

World News of Natural Sciences

An International Scientific Journal

WNOFNS 63(2) (2025) 310-330

EISSN 2543-5426

Effects of Bambara groundnut [*Vigna subterranea* (L.) Verdc.] interaction with *Rhizobium* spp. for viable yield crop advancement

Olalekan Ayodele Adedayo^{1,*}, Bukola Rhoda Aremu², Olubukola Babalola¹

¹ Department of Microbiology, North-West University, Potchefstroom, South Africa

² Department of Chemistry and Biochemistry, University of Windsor, Windsor, Canada

*E-mail address: olalekan_ayo@yahoo.com

ABSTRACT

Viable yield crop remains a preference towards avoiding food insecurity in any country, yet, the fertility of most of the soils in Africa is low, which is the main reason why sustainability does not receive enough support by any means. Various agricultural systems have been carried out to solve the challenges, but many restrictions have been recorded, thereby resulting to a constant little or no crop of local basic food crops in several countries in Africa. Scientists and farmers have become interested in the symbiotic relationships between “Legumes” and “Rhizobia” because of their effectiveness in nitrogen fixation as a true alternative. The blend of Nitrogen Fixing Legumes (NFL) with novel essential reverence yields among small-holder farming structures is possible to improve the fertility of soil. The seed of legumes, in particular, Bambara groundnut (i.e. African Bambara groundnut) creates nitrogen fixing symbiotic interaction together with the bacteria of root nodule collectively termed “Rhizobia” in such a manner that sufficient nitrogen are released for legume and diverse yields during inter-crop or crop rotation. Through this method, it is expected to be considered as a food crop that is necessary for food security thereby giving serious considerations on its usefulness and healthy benefits. As a discourse of significance, it is expected to be referred as a cash crop, as well as an essential preference for promoting the soil's nitrogen fertility.

Keywords: Bambara groundnut, Fertilizers, Food security, Nitrogen-fixation, *Rhizobium*, Symbiosis

1. INTRODUCTION

Sub-Sahara African (SSA) forms the larger portion of the African countries with extended population growth which stimulates food shortage, which is the major cause of food uncertainty. This food shortage emanated from little production of crop, as a product of worn-out soil fertility (Ajiboye, 2015). This limitation stimulates the differences among available volume of crops formed and stresses associated with the environment and the population on both sides (Ajiboye, 2015).

With a conclusion aim of improving crop production, a great amount of tropical countries employs inorganic fertilizers, which had been tentatively remained as possible threats to human well-being and the natural world (Margni et al., 2002). Such indicates nevertheless a huge expense, which is one key significant for the lack of specific contemporary producers of natural fertilizer. Due to the lack of food that is high in protein around the world and in many developing nations, experts are searching for alternate sources of protein to balance their diets. (Ahmed and Abdallah, 2010). Henceforth, the pollution of environment, insecurity of food, and the soil fertility difficulties should remain acceptable, if the improvement of genomic and maintainable production of food would be efficient using several methods of techniques such as enhanced fallows, inter-cropping, agro-forestry or bio-fertilizers. On top of these methods, bio-fertilizers have been shown to upturn the yield of most crops in Cameroon (Ngakou et al., 2011). In contrast to most other legume plants, relatively little is understood about the hidden connections between *Rhizobium-Mycorrhiza*, and *Vigna*. Different from the most of other leguminous crops, the hidden relationships of *Rhizobium-Mycorrhiza-Vigna* are poorly known.

Therefore, this present review pinpoints the:

- Biological function of legumes that fix nitrogen enhances crop output in Sub-Saharan Africa.;
- Food insecurity difficulties stemming from nitrogen deficiency and constraints impeding legumes' use of biological nitrogen fixation in small-holder farming methods;
- Prospects of *Rhizobium-mycorrhiza-Vigna subterranean* relationship for viable farming methods; and
- Promising measures where deeper study is needed by including legumes proficiently into the background of both animal and crop productivity.

2. FOOD INSECURITY DUE TO NITROGEN SHORTAGE

Food insecurity is a situation of being in a lack of balanced source of adequate amount of inexpensive healthy food. The amount of food available and people's ability to obtain it are related factors to food security. Problems of food availability have existed for a long time. At the 1974 World Food Conference, Security of food was clearly defined by focusing on a sufficient amount. Food security refers to accessibility of sufficient world food supplies of basic crops at all times to withstand a confident growth of food consumption and to stabilize differences in prices and productivity (FAO, 2003). Food insecurity, in another way, a state of being “embarrassed or uncertain accessibility of adequate nutrition and safe foods or scarce or uncertain capacity to obtain suitable foods in a manner that is socially acceptable”, as well-defined by the United States Department of Agriculture (USDA) (Hannum et al., 2014). The constant major region in the entire globe wherein food production per person has remained

latent for the past 40 years is Sub-Saharan Africa (SSA). About 180 million people in Africa—since almost all of them lack a source of adequate nutrition to live productive lives in good health as of 1970, they become more susceptible to infections like HIV/AIDS, TB, and malaria. Complete hardship, defined as daily earnings of no more than \$1 for each individual, is coupled with an ineluctably diminished natural reserve base. Concerted attempts on HIV/AIDS management, survival of a child, authority improvement, growing external asset, resolving trade difficulties, and providing bill support are all compulsory, however, Considering that they do not adequately handle food production, the industry in which 70% of Africans are employed, they are insufficient. Contrary to the southern part of Asia and numerous other regions where food scarcity exists arises from insufficient quantity and low purchase power, food instability in Africa is primarily identified by low overall agricultural output.

African Agriculture has been managed terribly, in variation with Latin America and Asia these are regions that benefitted from the Green Revolution. Quite a lot of states and developed nations in Africa are at the moment considering reinventing the need to develop farming, (Sanchez et al., 2009). Difficulties with soil fertility and the related challenges of diseases, weeds, and pests are a major environmental source of Africa's low per capita food output. This is the result of an analysis of traditional methods in use and the government's need for more attention to the rural areas (Syampungani et al., 2010). Subsistence farmers have been exploiting large amounts of nutrients out of their soils for decades without adding enough manure or fertilizer to restore the soil. Over the last 30 years, this has led to a widespread annual loss ratio of 22 kg of nitrogen (N), 2.5 kg of phosphorus (P), and 15 kg of potassium (K) per capita hectare of cultivated land in 37 African countries. This represents a yearly deficit that is comparable to \$4 billion in fertilizers in the United States of America. (Syampungani et al., 2010).

Southern Africa's yield of basic foods has been declining, which is worrisome for the security of its food supply (Rosenstock et al., 2014). The main barrier to food production in southern Africa, particularly in South Africa, is still inadequate and unproductive soils. The naturally porous soils have kept the arable land limited, but some variety of crops and methods (for example, continuous rice mono-cropping), have a propensity to be completely exploitive, subsequently draining the effectiveness of these soils. Prolonged farming effectiveness and food production among Southern Africa can basically be proficient to improve the reserve the soil's foundations.

3. LEGUMES' USEFUL ROLE IN DEVELOPING SUSTAINABLE CROP YIELDS

A substantial part of the increase in agricultural productivity can be attributed to legumes, including tree legumes, nitrogen-fixing crops, and fodder pasture. Important native legumes grown throughout Sub-Saharan Africa include *Macrotyloma geocarpum* (Kersting's beans), *Vigna unguiculata* (cowpeas), *Vigna subterranea* (Bambara groundnuts), and Rhizobia and Bradyrhizobia, which are nodulate with inclusive mixed qualities. These are cultivated in various natural areas throughout the landmass, including poor soils. Conversely, well-known legume crops including common beans, soybeans, pigeon peas, and groundnuts are crucial components of conventional cropping techniques.

Many studies conducted in current times have preserved the important role that legumes play in agricultural systems (Cinar and Hatipoglu, 2014, Omokanye, 2001, Kadiata et al., 2012).

