Chapter

Soybean and Sustainable Agriculture for Food Security

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Abstract

Global food security is under-challenged due to over increasing human population, limited cropland, and risk of climate change. Therefore, an appropriate agricultural policy framework needs to be developed for food security that should be sustainable economically and ecologically. Nitrogen (N) is a crucial element that controls the growth productivity of crop plants. N accounts for around 78 volume per cent of the atmosphere but all crop plants cannot use it directly. Agricultural land is mostly dominated by cereals (e.g. rice, wheat, maize) which have specifically high N demand as compared to food legumes. Soybean exemplifies the most significant and cultivated food legume, presently cultivated worldwide under varying climatic conditions. It plays a significant role in global food security as well as agricultural sustainability due to a high seed protein and oil concentration, and low reliance on N fertilization. Soybean enriches soil health by fixing atmospheric N through biological nitrogen fixation (BNF), the most productive and economical system for N fixation and crop production, associated with more intensive production systems. However, the efficiency of BNF depends on several factors. This study is focused to develop more reliable guidelines for managing BNF by using the potential of natural agro-ecosystems.

Keywords: soybean, food security, biological nitrogen fixation, climate change, agro-ecosystems

1. Introduction

The global population is predicted to reach 8.6 billion in 2030, 9.8 billion in 2050, and 11.2 billion in 2100 [1]. This expanding population and their subsequent consumption will lead to an increase in the global food demand, and it will be great challenge for food security under climate change and land-use scenarios. Exclusively, abiotic and biotic stresses caused by the global climate change progressively affected the cropping systems which will pose serious intimidations for global food production [2]. Most developed countries have had to embrace modern-day agricultural technologies to achieve food security for increasing populations, as well as to support agri-business and income generation. Currently, scientists have been propagating to explore crop diversification as an alternative strategy for developing countries. The ecological consequences of technologically focused agricultural systems that have been adopted and appreciated for many decades without the consideration of the environment, and the impact on the ecosystem is now coming into focus and scrutiny with the vivid and negative environmental impact of modern-day agriculture, and how it has greatly contributed to climate change. The current agricultural practices are not sustainable due to their misuse of valuable resources and environmental degradation. Hence, the philosophy of basic plant science research, and the direction of demand-based plant breeding should be changed to allow the plants for growing well in normal and limited resources in a sustainable way. In these reflections, it is suggested to grow soybean due to its higher adaptation and mitigation approaches in changing climates and multiplicity effects.

In history, soybean (*Glycine max* L. Merr.) was domesticated in China and afterward introduced into the USA and Brazil [3]. Currently, Argentina, Brazil, and the USA are the top soybean-producing countries at the global scale comprising 16, 32, and 33%, respectively [4]. Globally soybean production is projected to increase 311.1 and 371.3 million metric tons in 2020 and 2030, respectively. The annual growth rates of soybean from 2005 to 2007 to 2010, and 2010 to 2020 were 2.9 and 2.5%, respectively, and the rate is projected to increase 1.8% from 2020 to 2030 [5]. All the same, it is estimated that the demand in 2030 will be increased approximately 1.7 times greater than that of 2005–2007 [5]. Climate change has the potential to allow a significant increase in soybean production in Africa, irrespective of which production scenario becomes reality in the future [6]. Despite biotic and abiotic stresses, soybean production is continuing to increase over time [7, 8]. Soybean is known as the 'Africa's Cinderella crop' owing to the increasing demand for soybean production in recent years in Africa [9]. This chapter will focus on the potential role of soybean in agriculture for food security.

2. Soybean for sustainable development

2.1 Potential source of food and health benefits

Soybean is one of the most valuable crops in the world due to its multiple uses as a least expensive source of protein, healthy unsaturated fats and carbohydrate for the human diet, livestock and aquaculture feed, and biofuel. It is predominantly grown worldwide for high-quality, inexpensive proteins, and oil. It is highly nutritious food commodity as a source of vegetable protein and low cholesterol at an affordable price and is considered as a good substitute for animal protein due to containing essential amino acids required for human nutrition. The approximate composition of soybean is 36% protein, 19% oil, 35% carbohydrate including 17% dietary fiber, 5% minerals, and several other components including vitamins [10]. Soybean oil contains 16% saturated fatty acids, 23% monounsaturated fatty acids, and 58% polyunsaturated fatty acids [11]. In addition to edible oil, soybean is used as many processed foodstuffs such as soybean sprouts, toasted soy protein flours, soy milk, tofu, tempeh, miso, natto, soybean paste, and soy sauce [12], and also, bean curd, oncom, tauco, soybean cake, ice cream, soy flour, etc. [13]. Soybeans are also an important food commodity after rice and maize. Soybean is by far the cheapest source of protein for the poor smallholders as compared to other quality foods that are rich in proteins such as animal meat, fish, eggs, and milk. Based on the protein quality (protein digestibility corrected amino acid score), the value of soybean protein is equivalent (whole soybeans 96, soybean milk 91) to eggs (97) [14]. Several bioactive compounds like isoflavones, peptides, flavonoids, phytic acid, soy lipids, soy phytoalexins, soyasaponins, lectins, hemagglutinin, soy toxins, and vitamins are isolated from soybean and soy food products [15]. It has been reported earlier in many studies that consumption of soybean in different forms provides bioactive compounds as well which significantly lowered the risks for several cancers including breast [16], prostate [17], lung [18], colon [19], liver [20], and bladder [21], hypercholesterolemia and cardiovascular diseases [22], osteoporosis [23], hypertension [24], and blood pressure [25]. The consumption of protein from soybean sources by human beings is currently low worldwide, although there is increasing public and commercial interest since the crop could be a major source of dietary protein for the future. Malnutrition is a major global health problem, especially for developing countries, and food insecurity is the prime factor for malnutrition [26]. However, soybean-based foods are cheaper and readily available which can solve the problems.

