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Review Article

Role of Phosphorus and Inoculation with *Bradyrhizobium* in Enhancing Soybean Production

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Soybean (*Glycine max* L. Merril) is among the key oil seed crops worldwide, providing several benefits from human consumption to the enhancement of soil productivity. In Uganda, legumes are cultivated on roughly 1.5 million ha, with soybean being produced on a lower production area of 150,000 ha compared to beans (925,000 ha) and groundnuts (253,000 ha). In terms of achievable yield, soybean emerges the highest at 1.2 $t{\cdot}ha^{-1}$ as compared to beans (0.5 $t{\cdot}ha^{-1}$) and groundnuts (0.7 $t{\cdot}ha^{-1}$). Despite the smallest production coverage area, the crop's feasible grain yield is projected at 4.6 $t{\cdot}ha^{-1}$ under optimal environmental conditions. The major bottleneck to the crop's production is the decreasing soil fertility, mainly caused by low nitrogen (N) but also phosphorus (P) levels in the soil. There is a high potential for supplying N from the atmosphere through biological N fixation (BNF), a natural process mediated by the symbiotic bacteria *Bradyrhizobium japonicum*, which requires optimum P levels for effective N fixation and increased yield. The current work reviews the present status of soybean production in Uganda, highlights its ecological requirements, importance, and constraints, and proposes the use of inoculation and P application to boost its production.

1. Introduction

Soybean, which belongs to the family *Fabaceae*, is the most important legume oil seed crop to many people globally and particularly in the tropics [1–3]. Integration of grain legumes into farming systems enhances soil fertility and increases household incomes [4–6]. Indeed, legume provides the cheapest source of protein for vegetarians by supplementing mineral and vitamin requirements [7, 8]. Soybean provides dietary proteins for not only human but also animal feed in the form of soy meal, which makes up approximately 98% of global livestock feed [6, 9]. In addition to being utilized as a source of biodiesel fuel, soybean accounts for nearly 30% of the global refined vegetable oil [10, 11].

In Uganda, Ronner and Giller [12] documented that legumes are grown on around 1.5 million hectares. Soybean, which is cultivated on 150,000 ha comes third in cultivated land after common beans (925,000 ha) and groundnuts (253,000 ha). Even though common beans occupy a hefty share with nearby a third of the cultivated land, soybean in its place displays the most favorable efficiency with a yield of 1.2 $t{\cdot}ha^{-1}$ as related to 0.7 $t{\cdot}ha^{-1}$ for ground nuts and 0.5 $t{\cdot}ha^{-1}$ for beans [13]. In comparison, in Uganda, Mutegi and Zingore [14] estimated a 100% increase in soybean yield under integrated soil fertility management (ISFM) technologies. The transformation and modernization of the agricultural sector to increase productivity have been embraced by the Ugandan government, which in 2010 introduced the vegetable oil development project. The aim was to support soybean and other oilseed-producing farmers in terms of increasing yields and value chain development [15].

Despite its importance, soybean yield has remained low in sub-Saharan Africa (SSA). For instance, AASR [16] stated a low legume yield of less than 1 t·ha^{-1} and Mutegi and Zingore [17] reported a stagnated average legume yield of about 0.7 t·ha^{-1} contrary to the expected 3 t·ha^{-1}, which exacerbates food insecurity in SSA. The major cause of such low productivity is low soil fertility caused by insufficiencies in mostly N and P [18–22]. Low soil fertility is equally attributed to negative nutrient balances for these minerals resulting from low use of inorganic fertilizers, leaching, and continuous nutrient mining through crop harvests [23–26].

Declining soil fertility coupled with traditional varieties has a negative effect on soybean production [5, 15]. This is particularly so because farmers are less informed and less willing to adopt high-yielding varieties and ISFM production technologies like BNF. For instance, a 30% increase in soybean production has been reported globally with the embracing of new varieties and better crop management techniques [27]. In Uganda, a study by CRAFT [28] revealed that with inoculation, 4,100 farmers harvested 1450 t of soybean as compared to their previous harvest of 1,040 without inoculation. Therefore, integration of inoculated improved soybean varieties into most cropping systems in the tropics, Uganda inclusive, could help a great deal in increasing N fixation and boosting soybean economic returns.

2. General Information about Soybean Production

Globally, soybean has emerged as the most valued legume crop in relation to not only overall production but also international trade [2, 29]. The world's leading soybean producers include Brazil, the USA, Argentina, India, and China, with 34, 31, 18, 11, and 9 million ha dedicated to soybean cultivation, respectively [30]. Akibode and Meredia [31]; noted that over 75% of the pulses harvested in Asia and SSA come from rain-fed production systems. Subsequently, this has resulted in a 0.4% negligible increase in crop yield in the last 10 years, from 800 to 850 kg·ha^{-1} [13, 31]. Specifically, the on-farm soybean yield in SSA is 700 kg·ha^{-1}, a value that is nearly four times below the achievable yield of 3000 kg·ha^{-1} recorded in station studies. This could be due to the different management efforts highly accrued to the research station fields as compared to the on-farm conditions. The low crop yields reported on smallholder farms have exacerbated poverty, food insecurity, and malnutrition in many parts of SSA [14].

Ohyama et al. [32] reported that soybean yield could increase up to 4.6 t·ha^{-1} under prime environmental (climatic and soil) conditions. However, the USA and Japan have reported greater potential soybean yields of 10 and 8 t·ha^{-1}, respectively [32, 33]. Hence, soybean productivity potential could be maximized than we have thought if proper soil and crop management practices are used [34].