The impact of legumes is profound on atmospheric nitrogen fixation through their symbiotic interaction with *Rhizobium* spp.; this relationship occurs more regularly with legumes than with those associated with the root system of the host (Table 1). Through either direct nodule degradation or indirect breakdown of nodules within roots and tissues, this supplies nitrogenous chemical substances into the soil. In reality, nitrogen is released into the soil from the top growth onward using leaf drops, weathering from above-ground portions of rain, and elimination of waste disposal contents from herbivores both below and above ground.

This primary function of fixing atmospheric nitrogen highlights two primary functions of legumes: increasing soil fertility and providing a great deal of protein in the herbage, which in turn makes them excellent for mulching or feeding.

Table 1. Identification of Diversity of *Rhizobium* spp. from legumes that fix nitrogen.

Common Names	Scientific names	Linked Rhizobium	Original source
Bambara groundnut	<i>Vigna subterranean</i>	<i>Rhizobium</i> spp. <i>Bradyrhizobium</i> spp. <i>Burkholderia</i> spp. <i>Azorhizobium</i> spp. <i>Sinorhizobium</i> spp. <i>Mesorhizobium</i> spp.	Benson et al. (2015b) Pillai (2012)
Geocarpa groundnut	<i>Phaseolus vulgaris</i>	<i>Rhizobium etli</i> , <i>Rhizobium phaseoli</i> <i>Rhizobium leguminosarum</i> <i>Rhizobium gallicum</i> <i>Rhizobium giardinii</i> <i>Rhizobium tropici</i> <i>Sinorhizobium meliloti</i>	Faghire et al. (2011) Makoi et al. (2013) Pule-Meulenberg and Dakora (2009) Bargaz et al. (2013)
Black-eyed pea	<i>Vigna unguiculata</i>	<i>Bradyrhizobium</i> spp. <i>Rhizobium</i> spp. <i>Allorhizobium</i> spp. <i>Sinorhizobium</i> spp. <i>Azorhizobium</i> spp.	Belane and Dakora (2009) Benson et al. (2015b) Pillai (2012)
Geocarpa groundnut	<i>Macrotyloma geocarpum</i>	<i>Rhizobium meliloti</i> <i>Rhizobium trifoli</i> <i>Rhizobium vaciae</i>	Pule-Meulenberg and Dakora (2015)
Peanut	<i>Arachis hypogea</i>	<i>Rhizobium</i> spp. <i>Agrobacterium</i> spp. <i>Burkholderia</i> spp. <i>Acromobacter</i> spp. <i>Enterobacter</i> spp. <i>Bradyrhizobium</i> spp.	Pule-Meulenberg and Dakora (2015) Kumar et al. (2014)
Soybean	<i>Glycine max</i>	<i>Bradyrhizobium japonicum</i>	Argaw (2014)

River Tamarind	<i>Leucaena leucocephala</i>	<i>Rhizobium</i> spp. <i>Sinorhizobium morelense</i>	Bakhoun et al. (2014)
Pigeon pea	<i>Cajanus cajan</i>	<i>Bradyrhizobium</i> spp. <i>Rhizobium</i> spp. <i>Sinorhizobium</i> spp. <i>Mesorhizobium</i> spp.	Belane and Dakora (2011)
Purple Bush-Bean	<i>Macroptilium atropurpureum</i>	<i>Burkholderia</i> spp. <i>Bradyrhizobium</i> spp. <i>Rhizobium</i> spp.	Lindstrom et al. (2010)
Wattles	<i>Acacia</i> spp	<i>Bradyrhizobium</i> spp. <i>Rhizobium</i> spp. <i>Bradyrhizobium</i> spp.	Lindstrom et al. (2010) Soumare et al. (2013)

In biological terms, Legumes are some sort of successional habitat; hence, management plays an integral part in maintaining stable legume-based partnerships. Legumes' remarkable capacity for fixing nitrogen through biological processes is dependent on a variety of biological, nutritional, hereditary, and environmental factors. As a result, under management control, its effect on soil fertility is equally adaptable and evident.

The end product that leguminous plants have on the value of herbage is important and there is complete validation of considerable improvements in the production of food crop is actually encouraging. Likewise, they also have great mulching significance for the production of crop. The agricultural practices of Australia and a small portion of tropical America are very different from those in the majority of Sub-Saharan Africa (SSA). Strategies for small- and medium-integrated livestock-crop farming are common in Africa's vast population, with the two sectors fully linked. There are several legumes that fall within the categories of both crops and livestock in the variety of these techniques. Legumes contribute to the crop period in such a structure with negligible fertilizer contributions, lowering the degree of soil fertility degradation or boosting crop output in any case, and also minimizing the length of the fallow phase for fertility regeneration. Legumes improve the quality and crop usage leftovers, as well as natural forages on fallow areas, during the pastoral stage. The tropical, dry and sub-humid agricultural ecosystems have a similar range of farming systems.

Several components comprise the contribution of legumes. The management of nutrients and how they determine the final productivity level are the most important factors. This depends not only on the true ratio of the nutrients but also on how well they are circulated. Furthermore, without going any further, the agricultural systems might be described more like an organism or natural method system than is currently the case. The largest number of legumes may not have developed their capacity to fix nitrogen by accident. Whether the biological justification for legumes' regular dissemination throughout the world's flora could be investigated, some may conclude that they occasionally occur at all normal or at high levels of production during peak flora. In successional circumstances, however, they are typically the most fundamental and reliable, especially in cases when soil fertility or plant nutrient accessibility is limited.

Therefore, roadsides and other densely populated areas are frequently closely linked to legumes. Due to the effects of this disruption, legumes effectively participate together with the organisms unable to fix nitrogen once nutrients other than nitrogen are possibly more available

than predicted. This is seemingly why many leguminous plants maintain the ability to react to such essential secondary nutrients such as Phosphorus; meanwhile this is ultimately vital for positive beneficial interactions.

4. THE ROLE OF NITROGEN-FIXING LEGUMES (NFL)

The last twenty years have recorded remarkable advancement in the farm-level resourceful methodology of research, which were for the creation of advanced agricultural technologies that are pertinent to agricultural settings, aims and objectives. The Soil Fertility Consortium for Southern Africa (SOFECSA), which was founded in response to worries about the inadequate use of soil fertility improvement among the local smallholder groups, has advocated for the expansion of agricultural systems that are typically focused on maize in order to help farmers escape the "maize shortage trap" (Nezomba et al., 2010).

The incorporation of nitrogen-fixing legumes (NFL) and other highly significant crops into peasant agricultural methods is one of the most widely acknowledged opportunities for improvement. For example, a few studies have discovered the prospect that grain legumes could function as both a diet source and a means for enhancing the fertility of a soil (Kamanga et al., 2014). In the mid-1950s, legume green manures have been an excellent source of nitrogen for the majority of crops, including maize and potatoes, on commercial farms in Zimbabwe. (Nezomba et al., 2010).

Scientists from the International Institute for Research in Agroforestry, together with national and international collaborators, have developed a soil fertility approach for renewal that works with farmers to develop and make abundant resources available in Africa over a ten-year period. Farmers' fields were used to conduct activities in conjunction with researchers during collaborative study trials. Farmers constructed experiments to watch these activities and make necessary adjustments to the new approaches after they were tried. The conclusions are divided into three sections that can independently or together in combinations be employed: (i) Fallows from leguminous trees that fix nitrogen, (ii) original rocky phosphates in topsoil depleted in phosphorus, and (iii) plant nutrient accumulation brought on by biomass exchange of leaves (Pypers et al., 2011).

In the Eastern and Southern Africa's sub-humid tropical areas, leguminous leaves belonging to the genera *Cajanus*, *Gliricidia*, *Crotalaria*, *Tephrosia*, and *Sesbania* had grown within certain varieties of maize and were left to develop as grazing fields during dry periods. During this time, they accumulated up to 100–200 kg N ha⁻¹ over a period of six months for two years. Such leguminous leaves were shown to emit comparable amounts of nitrogen as industrial farmers' manures, which are applied to improve maize in developed nations. Before growing maize, once the next season of rainfall begins, a subsequent crop rich in nitrogen leaves, peapods, and green branches from the fallow tree were integrated into the soil. This litter that lies above the soil, decomposes its roots, and enriches it with nutrients like nitrogen. The primary crop in this zone, maize, produced yields that increased two to four times due to widespread nitrogen deficiency. In regions of East Africa with bimodal rainfall, farmers are presently setting up rotations of one year's worth of leaves, followed by one maize crop, and two years' worth of trees, subsequently between two and three crops of corn, in some parts of Southern Africa with unimodal rainfall. It comes as no surprise that these fallows are naturally

stable economically and that they align well with farmers' activities and work records, as their enhancement was made in collaboration with agriculturists. (Pypers et al., 2011).

