients through biological activity and increases the population of microflora, leading to improved soil health [116]. The improvement in soil health indicators such as soil EC, pH, available N, P, K, S, and soil organic matter due to combined use of PGPR and organic manure in mungbean fields was also reported in previous studies [116]. The mucous material and exopolysaccharides (EPS) produced by PGPR bind the soil particles and help in the stabilization of soil aggregates, which improves soil structure. Microbial inoculants have the potential to improve the productivity of organic farming systems through solubilization/mobilization of bound nutrients in soil organic matter [117]. The mungbean crop can fix up to 31 - 85 kg N ha^{-1} that not only meets the N requirements of mungbean crop but also leaves behind enough N for subsequent crops [116]. The increase in soil organic matter and total N contents was reported due to inoculation of legume crops with *Rhizobium* [118].

The PGPR inoculation decreases Na^+ accumulation in plant leaves [119], which can be attributed to the bacterial EPS production. These EPS bind the Na^+ and prevent their transfer to leaves, thus helping plants to tolerate higher levels of salt stress [120]. Recently, Zahir *et al.* [121] reported that mungbean plants inoculated with biofertilizer prepared through the combined use of *Pseudomonas* strains and *Rhizobium phaseoli* performed better in terms of nodulation, growth and yield parameters. Moreover, different mungbean genotypes responded differently to inoculation. Inoculation also improved the bacterial population in the rhizosphere as compared to un-inoculated plants when measured in terms of number of copies of bacterial DNA. These studies suggested the positive influence on soil fertility by the increase in bacterial population and nodulation, strong indicators of fertility. From the available literature, it can be concluded that bacterial inoculation improves soil fertility, by improving soil aggregation, better nutrient acquisition and higher root proliferation, helping plants to grow better under harsh soil conditions.

4.3. Conservation Agriculture

Currently, sustainable intensification of agriculture has become a key issue, as soil degradation increased worldwide over the past decades.

In Central and South Asia, mungbean may play an important role in sustainable intensification of agriculture due to its potential for BNF, particularly in settings where CA aspects or water-saving techniques are included. Laik *et al.* [122] indicated that CA, together with best management practices, is important for improving cereal-based systems in the Eastern Indo-Gangetic Plains of India. Parihar *et al.* [123] argued that adoption of conservation tillage practices with improved nutrient management could be a viable option for achieving higher biomass productivity, water and energy-use efficiency and profitability in maize-wheat cropping systems, particularly when mungbean is introduced to rotations. Long-term experiments from India suggest that the adoption of CA-based tillage under maize-chickpea-sesbania and maize-wheat-mungbean systems can enhance crop productivity, profitability and nutrient uptake of kharif maize in the north-western region of India and under similar agro-climatic conditions [124].

Choudhary *et al.* [125] evaluated the effects of CA-based management practices, such as zero tillage, direct seeding of rice, crop diversification, residue recycling and legume integration for sustainable intensification of agriculture in comparison to conventional crop management on soil quality and biota of cereal-based cropping systems. CA-based sustainable intensification of rice/maize systems improved soil quality and biota, resulting in higher system yields in alluvial soils of the Indo-Gangetic plains. Among the tested CA-based systems, the maize-wheat-mungbean system was found to be the best alternative option to achieve sustainable productivity, while improving the soil quality index by 35% and conserving natural resources. Similar positive results were reported for the High Ganges River Floodplain of Bangladesh. Minimum soil disturbance together with incorporation of a legume/green manure crop into the rice-wheat system as well as the retention of their residues increased soil carbon (C) status, improved soil properties and maximized grain yields. CA with directly seeded rice and mungbean residue retention as an *in situ* green manuring lead to significantly higher Walkley-Black C, $KMnO_4$-C and very labile soil organic carbon (SOC) in Bangladesh compared to the conventional tillage practice in topsoil [126]. Interestingly, addition of residues with mixed C:N ratios (legume and rice residues) failed to improve soil mineral N, possibly due to the greater partitioning of N towards soil microbial biomass and particulate organic matter associated pools.

Mungbean can also improve soil nutrients. Jat *et al.* [127] found that mungbean integration in cereal cropping systems along with CA increases DTPA extractable zinc and manganese significantly compared to conventional cropping without CA. This study also showed a saving of 30% N and 50% potassium in wheat after four years. CA improved soil properties and nutrient availability with a potential to reduce external fertilizer inputs in the end.