There has been a substantial upsurge in soybean production over the years. In Uganda, soybean production was done in less than 100 ha till the 1990s, when the area cultivated increased steadily (Figure 1). Nonetheless, the yield stagnated at around a ton per ha. In the last decade, the country's soybean production has been faring well compared to some key African nations. For instance, her annual production is approximately 49000 t, compared to Egypt (3900 t), Kenya (2400 t), Rwanda (24000 t), Ethiopia (97000 t), and South Africa (1018000 t) (Table 1). Her mean yield is 1.01 t·ha^{-1}, a figure that is above that of Rwanda (0.5 t·ha^{-1}) and yet far below those of Egypt (3.2) and Ethiopia (2.2).

Soybean production is common in the Northern and Eastern regions of the country [35] (Figure 2). According to UBOS [35]; in the seasons of 2008/2009, northern Uganda produced 16,000 Mt of soybean, which was harvested from 26,000 ha. Western Uganda followed with 2000 Mt being produced from 2000 ha, whilst the Central region produced 200 Mt from an area of 1000 ha. Thereafter, the soybean production area remained stagnant, after a steep increase that was observed between 2000 and 2003 [12]. In 2008, Kasese among the six national evaluation locations recorded the uppermost mean grain yield of 2385 kg·ha^{-1} while Hoima recorded the lowermost mean yield of 935 kg·ha^{-1}. In a similar study conducted by UBOS [36], the Lango subregion ranked as the largest producer with 73,969 t, followed by Busoga with 11,095 t, Acholi with 6,161 t, and lastly Bukedi with 5,603 t. The northern region had the highest soybean production area (26,195 ha), followed by eastern (7,279 ha), Western (2,220 ha), and Central (750 ha) [36].

Soybean production in Uganda has steadily been increasing, but due to the soybean leaf rust disease outbreak, its growth stagnated, hence devastating soybean production farmers throughout the country in the past years. The Soybean Breeding and Seed Systems Program, in partnership with the Ministry of Agriculture, Animal Industry, and Fisheries (MAAIF), Regional Universities Forum for Agricultural Development (RUFORUM), National Crops Resources Research Institute (NaCCRI), Alliance for a Green Revolution in Africa (AGRA), and soybean Africa immensely and successfully bred, released and recommended early maturing, better yielding, and rust-resistant soybean varieties from 2004 to 2013. Among the new varieties released were, Namsoy 4M and Maksoy 1N in 2004, Maksoy 2N in 2008, Maksoy 3N in 2010, whereas, Maksoy 5N and Maksoy 4N were released in 2013. There has been an increase in the adoption of these improved soybean varieties particularly in Uganda, for commercial production, resulting in an increase in soybean yield of up to about 2500 kg per hectare. This has provided a high source of income and an affordable protein source for Uganda's poor rural population [37].

In SSA, the total land area under soybean production covers about 1.3%, while the world soybean production accounts for 0.6%. Whereas in the past four decades'

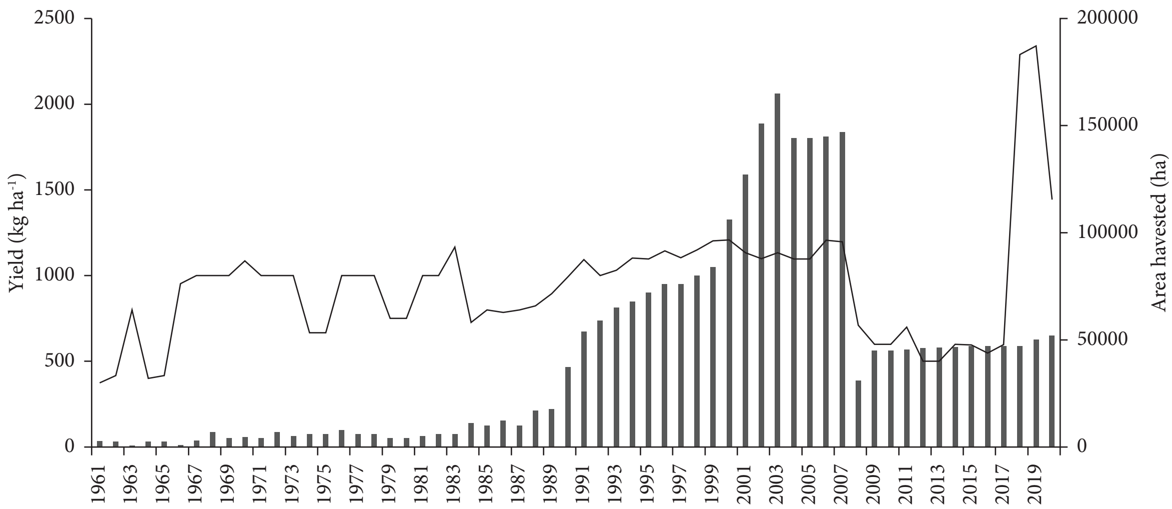

Figure 1: Soybean production trend in Uganda in kg per ha (line graph) and area harvested in ha (bar graph) from 1961 to 2020 (source: [13]).

Table 1: Soybean total production and average yield per hectare in selected African countries from 2001 to 2020.