A challenge in the Sahel and Eastern Africa is phosphorus shortage. Eighty percent of small-scale farmers' land in Kenya's Western Zones, that had been formerly utilized to grow maize, is severely deficient in phosphorus. An alternative to importing superphosphates is to use native rock phosphate resources. Many African soils have moderate acidity (pH 5–6), which degrades superior-grade rock phosphates at an amount that is able to provide crops with phosphorus for a comparatively long period of time. In these situations, their immediate intervention is substantially increased to maize harvests, and 90% of the superphosphates are adequate for five years. (Pypers et al., 2011). Without the need for fertilizers, the movement of nutrients that are accumulating from the leaf biomass tree *Tithonia diversifolia* from roadside ditches and holes into newly harvested fields improves nutrients and steadily boosts maize yields at the same amounts that farmers use.

5. THE DISADVANTAGES OF USING NITROGEN-FIXING LEGUMES (NFL)

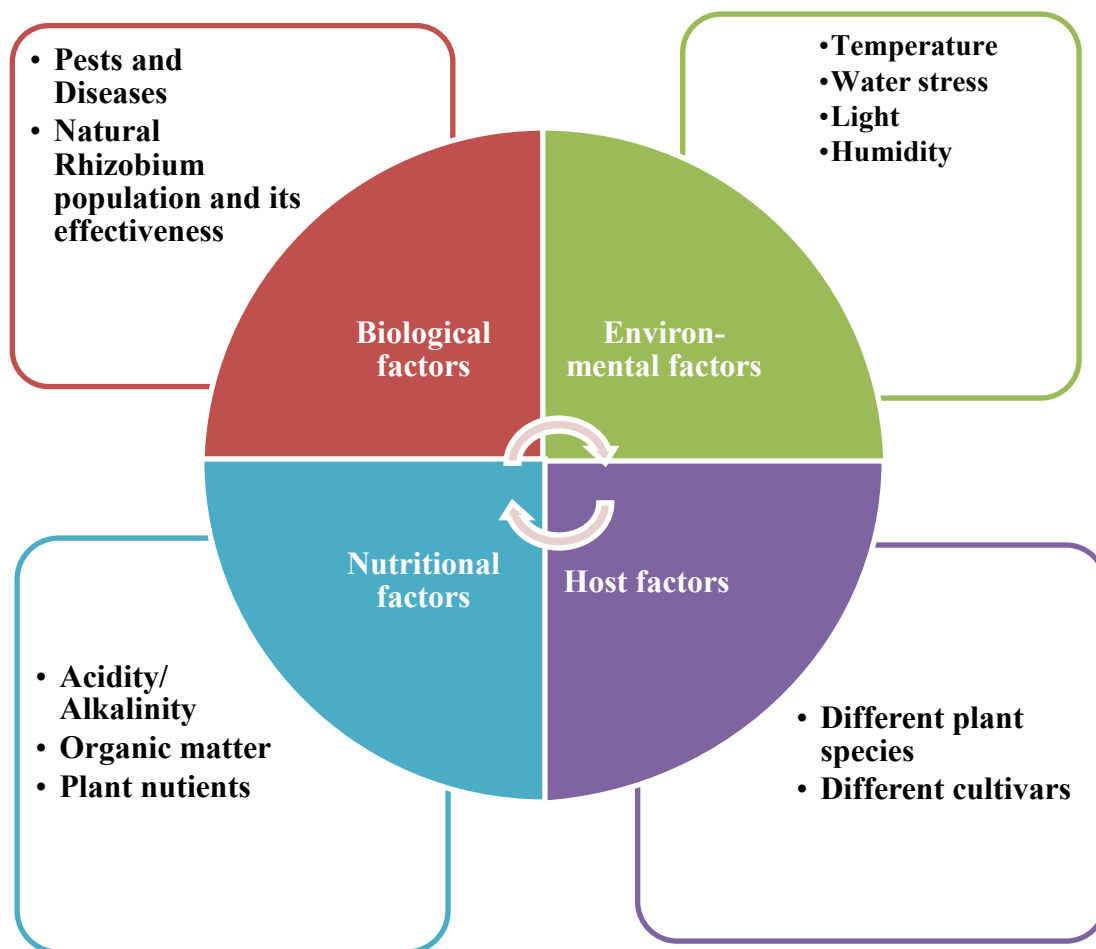


Figure 1. The principal constituents influencing legume nitrogen fixation.

The combination of NFL with other great value crops in small-scale agricultural systems remains prospective for soil fertility enhancement (Pypers et al., 2011). Since the early 1950s, legume fertilizers have been used on industrial farmsteads in Zimbabwe as a supply of nitrogen for plants such as potatoes and maize. However, the small-scale agricultural sector has not yet been able to adopt this innovation. (Manzeke, 2013). Although there is proof that legume enhancements for soil fertility renewal have been thoroughly investigated on a variety of crops throughout numerous Sub-Saharan African nations, its theory has not yet largely impacted rural economies. (Abate et al., 2012).

It is consistently the case that small-scale farmers' allotted land for these plants is frequently insufficient to produce the intended outcome. Farmers often plant both maize and legumes together because they want to grow some kind of legume crop eventually without sacrificing the necessary large yield from plain maize, paying only a passing consideration to the planting method. Nitrogen up to 100 kg N ha⁻¹ established by numerous grain legume modifications is noteworthy. This happens frequently in homes with fewer resources and a higher susceptibility to hazards. (Nezomba et al., 2010). The responsible use of inorganic fertilizers is the cautious way to stop the decline of nutrients. Nevertheless, manures in Africa are worth around six times as much as those in Europe, North America, or Asia. Checks on the spot confirm that a metric shipment of urea costs up to the U.S. \$120 delivered at the ports of Mombasa, Kenya, or Beira, Mozambique; \$90 FOB (free on board) in Europe; \$400 in Western Kenya (a 700-kilometer distance from Mombasa); \$500 other than Eastern Uganda; and \$770 in Malawi (Pypers et al., 2011). Additionally, a lot of other elements continue to influence the use of NFL in a positive or negative way (Figure 1).

6. SOIL FERTILITY RENEWAL METHOD WITH NUMEROUS LIMITATIONS

Though they perform well, farmers around the edges of humid tropical plantations do not want improved bush fallows; in the Congo Basin, in particular, enhanced land-use alternatives are a result of growing population pressures. (Norgrove and Hauser, 2016). In the semi-arid tropics of Africa, enhanced fallows have not yet shown to be significant due to the reason that their development and ability to fix nitrogen are restricted by a continuous dry season. Additionally, fallows do badly in areas that are prone to frost, poor drainage, or have been badly washed out. Restricted market enhancement limits the distribution of highly reactive reaction rock phosphate, but demand is rising. A significant portion of Africa's rock phosphate reserves are inadequate reactions and have limited potential for useful applications. It is unknown if *Tithonia diversifolia* has a nutrient-accumulating counterpart in semi-arid tropical regions. Nonetheless of those disadvantages, this method may prove beneficial in regions that belong to the sub-humid climates with a high concentration of "red" soils, such as rural areas of Africa. (Pypers et al., 2011).

7. BAMBARA GROUNDNUT: KEY TO CROP YIELD IMPROVEMENT

Throughout history, legumes have been an integral component in inexpensive food due to their significant contribution to the fight against hunger and starvation. Their consumption patterns, and these have become inadequate in several developing nations, will be improved in

this way. Proteins from plants provide for about 65% of the total protein consumed by humans worldwide; grains account for 45-50% and legumes for 10-15%. Legumes function as a good basis for unprocessed protein, fiber, strong starch, and diverse nutrients for poor nations of the world, predominantly the rural and urban dwellers of the populace. Because the starch in them is neither resilient nor absorbed gradually, they are among the lowest glycemic forms of carbohydrates. (Musa et al., 2016).