2.2 Imperative source of animal feed

Soybean is not only a good source of high-quality edible oil and proteins for human beings but also a high-quality forage protein in animal feed worldwide. Feed is a key pillar in the journey of improving the productivity of livestock. Quality feed is the fundamental factor to increase the productivity of livestock. Soybean is also widely used as high quality and protein-rich animal feed [13] due to its auspicious attributes such as relatively high protein content, suitable amino acid profile except for methionine, and minimal variation in nutrient content. Soybean byproducts (raw materials and soybean meal) are used as a source of protein feedstuff for domestic animals including pig, chicken, cattle, horse, sheep, and fish feed and many prepackaged meals [10]. Soybean meal (SBM) contributes about 30% to poultry feeds [27]. It represents two-thirds of the total world output of protein feedstuffs [28]. Its feeding value is unparalleled by any other plant protein source [29]. SBM usually contains 47–49% crude protein (CP) and 3% crude fiber (CF) [30]. SBM is considered superior to other vegetable protein sources in terms of CP content and exceeds them in both total and digestible amino acid content [31]. The protein digestibility of SBM in poultry is approximately 85% [32]. Among the vegetable protein sources, SBM is used to meet the feed requirement of animals for limiting amino acids in cereal-based diets due to being the most cost-effective source of amino acids [33]. Therefore, the production of soybean, which is used extensively as animal feed, must be increased beyond the current production level due to meet the animal protein demand of overgrowing population in the world.

2.3 Contribution in biological nitrogen fixation

Nitrogen is a critical limiting element for growth and development by increasing chlorophyll as well as photosynthesis in crop plants. It is also the most abundant element in the atmosphere and exists in the diatomic form (N_2) but the plant cannot uptake and use N_2 directly. Only a group of plants known as legumes under the family of Fabaceae are well-known for being able to harvest N_2 from the atmosphere and incorporated it into the soil which is termed biological nitrogen fixation (BNF). BNF is firstly discovered by Beijerinck in 1901 [34]. The conversion of atmospheric dinitrogen (N_2) to ammonia (NH_3) under the combined action of biological and chemical activities is known as BNF [35]. It is a chemical process by which molecular N_2, with a strong triple covalent bond, in the air is converted into ammonia (NH_3) or related nitrogenous compounds, typically in soil or aquatic systems [36]. It is an important microbially mediated process that converts N_2 gas to NH_3 using the nitrogenase protein complex [37]. Some bacteria contain enzymes that can reduce N_2 and turn it into ammonia. Consequently, the NH_3 is used to produce essential elements, and it is a process known as BNF [38, 39]. The BNF can be symbiotic (mutualistic associations between plant species and fixing microorganisms, mainly rhizobia), or asymbiotic (when transmitted by free-living fixing microorganisms, like the species of the genera Azotobacter and Beijerinckia) [40].

Soybean also improves soil fertility, another benefit of soybean cultivation, by fixing atmospheric nitrogen through BNF [41, 42]. Soybean plants can freely assimilate NH_3 to produce nitrogenous biomolecules. These prokaryotes include aquatic organisms (cyanobacteria), free-living soil bacteria (*Azotobacter*), bacteria (*Azospirillum*) which make associative relationships with plants, and bacteria (*Rhizobium* and *Bradyrhizobium*) to build up highly significant symbiotic relationships with legumes and other plants [43]. The productivity of soybean largely depends on the BNF, the most important source to supply N in the soil. It has been reported earlier [44] that soybean seed yield is strongly linked to the N fixation process and N uptake of seed. It has been estimated that the contribution of N fixation to plant N demand ranges from 40 to 70% depending on the plant growth conditions (environments) and the association with the host-bacteria symbiosis [45–47]. In soybean, N derived from the atmosphere (NDFA) via BNF is recorded by 0–98% of the total N uptake, equivalent to 0–337 kg N ha^{-1} [48], and the total N uptake greatly depends on the activity of rhizobia. The yield of soybean increased over time in the last decades [49] by maintaining a high seed protein and N fixation process. Therefore, the N fixation process has become a growing concern on a global scale [44]. This BNF would be a major benefit to smallholder farming systems in developing countries where soil degradation and nutrient depletion have gradually increased because of high cropping intensity, and now pose serious threats to sustainable food production. Soybean farming is considered as one of the most cost-effective ways for sustaining soil fertility, especially for smallholder farmers which helps them to promote improved living standards and food security. Hence, soybean production and commercialization would be a milestone for improving food and nutritional security as well as to meet sustainable agriculture.