	Year	Egypt	Ethiopia	Kenya	Rwanda	Uganda	Zimbabwe	South Africa
Total county's production (*t*)	2011	29785	35880	2181	37426	31847	53849	710000
	2012	26000	63653	2866	18544	23000	77124	650000
	2013	32757	61025	2498	24838	23205	66740	784500
	2014	39872	72184	2368	17901	27929	71328	948000
	2015	46843	89554	2603	21739	28013	41768	1070000
	2016	45165	81235	2007	21942	25730	47755	742000
	2017	36388	86468	2518	23934	28097	36478	1316000
	2018	46997	149455	2398	22809	107624	69688	1540000
	2019	36260	125623	2396	24526	117000	23460	1170345
	2020	50000	208676	2396	23755	75077	59656	1245500
	Mean	39007	97375	2423	23741	48752	54785	1017635
County's average yield (kg·ha^{-1})	2011	3120	1850	1258	780	700	1205	1699
	2012	3619	1998	1500	586	500	1530	1377
	2013	3477	2000	1222	676	500	1314	1519
	2014	3329	2047	1064	475	600	1177	1885
	2015	3282	2346	943	473	596	946	1557
	2016	3354	2217	906	472	547	1196	1476
	2017	2825	2271	1047	449	598	1551	2293
	2018	2920	2309	1003	416	2290	1868	1956
	2019	2925	2303	999	525	2340	692	1602
	2020	2941	2490	999	490	1444	1815	1767
	Mean	3179	2183	1094	534	1012	1329	1713

Data source: FAOSTAT [13].

soybean average yield in SSA was very low (1.1 t·ha^{-1}) compared to the world average (2.4 t·ha^{-1}). For example, in 2016/2017, the mean soybean yields in South Africa, Nigeria, Zambia, and Uganda were 2.29, 0.96, 1.94, and 0.6 t·ha^{-1}, respectively [5].

Globally, two soybean traits make it largely popular due to its high oil (20%) and protein content (40%), which all emanate from processed seed. Soybean, among crops, has proven to be the highest legume oilseed in protein content per unit area. In fact, Uganda's science-led interventions contributed to the steady rise in soybean production from as low as 158,000 ha in 2004 to a higher value of 180,000 ha in 2010 [35].

2.1. Economic Importance of Soybean. Pulse crops are essential sources of not only nutrition and food but also energy that contribute around 30% of crop production globally [10, 11]. Soybean, as a grain legume, plays a key role in fixing atmospheric N [3, 38]. In addition, it is a crucial source of not only micronutrients but also macronutrients and vital secondary metabolites that are key components to promote health [39, 40]. It is also a critical source of dietary proteins

(a) (b)

Figure 2: A soybean field experimental at Lira in Uganda.

and amino acids such as valine, methionine, cystine, tyrosine, theonine, isoleucine, tryptophan, phenylalanine, and lysine, which are critical components of the protoplasm and de-oxyribo nucleic acid [41].

Soybean is composed of about 42% proteins and 20% oils [42], in addition to fat-soluble vitamins, which are used to produce many products such as lecithin [43]. This could be a good alternative to quite expensive protein-rich foods like fish and chicken, particularly in developing nations [42]. In many parts of the SSA countries, it provides about 4% of the daily calorie intake, whilst, in Latin America and South Africa, it provides about 3% of the daily protein intake. Thus, soybean remains to be an important crop, especially for vegetarians [44].

Agricultural food legume crops such as soybean are very significant in developing nations since they are accountable for addressing both food and nutritional uncertainty [8, 31, 45]. They are very crucial for livestock and human nutrition [9, 46]. In reality, they serve as rotation crops, where they furnish cereal crops with N besides helping in reducing soil pathogens [3, 8, 34, 47–49]. Many legumes form synergy associations with bacteria that have the capability of fixing atmospheric N [6, 45, 50]. For example, in Brazil, the quantity of organic N formed in such relations of rhizobia and legumes is about 20 million tons per year, with soybeans, in precise, have been observed to fix around 300 kg N·ha^{-1} [3, 6, 51].

According to Giller and Wilson [52] and Giller [53]; the BNF input in terms of total N uptake through symbiotic N fixation for soybean, pulses, groundnut, and sugar cane is 67, 55, 65, and 17%, respectively. The average percentage of crop N extracted from atmospheric N is almost 70% worldwide, so legume N fixation in agroecosystems is considered the most significant source of N in soils. Although it mostly fixes the N for its use, if the residues (above ground and roots) are incorporated back into the soil, it would reduce the N demand of the cereals in the rotation by 40% [48].

In many farming systems, food legumes such as soybeans often serve as a feed crop, obtaining higher price values than cereals, and they are progressively cultivated to complement the income of farmers [4, 54]. Thus, this is an economically important crop for trade both in international and local markets, with the largest exporters of soybean being the USA, Brazil, Argentina, and China [55]. In Uganda, soybean has been reported to contribute to about 1% of the gross domestic product majorly due to exports to the neighbouring countries between the years 2008 and 2009 [36]. For instance, Ssengedo et al. [56] observed an increase in export earnings of soybean in Uganda from USD 300,000 in 2006 to USD 1,163,000 in 2009, accounting for a 288% increase. In 2019, the country's total soybean export volume was 1150 t against a total export value of USD 722,440. Thus, due to their economic importance, legume crops, and specifically soybeans have become central targets not only from the environmental and biotechnological point of view but also for agricultural research [3, 50, 57].

2.2. Constraints to Soybean Production

2.2. Constraints to Soybean Production. Many biotic and abiotic factors have inhibited soybean production, which includes low soil fertility status and minimal soil moisture content [5, 57]. The abiotic factors can further be categorized into edaphic and climatic factors [58].

2.2.1. Biotic Constraints. Many diseases affect the yield of soybean globally, such as red leaf blotch, leaf spot, anthracnose stem, fusarium wilt, charcoal rot, blight brown stem rot, stem blight phytophthora root rot, stem rot pod, and alfalfa mosaic, whereby the intensity varies depending on the location [59]. Specifically, in Uganda, the yield of this crop is severely affected by soybean leaf rust (*Phakopsorapachyrihizi Syd*) (Figure 3).