The family of underutilized grain legumes known as Bambara groundnuts maintains excellent regular protein levels of 22 and 37%. (Fasoyiro et al., 2004). It is also the third most significant crop, behind cowpeas (*Vigna unguiculata*) and peanuts (*Arachis hypogaea*) (Ngakou et al., 2011). Therefore, increasing the productivity of this crop recognized for its nutritional value and ability to thrive in low-fertile soils with periods of drought and little rainfall is imperative. (Berchie et al., 2010). Small-scale farmers cultivate the plant in a very limited area of semi-arid Africa, and agriculturists primarily use it as a "famine culture" crop because of its little natural agronomic characteristics, which include its increased nutritious content, resistance to drought, and ability to produce food in soils that are known to be inefficiently rich for the growth of other more favored species, like groundnuts and common beans.

The nuts are also known by the following names: Okpa (Ibo, Nigeria), Epa-Roro (Yoruba, Nigeria), Gurjiya or Kwaruru (Hausa, Nigeria), ntoy ciBemba (Republic of Zambia), and Nyimo beans (Zimbabwe). The Bambara groundnut were originally from what has become West Africa's Sahelian region and are now primarily settled in Central Mali (henceforward it is called Bambara groundnut) (Alhassanm et al., 2014).

In agreement with article written by Bamshaiye et al. (2011), The Bambara groundnut is an annual, perennial, transient crop with climbing branches near the ground. This type of legume is a little plant which may grow to a height of 0.30 to 0.35 meters. It has three leaflets on each leaf. The plant resembles assembled leaves that are growing stems with branches on a soil's level to form a crown. Upon fertilization, the quickly spreading stems bear light yellow flowers; these stems then grow down into the earth, carrying the emerging seed with them. Similar to peanuts, the seeds will develop pods that enclose seeds just below the surface.

The pods of the Bambara groundnut are spherical, folded, and more than half an inch long. One or two smooth, spherical, and extremely hard seeds are often found inside each pod after it has dried. Bambara groundnuts have a high proportion of carbohydrates (65%), relatively high protein content (18%), and sufficient amounts of fat (6.5%), providing a balanced diet. (Mazahib et al. (2013). As maintained by article written by Bunde and Osundahunsi (2010) which was accepted by Bamshaiye et al. (2011b), found that Bambara groundnut seeds were higher in important amino acids, including valine, threonine, phenylalanine, methionine, lysine, leucine, and isoleucine—than peanuts (groundnuts). This is a crucial component if Bambara groundnuts are to be utilized as a nutritional supplement for diets deficient in those essential amino acids. Linolenic, palmitic acids, and linoleic acids make up the majority of the fatty acids. (Minka and Bruneteau, 2000).

It is not considered as a valuable revenue commodity, but instead as a snack or food supplement. (Ndidi et al., 2014). Furthermore, because it is grown by women, it usually has lower value and less importance when it comes to land allocation. The remaining produce, which ranges from 10% to 40%, is fed by the farmers in the rural areas themselves. Seeds from the Bambara groundnut variety may differ in size, shape, and seed coat color. They could have round or curved shapes, with cream, white, red, speckled, or black eyes, with a seed mass that ranges from 280 to 320 g. (Falade and Nwajei, 2015). Since the seventeenth century, the crop

in humid locations has stayed highly advanced. Even so, it is today found in many regions of Asia, Oceania, and South America, except from Sub-Saharan Africa. It is the ideal crop for farmers since it can yield large amounts of food with minimal work. It was found that nearly 98% of Swaziland's farmers known Bambara groundnut, was a useful crop. (Begemann et al., 2002). As a crop and a food, Bambara groundnuts have a lot of potential and deserve more attention.

The article written by Greenhalgh (2000) discovered that Approximately 330 000 tons are produced annually, with Nigeria being the primary producing nation in Africa. Because Bambara groundnut production and development have been disregarded by researchers for a long time, the crop is not as profitable as it could be for smaller-scale farmers, which is why harvests have been low. However, it develops mostly in Nigeria (Bamishaiye et al., 2011). It remains among the undervalued and less cultivated legumes. The crop is reported to be very disease-free, hardy to drought, and to require little of the soil. It can thrive in nutrient-deficient soils, an environment in which most crops would perish. The primary producing region is mostly dry Africa, with Malaysia, Thailand, and Indonesia serving as the unrestricted enhancement epicenter surrounding South East Asia. In fact, the seeds are nutritious, and both people and animals eat them. It may grow in regions with high or low rainfall and is resistant to drought. It has been suggested that this legume can offer crops in regions with regular rainfall peaks of 900-1000 mm and less than 500 mm. (Bamshaiye et al., 2011b). Yakubu et al. (2010) Outlined how the use of phosphorus manure increased the ability of the Bambara groundnut to fix 28.4 kg N ha⁻¹ in poor soil of phosphorus in Nigeria to about 41 kg ha⁻¹.

The article by Mubaiwa et al. (2016) discovered that, in addition to its two present improvement facilities, Bambara groundnuts may be grown in a variety of locations, including several European nations like Greece, Portugal, Spain, and Italy and countries with a Mediterranean climate like Israel and Lebanon. The statement further demonstrated that the prospective yields of Bambara groundnut throughout present planting locations could be essentially improved without major agronomic efforts when factors like the changing patterns during rainfall, length of the day, and variations in the temperatures throughout the growing period are considered.

7. 1. Factors that limit nitrogen fixation

The hot weathers that usually exist throughout the Sub-Sahara Africa may equally decrease the fixation of Nitrogen. Even though legumes can withstand high temperatures (Brisson et al., 2009). In Sahelian Africa, the consequences of rising temperatures may negatively impact legume symbiotic activity. According to native varieties of *Acacia* found in Sudan along with other Sahelian nations, certain varieties familiar with this region can achieve significant levels of fixation with rising temperatures in the soil. (Astera, 2010). It is necessary for these plants and the micro-symbionts, they are linked to systems in soil rhizobia and bradyrhizobia that absorb temperature; these mechanisms may be connected to the synthesis of exopolysaccharide.

It's possible that grain legumes across Africa could fix nitrogen at rather high rates. (Table 2); Nevertheless, due to changes in soil characteristics, genotypes of legumes, bradyrhizobia species, and farming practices, values differed significantly between species and sites. Research conducted on the nitrogen fixation of legume fields in Africa's savanna has confirmed the impact of soil fertility on this process. As long as ten groundnut species developing in the soil of northern Ghanaian savanna are given full manures (without nitrogen), the symbiotic

performance between the plants is entirely enhanced compared to plants without fertilizer. Nutrient addition significantly improved the development of plants and nodulation in some groundnut varieties by 453% and 612%, resulting in a 60% improvement in yield from kernels and a 65% rise in fixed-nitrogen. Comparative research using dependent symbiosis of legumes farmed in nutrient-amended plots also revealed a markedly significant increase in nitrogen-fixation and nodulation of 10 cowpea cultivars and 5 Bambara groundnut cultivars at three West African savanna locales. Eastern African cowpea and common bean statistics are comparable to Western African ones. (Pule-Meulenberg and Dakora, 2015).

A current research from South Africa also confirmed that enhancing Boron nutrients embedded in Bambara groundnut bringing about the extraordinary quantities of Nitrogen fixed. These results are better compared to previous information that soils from lack balanced nutrient and suffer from mineral deficiencies, may potentially harm the host plant's ability to grow, symbiotic arrangement and the effectiveness of nodule in legumes field. Consequently, imbalances of nutrient or deficiencies usually reduce Nitrogen fixation in legumes under agriculturists' circumstances, and possibly the realization of their capacity to fix nitrogen. Most importantly, inadequate nutrition could be a factor in the inconsistent favorable reactions to legume inoculation with *Rhizobium* or *Bradyrhizobium* in African soils, thereby reducing the capacity of the legume-bacterial complex to reach its complete symbiotic potential. (Makoi et al., 2013).