In addition, recent and multi-year studies from the Indo-Gangetic Plains indicated that the integration of mungbean in either rice-wheat or maize-wheat cropping systems has positive effects on water and radiation use efficiency when CA measures and precision irrigation were integrated [128]. However, there is a lack of data for Pakistan and Uzbekistan. Hassan *et al.* [129] tested various wheat rotations with fallow, sorghum, green manure, mungbean, and chickpea and found that the use of legume-based cropping sequences is a sustainable and cost-effective practice in drylands of northern Punjab, Pakistan. The net benefit values were the highest in a mungbean-chickpea sequence (1008 and 596 US$ ha^{-1} under moldboard ploughing and minimum tillage, respectively), which gave cost–benefit ratios of 5.45 and 3.68, respectively. The impact of mungbean-based CA on cropping systems is summarized in **Table 2**.

Semiarid and arid areas are fragile ecosystems and adapted production systems are important to safeguard food production and economy of the rural

Table 2. Impact of mungbean-based conservation agriculture (CA) measures on crop productivity and farm income.

Country	Tested CA option	Response compared to farmers' practice	Source
Bangladesh	Zero tillage (ZT), crop rotation with mungbean (CRM)	Increase of rice yields and net returns	[130]
	Strip tillage, CRM, partial residue retention (PRR)	Lower production costs due to strip cropping; better prices for wheat and mungbean improved farm economy	[131]
	ZT, CRM and *Sesbania* sp., residue retention (RR), green manure	Soil organic carbon (SOC) increases under zero tillage, when residue were retained; improved water infiltration; higher water availability; decreased soil strength and bulk density; improved grain yields	[132]
India	No tillage, mungbean, residue management	Increase of wheat and rice yields; higher net returns	[122]
	ZT, permanent bed (PB), legume-based crop rotations with mungbean, crop diversification	Lower production costs, improved water and energy efficiency; crop yield increase	[123]
	ZT, PB, legume-based crop rotations with mungbean	Positive yield responses of maize; improved energy efficiency	[124]
	ZT, PB, RR, precise irrigation	Decreased water use; higher water and crop productivity	[125]
	ZT, *Sesbania* sp., brown manuring, relay cropping with mungbean, RR	Increase of stable and labile SOC fractions; no effects on soil mineral N, but on soil microbial mass	[126]
	Partial tillage and ZT in CRM, crop diversification	Improved soil properties and nutrient availability; potential to reduce external fertilizer inputs in the long run	[127]
	PB, RR, CRM, site specific nutrient management (SSNM)	Positive effects of CA, SSNW and mungbean integration on water use efficiency and crop productivity	[133]
	ZT, PB, CRM, SSNM	Higher system productivity, water use efficiency, and incident radiation conversation efficiency	[128]
Pakistan	Minimum tillage (MT), green manure, CRM and chickpea	Legume-based cropping sequences are sustainable and cost-effective practice in drylands	[129]

population in these regions. Therefore, integration of N-fixing pulses with short growth cycles into the cropping calendar is a useful coping strategy, allowing for crop diversification under limited rainfall. According to Singh *et al.* [134] a lack of crop-saving, supplementary irrigation at critically low soil moisture levels hampers plant growth and crop productivity. Cultivation of drought tolerant pulses and management techniques such as zero tillage, relay cropping, residue retention, mulching, seed priming, lifesaving irrigations and foliar sprays of nutrients can improve agricultural production under challenging conditions. At the field level, managing or manipulating cultural practices can mitigate adverse effects of salinity and high temperature. A better understanding of physiological and biochemical mechanisms, regulating these two stresses is required to develop profiles of the genes, proteins, and metabolites responsible for mungbean survival [135].

5. Conclusions

The lack of improvement in salt tolerance of mungbean needs more attention in future research. Knowledge gaps on breeding against important pests and diseases have been addressed in the recent past. However, both issues need to be considered by national breeding programs, and accompanied with novel breeding approaches.

Additionally, more emphasis is required on exploring the potential of mungbean to fight hidden hunger by linking it to national food policies. This would also foster farm incomes, but would also require shifts in available on-farm technology to improve gender equality, as currently harvest is done mainly manually.

The N harvest index of mungbean is often low, as most of the biologically fixed N is removed from the field by the grains. However, the use of PGPR may improve the BNF efficiency of mungbean substantially, particularly when appropriate information on local rhizobacteria is available. Together with CA measures, the use of beneficial rhizobacteria can be a way forward towards coping with soil degradation, while sustaining or even improving crop productivity. Positive impacts of PGPR have been reported in South Asia, but there is still little emphasis on using CA in this region despite there being knowledge available, particularly from the Indian subcontinent. Nonetheless, there is still little known on the effect of mungbean relay cropping in cereal-based cash crop systems. Crop management options that promote integrating pulses into current cropping systems may allow mitigating the impact of erratic monsoon rains, an increasingly common phenomenon in parts of South and Southeast Asia.

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