In recent times, soybean leaf rust has become the most destructive soybean foliar disease and can cause up to approximately 90% loss of yield [37] if not well controlled. This disease has become endemic in areas where soybean is grown, having been first identified in Uganda in 1996, showing symptoms that include yellowing of leaves and tan sporulating lesions [12]. Leaf rust remains a problem in soybean production. Nonetheless, with the introduction of

Figure 3: Soybean rust susceptible (yellowish left side) and resistant (greenish right side) varieties. Closeup represents leaf rust symptoms.

new varieties such as Maksoy 1N, 2N, 3N, 4N, and 5N, which were introduced between 2004 and 2015, there has been increased resistance to soybean leaf rust, thus leading to increased yields [55]. Insect pests are also of economic importance in soybean production. These pests include pod-sucking and defoliating insects like aphids that suck the young succulent green part of the soybean plant and sucking bugs that suck the contents of pods and soft plant parts [60]. During storage, the grains are susceptible to attack by storage moths.

2.2.2. Abiotic Constraints. The average soybean yield (grain) in tropical Africa is relatively low at 1000 kg ha^{-1} in comparison with 2500–3500 kg·ha^{-1} attainable in developed nations [61]. This is largely ascribed to the lack of better varieties, which is a major determent of soybean production in African countries. In other areas, low grain yield is compounded by pod-shattering, especially in the dry savannah environment with high average temperatures and low average rainfall [44, 62], which further reduces yield [58, 63, 64].

Some farmers have failed to use rhizobia due to inaccessibility and ignorance, and there is a problem of fake seeds on the market and a lack of promiscuous soybean varieties [65]. A study by N_2Africa [66] indicated a total number of 17,297 farmers who adopted inoculation, comprising 11,245 women (65%) and 6,052 men (35%) (Table 2). In some African countries, farmers too lack interest in soybean production due to lower soybean grain demand and a lack of soybean processing equipment.

Table 2: Farmers reached by gender and district through m-Omulimisa in 2018 (adopted from N_2Africa, 2019).

District	No. of groups	No. of females	No. of males	Total
Alebtong	80	1341	982	2323
Amuru	33	692	232	924
Agago	34	755	176	931
Dokolo	25	417	313	730
Kole	83	1674	870	2544
Apac	35	764	600	1364
Kole	83	1674	870	2544
Gulu	34	754	234	988
Lira	88	1715	968	2683
Kwania	46	782	516	1298
Pader	35	628	320	948
Oyam	48	1021	536	1557
Total	624	12217	6617	18834

Adopted from N_2Africa [66].

3. Biological Nitrogen Fixation

Sustainable agriculture in recent studies is increasingly gaining fame as a means to address the above-mentioned challenges. These are technologies that focus to increase the availability of N, enhancing legume productivity, and production systems that improve economic and ecological environmental conservation [6, 49, 67–71]. BNF is an alternative example that can supply N, reduce the high cost of N fertilizers, and subsequently limit the environmental footprint of N [72]. Oil seed legumes such as groundnut (*Arachis hypogaea* L.) and soybean are more efficient in fixing N, estimated globally at 6.3 times greater BNF when combined yearly (18.5 Tg·year^{-1}) compared with food legumes like common beans (0.58 Tg), chickpea (*Cicer arietinum* L.) (0.60 Tg), pea (*Pisum sativum* L.) (0.57 Tg), and other pulses (0.47 Tg) [73]. Therefore, soybean is very pertinent in BNF.

The process of changing inert N_2 to biologically utilizable NH_4 is termed biological N fixation, in which only bacteria (rhizobia) mediate the process in nature [74]. Through the process of forming nodules, legumes such as soybeans have gained the capability to absorb N_2 gas from the atmosphere. The legume plant provides the bacteria with photosynthesis energy in the form of C, and it reciprocates by fixing N_2 gas into an available form for plant uptake [53, 77].

By optimizing the symbiotic relationship of rhizobia with soybean, under optimal conditions such as limitless critical nutrients such as P and Mo, the legume can fix up to 300 kg N·ha^{-1} [10, 11, 76, 77]. P and sometimes K are critical nutrients that mostly limit soybean production [52, 53]. The optimal efficiency of N fixation requires the presence of a satisfactory quantity of not only compatible but also effective rhizobia strains in the rhizosphere [52].

These root nodule-occupying rhizobia originate either from the commercial inoculants, for whom a total of 4,100 farmers in the year 2020 inoculated soybean and harvested 1,449,610 kg (1450 tonnes) of soybean from a total of 995 ha of land, or from the native rhizobia in the soil [28, 48]. With P being one of the essential elements that enhance the association, it requires that its supply be maintained at a certain optimum level for adequate yields to be attained, and this can be done only by periodically replenishing it through the use of mineral fertilizers [23, 78–80]. Besides P promoting rhizobia growth, it also encourages root nodulation, which consequentially enhances the BNF process [45, 81–83]. Findings by Dugje et al. [84] and Adjei-Nsiah et al. [85, 86] revealed that although P is very important in rhizobia inoculation of soybean, the increase in soybean yield is usually less compared to the crop's feasible grain yield, which is projected at 3 t·ha^{-1}.

Nonetheless, the high cost of the fertilizers is a key drawback to their wide application by farmers [48], more so if the appropriate P application rate is not well known. The high cost of fertilizers and high soil degradation due to a lack of knowledge on the optimum application P rates continuously lead to low crop, yields exacerbating famine in some sub-Saharan countries, a problem that has become a jinx for researchers to fix [23]. Exploiting low-cost alternatives of N sources through heightening the normal biological N fixation (BNF) in legumes such as soybean may be a judicious substitute if the cost of farming is to be lowered. Optimal nutrient use efficiency and productivity will be improved, besides decreasing the related environmental penalties of the use of N fertilizers [23, 51, 87].