The many soil types found in Africa have an impact on nitrogen fixation and legume nodulation, as well as soil alterations related to nitrogen status. High soil nitrogen levels are thought to have an adverse effect on many symbiotic legumes' ability to fix nitrogen. (Bruno et al., 2015). Research carried out in Zambia (Argaw, 2014), Kenya (Beres et al., 2010), Nigeria and Senegal (Makol et al., 2009) have shown that the act of combined nitrogen reduces the amount of nitrogen fixed in cowpeas, common beans, peanuts, and soybeans. Conversely, certain native African legumes, such as *Kersting's* bean and Bambara groundnut, show nitrate tolerance. (Baral and Izaguirre-Mayoral, 2016), and they could serve as models for learning about NO (nitrogen oxide); legume nodulation affects the fixation of nitrogen.

The cropping strategy used has a similar effect on legume nitrogen-fixation. The development of root nodule in planting techniques comprising four types of legumes (*Kersting's* bean, Bambara groundnut, cowpea, and groundnut) and maize has been observed to exhibit alterations in the dynamics of nodule population in response to farming strategy. Through intercropping, the nodule population of cowpea and groundnut was reduced. Compared to single planting, intercropping *Kersting's* bean and Bambara groundnut produced more nodules, which is fascinating.

The groundnut records held when compared to earlier statistics. (Sprent et al., 2010). Still, the demonstration of fixation of nitrogen in cowpeas was genuine through combined planting with maize in Nigeria should highlight distinctions in the symbiotic response of different cultivars to planting techniques (Sprent et al., 2010). However, this is obvious that current species, like soybeans, show a decline in fixation of nitrogen in mixed plantings. (Magulu and Kabambe, 2015).

In certain species, if the related grain in the combination applies intense competition for soil nitrogen, the symbiotic relationship with the intercropped legume could be revitalized. In that instance, it is a requirement for the legume to rely more on its symbiosis for Nitrogen nutrient as examined by cowpea-millet intercropped in Ghana's savanna, nearly every crop in the combination added more Nitrogen than single crop plants (Sprent et al., 2010).

Table 2. Nitrogen fixation by Nitrogen Fixation Legumes in selected African countries.

Legumes	Country	Amounts of fixed nitrogen	Connected Rhizobium	References
<i>Phaseolus vulgaris</i>	Kenya	17-27	<i>Rhizobium</i> spp. <i>Sinorhizobium</i> spp.	Makoi et al. (2013)
<i>Vigna unguiculata</i>	Kenya Ghana Nigeria	15-31 201-287	<i>Bradyrhizobium</i> spp. <i>Rhizobium</i> spp,	Benson et al. (2015b) Bado et al. (2012) Pillai (2012)
<i>Arachis hypogea</i>	Ghana Nigeria	11-63 103 38-79	<i>Rhizobium</i> spp. <i>Agrobacterium</i> spp. <i>Burkholderia</i> spp.	Pule-Meulenberg and Dakora (2015) Belane and Dakora (2009) Kumar et al. (2014)
<i>Glycine max</i>	Nigeria Nigeria	65-115	<i>Bradyrhizobium</i> spp.	Argaw (2014) Belane and Dakora (2011)
<i>Cajanus cajan</i>	Kenya Nigeria	86-142	<i>Bradyrhizobium</i> spp. <i>Rhizobium</i> spp. <i>Sinorhizobium</i> spp. <i>Mesorhizobium</i> spp.	Pypers et al. (2011) Kamanga et al. (2014) Bargaz et al. (2013)
<i>Acacia holosericea</i>	Senegal	36-108	<i>Bradyrhizobium</i> spp. <i>Rhizobium</i> spp.	Lindstrom et al. (2010)
<i>Sesbania rostrata</i>	Senegal	505-581	<i>Bradyrhizobium</i> spp. <i>Rhizobium</i> spp.	Soumare et al. (2013)
<i>Sesbania sesban</i>	Senegal	43-102	<i>Bradyrhizobium</i> spp. <i>Rhizobium</i> spp.	Soumare et al. (2013)
<i>Albizia lebbek</i>	Nigeria	94	<i>Bradyrhizobium</i> spp. <i>Rhizobium</i> spp.	Chianu et al. (2012)

8. THE RELATIONSHIP OF BAMBARA GROUNDNUT WITH RHIZOBIUM

Bacteria are primordial, microscopic, unicellular (single-celled) creatures that cause a wide range of fatal illnesses, because of their exceptional molecular and structural potential, which sets them apart from other kingdoms like viruses, fungi, and animals. Hence, they are classified under a particular kingdom. Although bacteria belong to many different categories and share many morphological traits, they are divided into five main categories based on factors such as their natural environment, laboratory features, staining methods, the requirement for specific nutrients to produce vitality, and expression of specific cilia or extensions of the cytoplasm that aid in bacterial motility (Green et al., 2005).

However, it has recently been found that although bacteria are known for their beneficial effects, their caustic effects have given them an unfavorable reputation. Approximately 99 percent of those bacteria are beneficial, but the remained ones are infamous. To be precise, a few are necessary for other living organisms to grow properly. They either live freely or develop symbiotic relationships with other plants or animals. Certain beneficial microorganisms have symbiotic relationships with nitrogen-fixing. These microorganisms are called cyanobacteria, and they cause aquatic environments to fix nitrogen. With the root nodules of leguminous plants, another class of bacteria known as "Rhizobia" has a symbiotic connection. Examples of these bacteria are *Rhizobium etli*, *Bradyrhizobium* spp., *Azorhizobium* spp., and several other species. (Pillai, 2012). These specific types of nitrogen-fixing bacteria can fix atmospheric nitrogen by reacting with ammonia, releasing nitrogen that plants may use.

Table 3. Factors influencing the fixation of legume nitrogen in Africa.

Factors	Location	Sources
Temperature	Sudan	Astera (2010)
Phosphorus	Namibia, Kenya	Benson et al. (2015b) Wang et al. (2010)
Relative humidity	Nigeria	Pillai (2012)
Nutrient disorder	Africa-wide	Bambara and Ndakidemi (2010)
Plant genotype	Ghana	Pule-Meulenberg and Dakora (2015)
Few bradyrhizobia	Togo	Belane and Dakora (2011) Soumare et al. (2013)
Drought	Tanzania, Kenya, Malawi	De Ponti et al. (2012) Somasegaran and Hoben (2012) Ndakidemi and Dakora (2011)

Although plants lose their ability to use air nitrogen, soil-dwelling nitrogen-fixing bacteria have become particularly important. Grain legumes, like African Bambara groundnut, may establish a symbiotic relationship with root-nodule bacteria known as "Rhizobia" that fixes nitrogen in a way that allows the legume to grow alongside a variety of crops in an intercrop or

under crop rotation. For example, *Rhizobium*, *Bradyrhizobium*, and *Burkholderia* types of bacteria are found in the root nodules of African Bambara groundnut. (Benson et al., 2015b). Remarkably, it has been found that Bambara groundnut can promote symbiotic nitrogen-fixation, which could lead to an increase in harvests. (Rajwar et al., 2013).

