Chapter

Enzymatic Processing of Pigeon Pea Seed Increased their Techno-Functional Properties

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Abstract

Neglected and underutilized crops (NUS) are those crops that are entirely ignored or little attention is paid to them by agriculture researchers, plant breeders and policy-makers. There has been renewed interest in NUS as many of these varieties and species, along with a wealth of traditional knowledge are being lost at an alarming rate. This chapter provides an overview of underutilized legumes in Sub-Saharan Africa (SSA). There is a recognized need to explore the diversity of indigenous micro symbionts associated with underutilized legumes. The biochemical mechanism in legumes remains elusive to date as evidence is mounting for allelopathic inhibition of nitrifying microorganisms by root exudation of phenolic compounds. A cross-sectional study was undertaken to explore the potential relationship between enzymatic processes of certain legumes and high tolerance to drought stresses, high biomass productivity, erosion control and dune stabilization and general soil health. Pigeon pea among other legumes have a huge untapped potential for improvement of both in quantity and quality of production in Africa.

Keywords: NUS, PGPR, PGPF, African legumes, pigeon pea, food security

1. Introduction

Cajanus cajan (L.) Millsp. (*C. cajan*) (Family: Fabaceae) also known as pigeon pea, is a famous food and cover/forage crop bearing a high amount of key amino acids like methionine, lysine and tryptophan [1]. It is one of the key promising sources of antioxidants and key enzyme inhibitors that can be exploited for future bioproduct development in tropical and subtropical regions in the world. This legume is one of the underutilized species in sub-Saharan Africa. Other economically important legumes include sword beans (*Canavalia ensiformis*), Bambara groundnut (*Vigna subterranea*), and Lima beans (*Phaseolus lunatus*) among several others [2, 3]. Neglected and underutilized species (NUS) has been a question of great interest in a wide range of fields.

The role of NUS in fighting poverty, hunger and malnutrition has received increased attention across several disciplines in recent years. There has been a growing recognition of the vital links between NUS, nutritional diversity, food sustainability and wealth creation. One well-known study that is often cited in research on NUS is that of Padulosi [2], who defined NUS as those species which are entirely ignored by agricultural researchers, plant breeders and policymakers. It is a widely held view that NUS is not traded as commodities. Agricultural species that are not among the major staple crops often come under the heading of 'neglected and underutilized species' (NUS) and are sometimes called 'orphan' crops.

If [2]'s findings are accurate, many of these varieties and species, along with a wealth of traditional knowledge about their cultivation and use, are being lost at an alarming rate. Evidence suggest that nearly 30,000 edible plant species have been identified, of which over 7000 plant species have been used in the history of civilization to meet food requirements [4]. Recent trends in NUS have led to a proliferation of studies as researchers have shown an increased interest in these species. It was established that barely 150 species are commercially cultivated and, of these, just 103 crops provide up to 90% of the calories in the human diet.

Several divergent accounts of NUS have been proposed, creating numerous controversies. The relationship between crop diversity, dietary diversity, nutrition and health has attracted conflicting interpretations from the scientific community. NUS offers opportunities to enrich diets with healthier food (particularly legumes, fruits and vegetables). The gradual shift from diets based on local foods to a 'Western-style' diet, high in fats, salt, sugar and processed foods, increases the incidence of non-communicable diseases, such as diabetes, obesity, heart disease and certain types of cancer.

African legumes can contribute significantly to the dietary supply of nutrients especially protein, essential amino acids, dietary fiber, vitamins, and minerals in the diet. However, compared to the well-known pulses, like the common bean, oilseed legumes, soybean, the African legumes are greatly underutilized and under-researched [5].

Numerous studies have attempted to explain the consistent contribution of NUS in fighting poverty, hunger and malnutrition and in generating income in both domestic and international markets [6–10]. This chapter examines the relationship between the biochemical mechanism through the enzymatic processes resulting to allelopathic inhibition of nitrifying microorganisms by root exudation of phenolic compounds in pigeon peas and related legumes. These could be exploited for future bio-product development to bring about sustainable crop production and to also ameliorate the effect of both biotic abiotic stresses to boost yield and restore depleted soil nutrients.