The number of native bacterial strains in the rhizosphere is often insufficient to induce substantial N-fixation [34]. Hence, inoculation of soybean legumes improves the process of fixation of N through BNF [48]. This is due to the increased development of root nodules, which houses the *B. japonicum* that enhances atmospheric N use by the plants [88].

Nitrogen is a main (macro) nutrient with momentous roles in the production of amino acids in legumes. It is also necessary for plant growth due to its key role in cell division [89]. It promotes vegetative growth and chlorophyll foliage. Specifically, it enhances photosynthesis and forms an important constituent of vitamins besides helping in the manufacture of carbohydrates, affecting both plant and plant energy reactions [90–92]. Soybean inoculation with particular *Bradyrhizobium* strains increases N uptake, dry biomass weight, and grain yield [48, 53, 92, 93]. This farming practice is gaining popularity among the SSA nations. For instance, in 2020, 4,100 farmers inoculated soybean in Uganda and harvested 1,450 t of soybean produced from 995 ha, compared to a previous low average yield of 1,040 t [28].

The use of BNF knowledge comprising *Rhizobium* inoculants in legumes can be a feasible substitute for pricy fertilizers, principally when targeting improved legume production [3, 70, 94]. Shahid et al. [95] reported that if a low number of native rhizobia strains prevail, inoculation with well-suited and sufficient rhizobia with optimal P levels may be necessary and is a key component that farmers may use to maximize yields.

The value of rhizobia is not well recognized and understood by farmers [96, 97]. In Uganda, a study by Wortmann and Kaizzi [98] showed that most farmers seldom inoculate soybeans but instead cultivate non-promiscuous varieties that rarely nodulate in the presence of native rhizobium strains. Moreover, biological N_2-fixation was low due to weak P availability. Soybean N-balances can be improved with inoculation, resulting in a 30–70% rise in yield [45, 99]. Wortmann and Kaizzi [98] and Rwakaikara-silver and Nkwiine [96] observed that although soybean plants were able to nodulate without the application of inoculation, there was still a yield improvement of about 600 $kg \cdot ha^{-1}$ when inoculant and fertilizer were combined. With inoculation and P-fertilizer use, only 21 demonstrations and 221 adaption trials were set up by AFRST. In northern Uganda, a total of 1440 farmers harvested 496,882 kg of soybean, while in eastern Uganda, 2000 farmers harvested 30 tons of soybean [66].

A lot of N is needed for high-yielding soybean plants and an estimated 70% of the plant's N is supplied through BNF [51, 96, 100]. Salvagiotti et al. [101] and Bhuiyan et al. [94] also noted that BNF supplied about 60% of the N needed by soybean plants. When introduced into a new place with soils that has inadequate rhizobia, soybeans respond most strongly to inoculation [100]. As cited by Abdul-Latif [101]; rhizobia inoculation resulted in increased nodulation subsequently increasing grain yield.

In another study, soybean trials were conducted for three consecutive years between 2009 and 2012 in Uganda, Kenya, Rwanda, Tanzania, and Malawi. The results indicated that without inoculation, planting soybeans with P fertilizer might increase soybean yields by approximately 100 percent relative to conventional farming practices with no inoculation added. There was a further increase in soybean yields by 70% with basal P application over yields without both P and inoculation. Several studies clearly showed that grain legume yields heightened further at the establishment stage when provided with small doses of N [91, 98, 102]. This is necessary before nodule production for meeting N demand. The influence of externally (organic or inorganic) supplied N on the efficiency of N legume fixation is restricted after complete nodulation [17].

4. Effects of Phosphorus (P) on Biological Nitrogen Fixation (BNF)

Globally, P is a critical element that lacks a related atmospheric gaseous component in its biogeochemical cycle [103–106]. Hence, this implies that besides its native source, which is the weathering of parent material, it can also be recycled from organic P compounds [107, 108].

In soybeans, P is at its greatest demand during production (seed and pod development stages), where over 60% of P ultimately ends up being translocated into these organs [109]. A study by DAFF [110] revealed that very high soil P levels reduce not only the seed protein but also oil content, and further noted that the crop yield optimally with available P (Olsen P) of about 30 $kg\ P \cdot ha^{-1}$. Nevertheless, reports are indicating a negligible increase in soybean yield when the concentration of soil P is more than 20 $mg \cdot kg^{-1}$ [111–113]. This calls for appropriate P-use efficiency in soybean farming.

Improving P utilization is important in lowering P fertilizer costs, thereby guaranteeing not only high yield but also optimal economic benefits at harvest [67, 103, 114–117]. Unfortunately, in tropical soils, P is generally limited [19, 103, 118, 119]. This is because of its high fixation coupled with its slow mobility, for it reacts chemically with oxides of Al as well as that of Fe or gets bound in organic form [77, 120, 121], rendering it inaccessible for plant uptake. Thus, rendering the efficient use of P is of high global importance since it is an essential and critical element [103].

Turan et al. [122] observed that approximately 80% of the soil P is fixed with calcium, magnesium, iron, and aluminium oxides; hence, its availability for plant root uptake varies greatly with P source, soil pH, and drainage. The optimal P obtainability to plants is customarily recorded at a pH range of 6-7 [123]. However, tropical soils are generally acidic, which exacerbates the situation of P fixation, and hence, crops show P shortages despite the total P content normally exceeding the plants' requirements in those types of soils [120, 122, 124, 125].