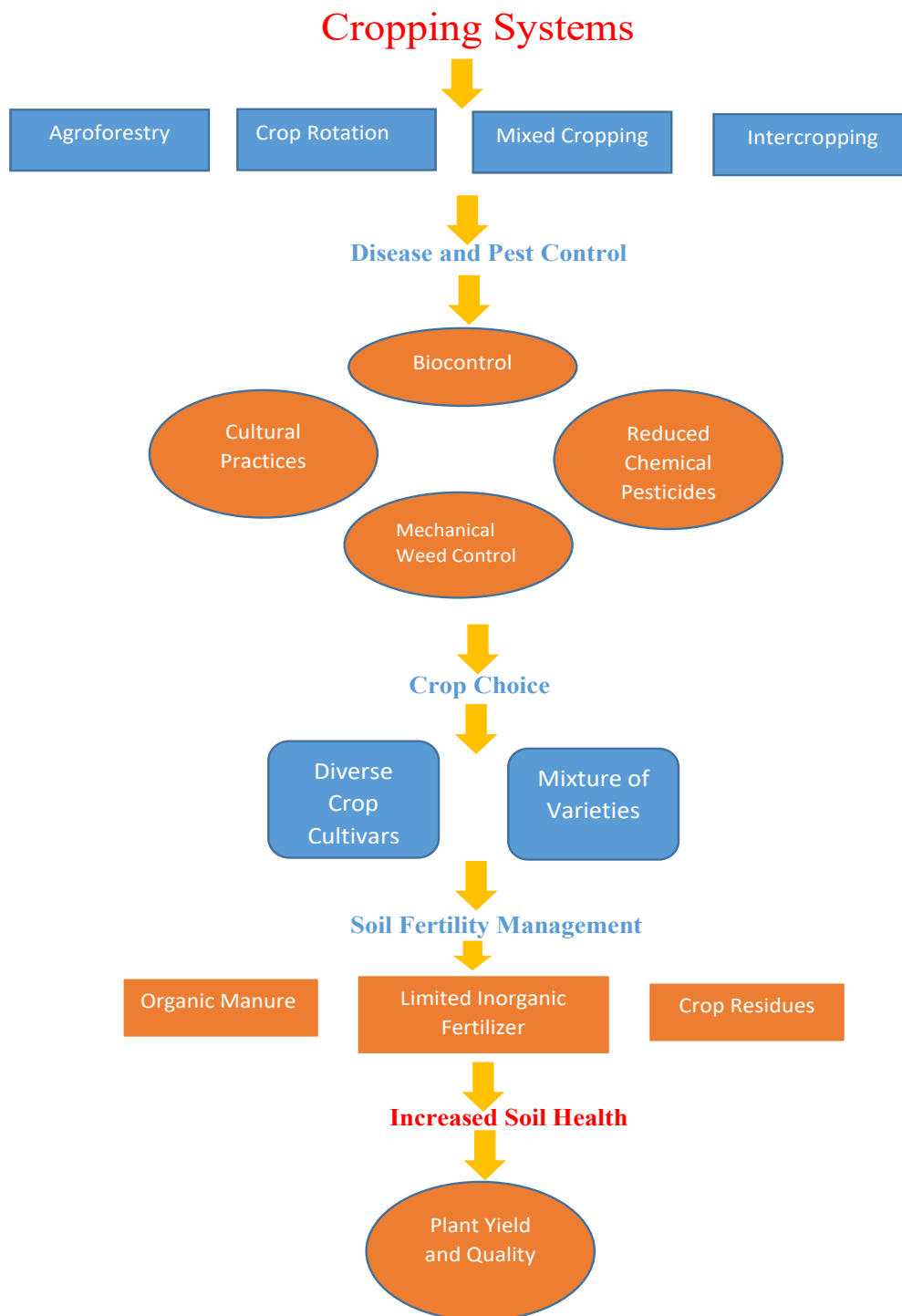


Figure 2. Elements that enhance the symbiotic relationship with rhizobial for improved crops.

As specified by Yakubu et al. (2010), Bambara groundnut has a great chance of fixing the nitrogen required for the engagement of an effective *Rhizobium* strain and the provision of other nutrients to the plants besides nitrogen. Many of the factors that influence legume nitrogen fixation are expressed in Table 3. The pH is a significant element that, in some parts of the world, restricts the efficiency of legume plants and their symbiotic nitrogen fixation (Bargaz et al., 2013, Faghire et al., 2011).

Many studies have determined the volume of nitrogen fixed in various legumes (such as soybean, cowpea, and groundnut) within Africa (Pule-Meulenberg and Dakora, 2009, Belane and Dakora, 2009). Though, the amount of fixation of nitrogen in Bambara groundnuts is extremely restricted (Nyemba and Dakora, 2010, Mohale et al., 2014). As itemized by Pedulosi et al. (2002), the possibility that abandoned and underutilized yields like Bambara groundnut might help combat Africa's food scarcity. In light of this, a variety of techniques have been developed to enhance symbiotic nitrogen fixation and increase crop yields in Bambara groundnuts.

These techniques include better crop selection, cropping techniques, management of disease and insect and enhanced soil health. Complete harvest increases in many leguminous crops have been achieved with rhizobium inoculants. They may also reduce the need for artificial fertilizer made from nitrogen, which is similarly costly and degrades the quality of soil. Rhizobia strain inoculation could improve plants' ability to fix nitrogen and nodulate under extreme conditions.

A research by Ngakou et al. (2011) outlined how, when compared to un-inoculated practice, inoculating Bambara groundnut, mycorrhiza, and *Rhizobium* greatly enhanced the effectiveness of nodulation and numbers of nodules by 64 and 80%, the seed weight by 52%, and the plant biomass by 30%. However, the use of an efficient rhizobial inoculant could help to some extent with the reproductive issue. These demonstrate the need for morphological characterization and screening of rhizobial isolates in conjunction with the molecular study of dominant bacterial strains that are adaptable to a variety of soil conditions. Therefore, to increase nitrogen utilizing Bambara groundnuts, more biological nitrogen fixation should be used (Figure 2).

9. CONCLUSIONS

Because Bambara groundnut is a legume and forms a symbiotic relationship with the bacteria that cause root nodules, it has equal benefits to be derived from both direct and indirect uses in farming. The bacteria can infiltrate the root tissues of plants by taking advantage of the free nitrogen present in the air. Consequently, the soil's nitrogen content will naturally rise, boosting the yields that legumes in plant rotation may eventually produce. Nevertheless, Bambara groundnut remains among the few widely utilized and unexplored legumes in many African countries. Bambara groundnuts are generally underutilized and inexpensive, but they receive little to no attention. However, there is a pressing need for deliberate efforts to focus on their applications and nutritional benefits, and they should not only be considered a cash crop but also a significant replacement for improving the soil's nitrogen fertility. The production, preservation, and application of Bambara groundnuts should be prioritized because there are few applications or advancements in Africa and other regions. Enhancing the yield and application of this constantly neglected crop is imperative, given the importance of agricultural

output to world population development. Furthermore, Bambara groundnut should ideally be considered a major crop for food safety rather than just being seen as a survival-female crop.

In summary, the worldwide community should work together to obtain funds for study on the cultivation, utilization, and preservation of Bambara groundnuts, as there is currently little of this type of study. It is advisable to support government efforts to finance studies aimed at improving the Bambara groundnut's ability to fix nitrogen, in order to maximize its potential for widespread use.

References

- [1] Abate, T., Alene, A.D., Bergvinson, D., Shiferaw, B., Silim, S., Orr, A. & Asfaw, S. (2011). Tropical grain legumes in Africa and South Asia: knowledge and opportunities (p. 116). Nairobi: ICRISAT.
- [2] Ahmed, G. M. & Abdallah, A. A. (2010). Nutritive evaluation of Bambara groundnut (*Vigna subterranean*) pods, seeds and Hulls as Animal Feeds. *J. of Appl. Sci. Res.* 6, 383-386
- [3] Ajiboye, A. A. (2015). Efficacy of mycorrhizal inoculations on seed germination and plant growth of Bambara groundnut, *Vigna subterranean* (TVsu 283). *Afr. J. Agric. Res.* 10, 1022-1030
- [4] Alhassan, M, A., Sule, M., Abubakar, H., Abdulmumin, T. & Dangambo, M. (2014). Fatty acid composition of Bambara groundnut (*Vigna subterranean* (L) Verdc) grown in Madobi, Kano State-Nigeria. *European Scientific Journal*, 10, 24
- [5] Argaw, A. (2014). Symbiotic effectiveness of inoculation with *Bradyrhizobium* isolates on soybean [*Glycine max* (L.) Merrill] genotypes with different maturities. *SpringerPlus*, 3, 753. <https://doi.org/10.1186/2193-1801-3-753>
- [6] Bado, B.V., Bationo, A., Lompo, F., Traore, K., Sedogo, M.P., Cescas, M.P. (2012). Long Term Effects of Crop Rotations with Fallow or Groundnut on Soil Fertility and Succeeding Sorghum Yields in the Guinea Savannah of West Africa. In: Bationo, A., Waswa, B., Kihara, J., Adolwa, I., Vanlauwe, B., Saidou, K. (eds) Lessons learned from Long-term Soil Fertility Management Experiments in Africa. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-2938-4_2
- [7] Bakhoun, N., Le roux, C., Diouf, D., Kane, A., Ndoye, F., Fall, D. & Galiana, A. (2014). Distribution and Diversity of Rhizobial Populations Associated with *Acacia senegal* (L) Wild. Provenances in Senegalese Arid and Semi-arid Regions. *Open Journal of Forestry*, 4, 136
- [8] Baral, B. & Izaguirre-Mayoral, M. L. (2016). Early signaling, synthesis, transport and metabolism of ureides. *J. Plant Physiol.* 193, 97-109
- [9] Bargaz, A., Faghire, M., Farissi, M., Drevon, J.-J. & Ghoulam, C. (2013). Oxidative stress in the root nodules of *Phaseolus vulgaris* is induced under conditions of phosphorus deficiency. *Acta Physiol. Plant* 35, 1633-1644