1.1 Neglected and underutilized legumes in Sub-Saharan Africa

Previous studies of NUS have established that in some countries like the Côte d'Ivoire, a considerable variety of minor leafy vegetables, legumes and vegetable crops are utilized and appreciated for their rich nutritional value. In the same way, minor forest and timber forest species are collected from the wild in Ghana which is utilized in developmental projects in the country such as housing construction, furniture and other arts and crafts. In the same vein, sword beans (*C. ensiformis*) are common food crops in the region. Similarly, in East Africa however, demand for leafy green vegetables is ever more recognized due to their nutritive value. In Uganda on the other hand, despite disregard on the part of stakeholders more especially the agricultural research and development programs, poor communities continue to grow and market miscellaneous underutilized species which are locally processed in form of artifacts and are mainly exported around the globe. NUS also serves as an alternative food source and is equally exploited for ornamental and medicinal value, generating significant income for some populations in West Africa. The use of some NUS is also significant in Malawi, particularly about Bambara groundnut (*V. subterranea*), sorghum, finger millets and pearl millets. In Nigeria, NUS such as fonio (*Digitaria exilis*, *Digitaria iburua*), Ethiopian tef (*Eragrotis tef*), Lima beans (*P. lunatus*), Pigeon peas (*C. cajan*) and *V. subterranea*, *Crotalaria* spp. and *Solanum nigrum*. Zimbabwe reports significant use of NUS, especially finger and pearl millets [2, 3].

*1.1.1 Sword beans (*C. ensiformis*)*

C. ensiformis (Sword beans) is a leguminous crop that could potentially be used as a biocontrol [11]. The article provides valuable insight into this leguminous vine. It is native to South and Central America however; it has adapted well to thrive in depleted soils of the tropics and subtropics worldwide. *C. ensiformis* is beneficial in curbing erosion, sandbank stabilization, soil rejuvenation, conservation, improvement and general soil health. It is grown for food, fodder, as a cover crop or green manure. *C. ensiformis* is resistant to drought and pests but does not grow well in excessively wet soil and has certain compounds such as Canavaine that increase its resistance to pest and herbivory due to the presence Concanavalin A—a lectin that guards against diseases caused by microorganism infections Canavanine is lethal as, when consumed, it could interchange L-arginine during protein synthesis and cause proteins to become malformed [11]. The beetle *Caryedes brasiliensis* thrives on *C. ensiformis* seeds as it contains an arginyl-T-RNA synthase that can discriminate between canavanine and L-arginine, countering the toxic effects.

*1.1.2 Bambara groundnut (*V. subterranean*)*

Bambara groundnut (*V. subterranea* (L.) Verdc.) is an indigenous legume crop, cultivated by subsistence farmers throughout sub-Saharan countries [12]. Neglected and underutilized legumes have for long been a question of great interest in a wide range of fields. In recent years, researchers have shown an increased interest in this neglected legume and considerable literature has grown up around the theme. It serves as the main source of income generation to subsistence farmers in Zimbabwe, Swaziland, Uganda and Zambia with a suitable land area (84, 100, 98 and 95%) respectively for cultivating this legume. A pilot study was initiated in seven rural districts of Zimbabwe aimed at improving nutrition, food security and maximizing its production. Follow-up studies according to Mubaiwa [12] report revealed a decline in production due to increasing climate and weather variability which in turns negatively affected food security. In an effort to keep this in check, agriculture and policy-makers in Zimbabwe have recognized the hidden potentials of NUS in improving food security by adapting to current climate change.

One major finding on Bambara groundnut in Nigeria is by Onuche et al. [13] who referred to it as "special" legume as it can adapt to high temperature and resistant to drought and suitable also for marginal soils where other leguminous crops are unlikely to thrive as it requires little resource from the soil in general. It is regarded also as special because it is not prone to total harvest failure even in low and uncertain rainfall regions. It increases soil fertility and boost yield of other crops cultivated around it. Therefore, it could potentially serve as great source of bio-fertilizer which is safe and free from high cost of synthetic chemicals commonly used as fertilizers which are indeed detrimental to health.