Under acidic soil conditions, it is vital to increase P use efficacy though such practice can be difficult specifically because of its low mobility [122, 124, 128, 127]. Therefore, to boost P efficiency, it is advisable to utilize the existing soil resources to offset the P exploitation, principally through crop harvest [78, 128, 129]. Exemplary, in soybeans, P removal through harvest is estimated to be at 81% of the total P that is utilized in plant tissue [130, 131]. Phosphorus is highly required by plants, specifically during their initial growth stages [1]. This calls for appropriate P levels in soybean production and inoculation for higher BNF to enhance root nodulation that will fix appreciable amounts of N and hence attain high growth and grain yield. This will therefore lead to great economic returns for soybean.

On the other hand, the ultimate N source in agroecosystems is BNF, which is a process that encompasses a weighty amount of P [48, 94]. With the limited application of P, rhizobia activity and N fixation are decreased. Early development of lateral, fibrous, and stable roots is stirred by P, rendering it very important for nodule growth and N fixation [1, 94].

According to Abdul-Latif [102]; inadequate P supply limits root development, sugar translocation, and the photosynthesis process among other functions that are directly influenced by N fixation in legume plants. Supplementing P stimulates crop growth by snowballing BNF, hence improving the availability of macronutrients in legumes [48, 94]. Nyoki and Ndakidemi [132]; Akpalu et al. [133]; and Bhuiyan et al. [94] recounted that synergetic use of P and beneficial bacteria like *Bradyrhizobiium* in legume plants improved growth, nodulation, and consequently grain yield as compared to the isolated use of any of the two. Phosphorus supplementation and *Bradyrhizobium* inoculation heightened the absorption of P, N, and K into the several organs of the entire soybean plant [132, 133].

Phosphorus is among the essential nutrients and is of great importance in BNF in legumes. A lot of energy is needed to facilitate this symbiotic process, which has a high demand for P [83, 134] to enhance metabolism [134–136]. Many reports indicated a strong P sink concentration in nodules, usually exceeding that of shoots and roots [110, 111, 137]. Nitrogen-fixing plants require more P as compared with N-supplied plants [132, 138]. Therefore, the application of P could boost its uptake and utilization in the establishment, growth, initiation of nodule formation, and nodule primordia increase, improving yield, quality of the crop, and function of nodules [75, 135], rhizobial strain's growth [137, 139], and host plant growth [137, 140]. Studies by Jones et al. [140] and Sa and Israel [111] proved that P increases the number of root nodules, and their weights, as well as enhances the pod yield. However, Jacobsen [142] and Graham and Rosas [143] revealed that the application of P increases N fixation by stimulating the growth of the host plant.

Application of P fertilizer together with inoculants of rhizobium affected not only the nodulation but also the N fixation of legume [94, 144]. Similar patterns were also noted by Hoque and Haq [145] on treating various legumes with P and rhizobium, which noticed a rise in the growth and nodulation. It is widely accepted, however, that the soybean response to the application of phosphatic fertilizer is dependent on crop, climate, and management practices [34].

In crop development, P plays key roles such as boosting energy storage and its transfer, flowering, root growth stimulation, nodule production, seed formation, and N_2 fixation [146]. Subsequently, the application of P can also upsurge the legumes' leaf surface area, promote root elongation and grain size; the concentration of N in biomass and grain, and the number of nodules [147, 148]. The process of N_2 fixation in legumes is susceptible to P insufficiency, leading to reduced nodule mass [94].

Nodules are an effective P sink, where its concentration in nodules typically exceeds that of shoots and roots [111, 137, 140, 149]. Thus, treating P-deficient soils with inorganic phosphatic fertilizer results in an increased number of nodules [148, 150, 151]. Nevertheless, Bremer and Mulvaney [152] observed increased dry matter and grain yield with the P use at the rate of 45 $kg\cdot ha^{-1}$ with no effect on N_2 fixation, suggesting that the host legume was more receptive than the rhizobia to P application. Therefore, P management under P-deficient soils is critical for achieving high soybean yields. Soil factors such as low P levels, on the other hand, aggravate pod abortion, thereby decreasing soybean yield [149]. Soybean crop response to P has also been observed by Mallarino and Reuben [153] to be based on soil available P. Further, in another study, it was noted that P application is unlikely to boost yield above 12 $mg\cdot kg^{-1}$ at soil P concentration [154].

Phosphorus plays the most significant role among the important nutrients in the BNF process in legumes like soybean posing a great concern for nutrient availability [155]. The demand for symbiotic N fixation is high since the process expends high energy [134, 136], and the metabolism of energy production depends intensely on P availability [135, 136]. Cassman et al. [138] noted that N fixation was more enhanced in soybean plants with P application than with N supplied. The P application is very important in the development and growth of nodules [75, 151]. Jacobsen [142] and Graham and Rosas [143] noted, however, that P fertilization improves symbiotic N fixation by encouraging the growth of host plants rather than directly affecting the growth and functioning of nodules.