- [10] Bambara, S. & Ndakidemi, P. A. (2010). Phaseolus vulgaris response to Rhizobium inoculation, lime and molybdenum in selected low pH soil in Western Cape, South Africa. *Afr. J. Agric. Res.* 5, 1804-1811
- [11] Bamishaiye, J., Adegbola, O. & Bamishaiye, E. (2011). Advances in Agricultural Biotechnology. www.woaj.org/AAB, 1, 60-72
- [12] BamshaiyeE, O., Adegbola, J. & Bamshaiye, E. (2011b). Bambara groundnut: An under-utilized nut in Africa. *Advances in Agricultural Biotechnology* 1, 60-72
- [13] Begemann, F., Mukema, I. & Obel-lawson, E. (2002). Promotion of Bambara groundnut (*Vigna subterranea*): latest developments of Bambara groundnut research. Proceedings of the Second International Workshop of the International Bambara Groundnut Network (BAMNET), 23-25 September 1998, CSIR, Accra, Ghana, IPGRI
- [14] Belane, A. K. & Dakora F. D. (2009). Measurement of N₂ fixation in 30 cowpea (*Vigna unguiculata* L. Walp.) genotypes under field conditions in Ghana, using the ¹⁵N natural abundance technique. *Symbiosis*, 48, 47-56
- [15] Belane, A. K. & Dakora, F. D. (2011). Photosynthesis, symbiotic N and C accumulation in leaves of 30 nodulated cowpea genotypes grown in the field at Wa in the Guinea savanna of Ghana. *Field Crops Res.* 124, 279-287
- [16] Benson, O., Beatrice, A., Regina, N., Koech, P., Skilton, R. A. & Francesca, S. (2015b). Morphological, genetic and symbiotic characterization of root nodule bacteria isolated from Bambara groundnuts (*Vigna subterranea* L. Verdc) from soils of Lake Victoria basin, western Kenya. *J. Appl. Biol. Biotech.* 3, 001-010
- [17] Beres, S. B., Carroll, R. K., Shea, P. R., Sitkiewicz, I., Martinez-Gutierrez, J. C., Low, D. E., Mcgeer, A., Willey, B. M., Green, K. & Tyrrell, G. J. (2010). Molecular complexity of successive bacterial epidemics deconvoluted by comparative pathogenomics. *Proceedings of the National Academy of Sciences*, 107, 4371-4376
- [18] Berchie, J., Sarkodie-Addo, J., Adu-Dapaah, H., Agyemang, A., Addy, S., Asare, E. & Donkor, J. (2010). Yield evaluation of three early maturing Bambara groundnut (*Vigna subterranea* L. Verdc) landraces at the CSIR-Crops Research Institute, Fumesua-Kumasi, Ghana. *J. Agron.* 9, 175-179
- [19] Brisson, N., Launay, M., Mary, B. & Beaudoin, N. (2009). Nitrogen transformations. Conceptual basis, formalisations and parameterization of the STICS crop model, Quæ, Versailles Cedex, France, 141-165
- [20] Bruno, I. P., Reichard, T. K., Bortolotto, R. P., Pinto, V. M., Bacchi, O. O. S., Douradoneto, D. & Unkovich, M. J. (2015). Nitrogen balance and fertigation use efficiency in a field coffee crop. *J. Plant Nutr.* 38, 2055-2076
- [21] Bunde, M. & Osundahunsi, F. & Akinoso, R. (2010), Supplementation of biscuit using rice bran and soyabean flour. *AJFAND*, 10, 9
- [22] Chianu, J., Chianu, J. & Mairura, F. (2012). Mineral fertilizers in the farming systems of Sub-Saharan Africa. A Review. *Agron. Sustain. Dev.* 32, 545-566

- [23] Cinar, S. & Hatipoglu, R. (2014). Forage Yield and Botanical Composition of Mixtures of Some Perennial Warm Season Grasses with Alfalfa (*Medicago sativa* L.) Under Mediterranean Conditon. *Turk J Field Crops*, 19, 13-18
- [24] De Ponti, T., Rijk, B. & Van Ittersum, M. K. (2012). The crop yield gap between organic and conventional agriculture. *Agric. Syst.* 108, 1-9
- [25] Faghire, M., Bargaz, A., Farissi, M., Palma, F., Mandri, B., Luch, C., Garcia, N., Herrera-Cervera, J., Oufdou, K. & Ghoulam, C. (2011). Effect of salinity on nodulation, nitrogen fixation and growth of common bean (*Phaseolus vulgaris*) inoculated with rhizobial strains isolated from the Haouz region of Morocco. *Symbiosis*, 55, 69-75
- [26] Falade, K. O. & Nwajei, C. P. (2015). Physical, proximate, functional and pasting properties of four non-and γ -irradiated Bambara groundnut (*Vigna subterranean*) cultivars. *Int. J. Food Sci. Tech.* 50, 640-651
- [27] FAO. (2003). Trade reforms and food security: Conceptualizing the linkages, London, Kluwer Academic Publishers, FAO, UN.
- [28] Fasoyiro, S. B., Ajibade, A.J., Omole, O.N., Adeniyi & Farinde, E. O. (2004). Proximate, minerals and anti-nutritional factors of some under-utilized grain legumes in south western Nigeria. *Nutrition of Food Science*, 36, 18-23
- [29] Green, N. M., Zhang, S., Porcella, S. F., Nagiec, M. J., Barbian, K. D., Beres, S. B., Lefebvre, R. B. & Musser, J. M. (2005). Genome sequence of a serotype M28 strain of group A *Streptococcus*: potential new insights into Puerperal sepsis and bacterial disease specificity. *J. Infect. Dis.* 192, 7
- [30] Greenhalgh, P. (2000). The market potential for Bambara groundnut. Natural Resources Institute (NRI), University of Greenwich, Chatham Maritime, Kent ME4 4TB UK, 33.
- [31] Hannum, E., Liu, J. & Frongillo, E. A. 2014). Poverty, food insecurity and nutritional deprivation in rural China: Implications for children's literacy achievement. *Int. J. Educ. Dev.* 34, 90-97
- [32] Kadiata, B. D., Schubert, S. & Yan, F. (2012). Assessment of different inoculants of *Bradyrhizobium japonicum* on nodulation, potential N₂ fixation and yield performance of soybean (*Glycine max* L.). *J. Anim. Plant Sci.* 13, 1704-1713
- [33] Kamanga, B. C., Kanyama-Phiri, G. Y., Waddington, S. R., Almekinders, C. J. & Giller, K. E. (2014). The evaluation and adoption of annual legumes by smallholder maize farmers for soil fertility maintenance and food diversity in central Malawi. *Food Secur.* 6, 45-59
- [34] Kumar, K., Rai, P., Kumar, A., Singh, B. & Ak, C. (2014). Study on the performance of groundnut (*Arachis hypogea* L) genotypes for quantitative traits in Allahabad region. *Carib J. Sci. Tech.* 2, 564-569
- [35] Lindstrom, K., Murwira, M., Willems, A. & Altier, N. (2010). The biodiversity of beneficial microbe-host mutualism: the case of rhizobia Research in Microbiology. *Int. J. Mol. Sci.* 161, 453-463