The fixation of atmospheric nitrogen is a complex process that requires a large input of energy to carry on [43]. For fixing nitrogen microorganisms require 16 moles of adenosine triphosphate (ATP) to reduce each mole of nitrogen [50]. Microorganisms obtain this energy by oxidizing organic molecules, such as non-photosynthetic free-living microorganisms obtain from other organisms, photosynthetic microorganisms (Cyanobacteria) obtain from sugars (photosynthetic product), and associative and symbiotic nitrogen-fixing microorganisms obtain from their host plants' rhizospheres [50, 51]. The BNF process is affected by several factors [52] like abiotic stresses water deficit or excess water, salinity, temperature, heavy metals, and biocides [53], mineral elements such as high soil nitrate concentration

[54], phosphorous [55] and sulfur [56, 57], acidity [58] and alkalinity [59], and biotic factors like ineffective rhizobia [60], plant diseases [61], and weeds [62]. At pH 7.0, we observed that there was low nitrogenase activity.

2.4 Contribution as rotational crop

Crop rotation is an important agronomic management practice that is followed to sustain soil fertility and reduce pests and diseases. It also enhances to form some beneficial soil microbes with the following crops when the rotational crops are legumes specially soybean, which pointedly increased the growth and productivity of the crops. It has been well established that cultivation of soybean in 2- and 3-year rotations with corn and wheat in agriculture is highly profitable and advantageous for soil [63]. It has also been reported that soybean as a rotational crop is significantly cost-effective and beneficial to soil health [64, 65]. It has been established earlier that crop rotation recovers soil health and resilience by increasing soil organic carbon (SOC) [66–68], improving soil structure [69], enhancing nutrient availability [70], decreasing pests and pathogens in crops, increasing the population disease-defeating soil microbes [71, 72], and consequently increases yield of crops [73]. It is well documented that crop rotation as corn-soybean-wheat increased soybean yield in 1-year out of 3-year rotations as compared to growing every other year in corn-soybean rotations [74]. The high frequency of soybean in a crop rotation has decreased the SOC storage, and reduced macro aggregation owing to low residue inputs of soybean [75–77]. Soybean provided N through BNF as well as exploiting soil N from chemical sources [78, 79]. The soybean yield is meaningfully increased under rotations of corn-soybean in 2 years as compared to growing continuously [80–82]. Soybean in a 2-year rotations with corn increased grain yield by 9.2 and 12% over continuous soybean growing under no-tillage and conventional tillage conditions, respectively [80]. Rotation of soybean with traditional crops such as maize increases soil fertility by fixing nitrogen in the soil consequently increasing yield by 10–20% [83].

As compared to cereal crops, the residues of soybean contain a low C to N ratio, which promotes the decomposition of residues rapidly [76, 84]. However, accumulation and sequestration of C in a stable soil aggregate from soybean residues is lower over the corn and cereal residues, indicating a lower C to N ratio, and lower phenolic acid content of soybean residues [85, 86].

Corn-soybean rotation including winter wheat increased soybean yield over mono-cropping soybean due to higher infestation of pest predation and/or soil-borne plant pathogens as well as reduced SOC levels owing to lower aboveground and belowground biomass from continuous soybean cropping [64, 87]. The soybean yield is significantly increased with rotation as compared to continuous soybean due to increasing soil organic matter plus improving soil properties [88, 89], increasing the resource available for heterotrophic soil microbial communities, and increasing C and N cycling [89, 90]. Moreover, the strong rotational benefits were observed by Giller *et al.* [91] for maize-soybean rotation as the crop broke the cycle of continuous maize cultivation and fixed nitrogen to the soil, and support to build up sustainable soil fertility systems and profitability. As well, soybean-maize rotation deducted N fertilizer which helps to reduce carbon emissions that ensure sustainable agricultural production. It has been reported earlier [92] that soybean contains the climatic resilience and native *Bradyrhizobium* strains which are well apposite to the current crop rotation system.