5. Effects of Inoculation on Soybean P Uptake and Yield

The number of native bacterial strains in the rhizosphere is often insufficient to induce substantial N-fixation [34]. Hence, inoculation of soybean legumes improves the process of fixation of N through BNF [48]. This is due to the

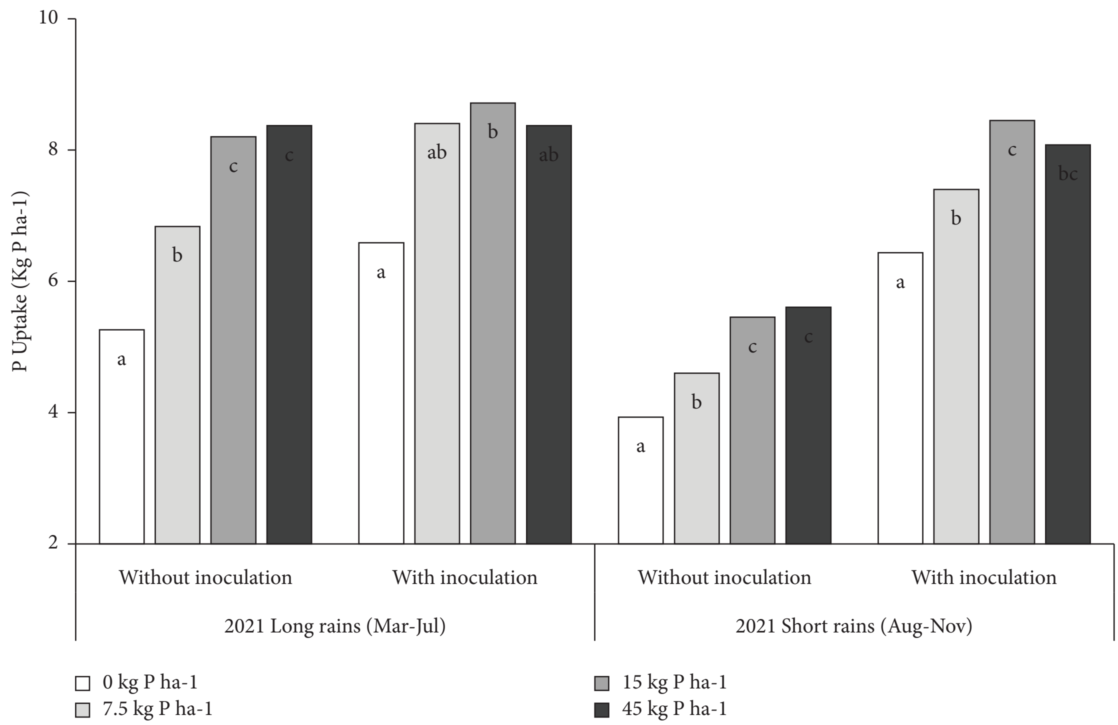

FIGURE 4: Phosphorus uptake as affected by phosphorus application and inoculation with *Bradyrhizobia* in Uganda. Bars bearing comparable letters within an inoculation level do not differ significantly at $p \leq 0.05$. (Adopted from reference [45]).

increased development of root nodules, which houses the *B. japonicum* that enhances atmospheric N use by the plants [88].

Nitrogen is a main (macro) nutrient with momentous roles in the production of amino acids in legumes. It is also necessary for plant growth due to its key role in cell division [89]. It promotes vegetative growth and chlorophyll foliage. Specifically, it enhances photosynthesis and forms an important constituent of vitamins besides helping in the manufacture of carbohydrates, affecting both plant and plant energy reactions [90–92]. Soybean inoculation with particular *Bradyrhizobium* strains increases the N uptake, dry biomass weight, and grain yield [48, 53, 93]. This farming practice is gaining popularity among the SSA nations. For instance, in 2020, 4,100 farmers inoculated soybean in Uganda and harvested 1,450 t of soybean produced from 995 ha, compared to a previous low average yield of 1,040 t [28].

Synergetic inoculation with *rhizobium* and application of P significantly improved p uptake in soybeans (Figure 4). Consequently, this affects growth, nodule formation, and yield in soybean production [45, 48, 93, 95, 156]. In Uganda, while applying P at a rate of 15 $kg \cdot ha^{-1}$ in soybeans, Otieno et al. [45] and Kaizzi et al. [144] that observed it resulted in significant yield gains and profitability (Figure 5). Explicitly, under P application and inoculation, treatments that received 15 $kg\,P \cdot ha^{-1}$ recorded the highest yield of 1.2 $t \cdot ha^{-1}$, which was 30% higher than control. This translated to a net income of US$ 414.93. In a separate study by Wortmann et al. [157]; yield upsurge was only eminent with the use of triple superphosphate mineral fertilizer (TSP) but not with an organic P supplied using Busumbu rock phosphate (9% P), as observed by Ronner and Giller [12]. Moreso, from a study carried out in Palisa Uganda, by Ebanyat [23]; soybean yields only showed a moderate response to the use of 30 $kg\,P \cdot ha^{-1}$.

The value of rhizobia is not well recognized and understood by farmers [96, 97]. In Uganda, a study by Wortmann and Kaizzi [98] revealed that most farmers seldom inoculate soybeans but instead cultivate nonpromiscuous varieties that rarely nodulate in the presence of native rhizobium strains. Moreover, biological N_2-fixation was low due to weak P availability. Soybean N-balances can be improved with inoculation, resulting in a 30–70% rise in yield [45, 99]. Wortmann and Kaizzi [98] and Rwakaikara-silver and Nkwiine [96] observed that even though soybean plants were able to nodulate deprived of the inoculation, there was a yield enhancement of roughly 600 $kg \cdot ha^{-1}$ when fertilizer and inoculant were combined. With inoculation and P-fertilizer use, only 21 demonstrations and 221 adaption trials were set up by AFRST. In northern Uganda, a total of 1440 farmers harvested 496,882 kg of soybean, while in eastern Uganda, 2000 farmers harvested 30 tons of soybean [66].