- [36] Magulu, K. & Kabambe, V. H. (2015). Fodder production, yield and nodulation of some elite cowpea (*Vigna unguiculata* [L.] Walp.) lines in central Malawi. *Afr. J. Agric. Res.* 10, 2480-2485
- [37] Makoi, J. H., Bambara, S. & Ndakidemi, P. A. (2013). Rhizobium inoculation and the supply of molybdenum and lime affect the uptake of macro-elements in common bean ('P. Vulgaris L.') plants. *Aust. J. Crop Sci.* 7, 784-793
- [38] Manzeke, M. G. (2013). Exploring the effectiveness of different fertilizer formulations in alleviating zinc deficiency in smallholder maize production systems in Zimbabwe. University of Zimbabwe.
- [39] Margni, M., Rossier, D., Crettaz, P. & Jolliet, O. (2002). Life cycle impact assessment of pesticides on human health and ecosystems. *Agric-Eco-Environ.* 93, 279-392
- [40] Mazahib, A., Nuha, M., Salawa, I. & Babiker, E. (2013). Some nutritional attributes of Bambara groundnut as influenced by domestic processing. *Int. Food Res. J.* 20, 1165-1171
- [41] Minka, S. R. & Bruneteau, M. (2000). Partial chemical composition of Bambara pea [*Vigna subterranea* (L.) Verde]. *Food Chem.* 68, 273-276
- [42] Mohale, K. C., Belane, A. K. & Dakora, F. D. (2014). Symbiotic N nutrition, C assimilation, and plant water use efficiency in Bambara groundnut (*Vigna subterranea* L. Verdc) grown in farmers' fields in South Africa, measured using ¹⁵N and ¹³C natural abundance. *Biol. Fertil. Soils*, 50, 307-319
- [43] Mubaiwa, J., Fogliano, V., Chidewe, C., & Linnemann, A. R. (2016). Hard-to-cook phenomenon in bambara groundnut (*Vigna subterranea* (L.) Verdc.) processing: Options to improve its role in providing food security. *Food Reviews International*, 33(2), 167-194. <https://doi.org/10.1080/87559129.2016.1149864>
- [44] Musa, M., Massawe, F., Mayes, S., Alshareef, I., & Singh, A. (2016). Nitrogen Fixation and N-Balance Studies on Bambara Groundnut (*Vigna subterranea* L. Verdc) Landraces Grown on Tropical Acidic Soils of Malaysia. *Communications in Soil Science and Plant Analysis*, 47(4), 533-542. <https://doi.org/10.1080/00103624.2016.1141928>
- [45] Nezomba, H., Tauro, T., Mtambanengwe, F. & Mapfumo, P. (2010). Indigenous legume fallows (Indi fallows) as an alternative soil fertility resource in smallholder maize cropping systems. *Field Crops Res.* 115, 149-157
- [46] Ndakidemi, P. & Dakora, F. (2011). Changes in $\delta^{15}\text{N}$ and N Nutrition in Nodulated Cowpea (*Vigna unguiculata* L. Walp.) and Maize (*Zea mays* L.) Grown in Mixed Culture with Exogenous P Supply. *Innovations as Key to the Green Revolution in Africa*. Springer.
- [47] Ndidi, U. S., Ndidi, C. U., Aimola, I. A., Bassa, O. Y., Mankilik, M. & Adamu, Z. (2014). Effects of processing (boiling and roasting) on the nutritional and anti-nutritional properties of Bambara groundnuts (*Vigna subterranea* [L.] Verdc.) from Southern Kaduna, Nigeria. *J. Food Process.*, 2014, 9.
- [48] Ngakou, A., Moctar, M., Njintang, N. Y. & Tamo, M. (2011). Cowpea quality seed indicators as influenced by field application of selected biofertilizers and

- mycoinsecticide in three agroecological zones of Cameroon. *Commun. Soil Sci. Plant Anal.* 42, 1276-1288
- [49] Norgrove, L. & Hauser, S. (2016). Biophysical criteria used by farmers for fallow selection in West and Central Africa. *Ecol. Indic.* 61, 141-147
- [50] Nyemba, R. C. & Dakora, F. D. (2010). Evaluating N₂ fixation by food grain legumes in farmers' fields in three agro-ecological zones of Zambia, using ¹⁵N natural abundance. *Biol. Fertil. Soils.* 46, 461-470
- [51] Omokanye, A. (2001). Research Note: Forage yield and chemical composition of centro (*Centrosema pubescens*) in the year of establishment at Shika, Nigeria. *Tropical Grasslands*, 35, 53-57
- [52] Pedulosi, S., Hodgkin, T. & Williams, J. (2002). Underlined crops: trends, challenges and opportunities in the 21st century. In Wallingford, UK: CAB International Plant Genetic Resources Institute (IPGRI).
- [53] Pule-Meulenberg, F. & Dakora, F. D. (2015). Nodule functioning and symbiotic efficiency of cowpea and soybean varieties in Africa, in Biological Nitrogen Fixation (ed F. J. de Bruijn), John Wiley & Sons, Inc, Hoboken, NJ, USA. DOI: 10.1002/9781119053095
- [54] Pypers, P., Sanginga, J.-M., Kasereka, B., Walangulu, M. & vanlauwe. (2011). Increased productivity through integrated soil fertility management in cassava–legume intercropping systems in the highlands of Sud-Kivu, DR Congo. *Field Crops Res.* 120, 76-85
- [55] Rajwar, A., Sahgal, M., Johri, B.N. (2013). Legume–Rhizobia Symbiosis and Interactions in Agroecosystems. In: Arora, N. (eds) Plant Microbe Symbiosis: Fundamentals and Advances. Springer, New Delhi. https://doi.org/10.1007/978-81-322-1287-4_9
- [56] Rosenstock, T., Tully, K., Arias-Navarro, C., Neufeldt, H., Butterbach-Bahl, K. & Verchot, L. (2014). Agroforestry with N₂-fixing trees: sustainable development's friend or foe? *COSUST*, 6, 15-21
- [57] Sanchez, P. A., Denning, G. L. & Nziguheba, G. (2009). The African green revolution moves forward. *Food Secur.* 1, 37-44
- [58] Somasegaran, P. & Hoben, H. J. (2012). Handbook for rhizobia: methods in legume-Rhizobium technology, Springer Science & Business Media. <https://doi.org/10.1007/978-1-4613-8375-8>
- [59] Soumare, A., Diop, T., Lahcen, O., Bassene, G., Duponnois, R. & Ndoye, I. (2013). Impact de *Eucalyptus camaldulensis* sur la diversité des *Rhizobium* associés à *Acacia senegal* et *A. seyal* au Sénégal. *J. Appl. Biosci.* 67, 5183-5193
- [60] Sprent, J. I., Odee, D. W. & Dakora, F. D. (2010). African legumes: a vital but under-utilized resource. *J. Exp. Bot.* 61, 1257-1265
- [61] Syampungani, S., Chirwa, P. W., Akinnifesi, F. K. & Ajayi, O. C. (2010). The potential of using agroforestry as a win-win solution to climate change mitigation and adaptation and meeting food security challenges in Southern Africa. *Agric. J.* 5, 80-88

- [62] Wang, L., D'odorico, P., Ries, L. & Macko, S. A. (2010). Patterns and implications of plant-soil $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values in African savanna ecosystems. *Quat. Res.* 73, 77-83
- [63] Yakubu, H., Kwari, J. & Ngala, A. (2010). N₂ fixation by grain legume varieties as affected by rhizobia inoculation in the sandy loam soil of sudano-sahelian zone of north-eastern Nigeria. *Nig. J. Basic Appl. Sci.* 18, 229-236