2.5 Impact on soil fertility

Soil is a nonrenewable resource that may be degraded due to inappropriate management practices. Intercropping systems allow to enhance resource-use efficiency and crop productivity which promote multiple ecosystem services [93]. Integration of legume crops is fundamental in many intercropping systems [94], and legume-based cropping systems improve soil fertility in many ways, such as increasing SOC and humus content, N and P availability, etc. [95]. It has been documented earlier that grain legumes are weak suppressors of weeds, but the mixing of crop species in the same cropping system improves the ability of the crop to suppress weeds [96, 97]. Soybean is characterized as a major economic crop in smallholder farming systems due to sustaining soil fertility [42], providing feed for livestock, and improving rural household nutrition and income. Inoculation of *Bradyrhizobium japonicum* strain 61-A-101 and mycorrhizal fungi with soybean potentially augmented the N and P uptake by the host plant through efficient colonization of *Glomus mosseae* [98]. It has significant agronomic benefits to refresh the soils such as the crop canopies protecting the soil from recurrent erosion, decaying root residues improving soil fertility, and fixing atmospheric nitrogen into the soil which leads to higher levels of sustainable agriculture with minimal input requirements. Soybean is primarily grown as an intercrop with maize, sorghum, finger millet, sugarcane, which may be a suitable approach for sustainable agriculture.

2.6 Impact on greenhouse gas emission

There are a number of the impact that grain legumes have on the environment and the soil in regards to quality. Meanwhile, the role of legumes like soybean to alleviate the negative effects caused by climate change has been rarely addressed. The emission of greenhouse gases (GHG) such as carbon dioxide (CO_2) and nitrous oxide (N_2O), methane (CH_4), etc. are the causes of global warming. Legumes reduce the emission of GHG in agricultural systems by reducing mineral N fertilization, sequestration of carbon in soils, and the overall fossil energy inputs in the system [99].

N_2O is much more active than CO_2 which represents nearly 5–6% of the total atmospheric gases [100]. Around 60% N_2O emission is occurred by agricultural practices which exemplify as the main source of emission [101], and the production of crops and animals are the main source of emission [102]. In crop production, the application of nitrogenous fertilizers is the birthplace of the majority of these emissions [101]. It has been estimated that about 1.0 kg of N is emitted as N_2O from every 100 kg of N fertilizer [95]. The amount of N_2O emission largely depends on several factors including N application rate, soil organic C content, soil pH, and texture [103, 104]. In most of cropping and pasture systems, de-nitrification is the leading source of N_2O emission [104–106]. Several studies in recent years have been signified the role of legumes in the reduction of GHG emissions. For example, it has been reported that legumes discharge around 5–7 times less GHG per unit area compared with other crops [107]. Generally, the losses N_2O from soils under legume crops are undoubtedly lower than those from both N_2O fertilized in grasslands and non-legume crops [95]. Among legumes, soybean most efficiently produced and provided the maximum protein (g) per GHG emission out of 22 plant and animal protein sources [108]. Adoption of sustainable agricultural systems mitigate the emission of GHG such as conservation agriculture systems, which is suitable for the cultivation of both grain, and green-manure legumes lessen the emission of GHG.

2.7 Socio-economic aspects

Food and water security will be a major global issue focus in the coming decades due to climate change and population pressure. Malnutrition, predominantly protein deficiency, is prevalent in many parts of the world. Therefore, appropriate technology should be addressed by lawmakers and scientists for food security, and the cultivation of legumes majorly soybean is a first step to address the food security issues worldwide. Soybeans produce the highest amount of protein per hectare [109] and are well positioned to meet the need of future global protein. Conventional protein sources are highly expensive as well as a vulnerable population is unable to purchase from these sources. Hence, soybean-based protein foods are an important strategy to relieve malnutrition and hunger problems. Since it has been evidenced that smallholder farmers have limited capability to overcome crop production challenges due to changing climate [110]. They produce soybean for gaining higher yields, family demand, and net profits with minimum N fertilizer input which eventually improved their living standards as well as food security [111].

3. Conclusion

A sustainable agricultural system is the only way to sustainably intensify food crop production without causing damage to human and environmental health. Soybean and other nitrogen-fixing legumes should be a viable crop included in all forms of cropping systems as they can efficiently utilize atmospheric nitrogen through the process of BNF. The most important thing is the integration of soybean and another legume across different cropping systems which would effectively reduce the usage of chemical nitrogenous fertilizers, and conserve soil fertility. It is important to focus on the cultivation of crops that provides higher yield, economic return by maintaining soil health as well as environmental balances. Some priority areas seem to emerge, and these areas require deeper investigation to fully understand how the BNF dynamics, and how to utilize BNF in best way for sustainable agriculture. Thus, soybean crops should be grown to reduce hunger, malnutrition, and poverty as well as to bring food security by sustaining agriculture in light of climate and population challenges.

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