A lot of N is required for high-yielding soybean, with a projected 70% of the plant's N being provided through BNF [51, 96, 100]. Bhuiyan et al. [94] and Salvagiotti et al. [101] also noted that BNF provided around 60% of the N required by soybean plants. Once introduced in a new area where the soils have insufficient rhizobia, soybeans respond well to inoculation (Abdul-Latif [102]). As noted by Van Kessel and Hartley [100]; rhizobia inoculation resulted in improved nodulation, consequently increasing grain yield.

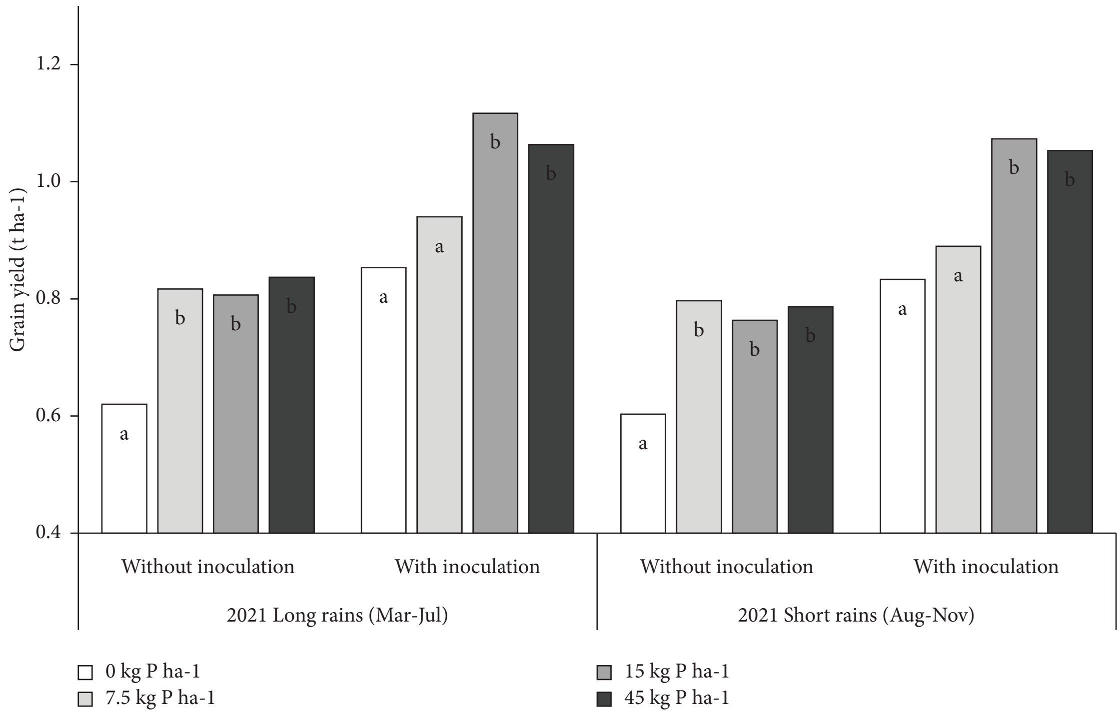

FIGURE 5: Soybean grain yield as affected by phosphorus application and inoculation with *Bradyrhizobia* in Uganda. Bars bearing comparable letters within an inoculation level do not differ significantly at $p \leq 0.05$. (Adopted from reference [45]).

In another study, soybean trials were conducted for three consecutive years between 2009 and 2012 in Uganda, Kenya, Rwanda, Tanzania, and Malawi. The results indicated that without inoculation, planting soybeans with P fertilizer might increase soybean yields by approximately 100 percent relative to conventional farming practices with no inoculation added. There was a further increase in soybean yields by 70% with basal P application over yields without both P and inoculation. Several studies clearly showed that grain legume yields heightened further at the establishment stage when provided with small doses of N [94, 98, 102]. This is necessary before nodule production for meeting N demand. The influence of externally (organic or inorganic) supplied N on the efficiency of N legume fixation is restricted after complete nodulation [14].

6. Conclusion and Recommendations

The review has demonstrated the greatest economic and industrial potential for soybean production in Uganda. This provides a leeway impetus for its increased production, especially in regions among others, the northern part exhibiting good climatic conditions with high production potential. The chief limiting factor in soybean production in the study area is declining soil fertility which stems from P and N as the most critical and limiting nutrients. Due to the nature of tropical soils, which are highly weathered and acidic, P is usually fixed in the soil making it inaccessible for crop uptake and use. N is also lost from the soil pool through many pathways such as leaching, denitrification, evapotranspiration, and crop harvest among others, and this leads to the negative N nutrient balance in the soil ecosystem.

Biological N fixation using a compatible strain, *Bradyrhizobium japonicum*, is an environmentally friendly and affordable measure of engaging the bacteria in the rhizosphere to enhance the BNF process through root nodulation. Root nodulation can positively influence soybean growth and yield due to an enhanced N_2 fixation by the bacteria and P applied, which facilitates faster root establishment. Therefore, with inoculation, soybean N-balances can be enhanced, leading to an increment in grain yield. Synergetic inoculation with *rhizobium* and application of P significantly influence growth, nodule formation, and yield in soybean production. Specifically, the study revealed a yield of over $1\,t{\cdot}ha^{-1}$ with P and inoculation against a value of below $0.7\,t{\cdot}ha^{-1}$ without the inputs. Unfortunately, farmers are not well informed about the prominence of rhizobia in fixing atmospheric N in the soil for legumes like soybean, which would be a cheaper option than the expensive inorganic N fertilizer. This calls for more farmer sensitization on the benefits of BNF with the use of optimum P.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest. The work reported in this study was carried out by Mirriam,

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