Bambara groundnut (*V. subterranea*) is a grain legume indigenous to sub-Saharan Africa where it is widely cultivated by subsistence farmers. The center of origin is most likely North-Eastern Nigeria and Northern Cameroon, in West Africa. The species is also grown to a lesser extent in some Asian countries such as India, Malaysia, Philippines and Thailand [4]. It is cultivated for its subterranean pods, is extremely hardy and produces reasonable yields even under conditions of drought and low soil fertility. There is notable paucity of empirical research focusing specifically on neglected underutilized legumes in relation to soil microbial interaction.

To date, very little attention has been paid to the role of NUS such as Bambara nut in sustainable crop production. Previous studies have failed to find any consistent association between neglected underutilized legumes and rhizosphere and rhizoplane microbial relations. Research studies in these areas should contribute to an increase in the utilization of African legumes. It has been proposed that African legumes are drought-tolerant crops, thus excellent candidates utilized as climate friendly food crops. Global warming and climate change with the resultant effects of low agricultural productivity and food insecurity are important global issues. African legumes therefore have great global potential as sustainable food sources [3].

Miscellaneous underutilized grain legumes play significant roles in the food cultures around the world as absolute sources of quality protein, natural medicine, animal fodder, natural fertilizers, and environmental restoration products, alongside the well-established soil enrichment property of symbiosis with nitrogen-fixing bacteria also contain high-quality proteins and micronutrients which are comparable to those found in conventional legumes. They are also indispensable in crop rotation strategies to fertilize agricultural soils [5].

*1.1.3 Lima beans (*P. lunatus*)*

P. lunatus L. was similarly reported to have tolerance and resistant traits against insects' attack [14]. Lima Beans roles in sustainable crop production have been investigated by Ruiz-Santiago et al. identifying plant-insect interactions as a determining factor for sustainable food and nutritional security. This could be utilized to influence the impact of herbivorous insects and their expression under varying climatic condition to achieve sustainable environmentally safe crop production. *P. lunatus* was similarly reported is an important legume for the poor population of the Brazilian northeast region [15]. The legume is able to take advantage of the nitrogen fixation process, but research to date has not been able to explore the diversity of indigenous microsymbionts.

*1.1.4 Pigeon peas (*C. cajan*)*

The study by Ayenan et al. [16] offers probably the most comprehensive empirical analysis. It was established from the report findings that in terms of production and quantity, pigeon pea is the 5th legume after cowpea (*Vigna ungulata*), Bambara groundnut (*V. subterranean*), Soy bean (*Glycine max*) and groundnut (*Arachis hypoaea*). Pigeon pea is a perennial shrub that has many advantages over annual legumes as it ensures several harvests and capable of enhancing soil fertility. The legume can withstand harsh environmental stress and has high drought tolerance which are the major challenges in this present-day climatic variability constraints.

Sinan et al. [1] in a recent study carried out the enzymatic assays, revealed that *C. cajan* has high amount of essential amino acids such as methionine, lysine and tryptophan. The study similarly was able to determine the total phenolic (TPC) content and total antioxidant capacity of the legume. Their study therefore serves as a baseline which gives opportunity for further investigation as the methanolic extract among other extract (hexane, ethyl acetate, aqueous) of prepared from *C. cajan* stem bark shows prominent antioxidant ability. This suggest that *C. cajan* could serve as a new source of antioxidant and key enzymes inhibitor (α-amylase and α-glucosidase enzymes) among others which could be exploited for future bioproduct development.

From the archives of the ECHO's Seed Bank [16], in a paper titled "factors to consider when selecting a pigeon pea variety" highlighted how pigeon pea requires lesser amount of nitrogen (N_2) into a form useful to the plant. Interestingly, *C. cajan* are reported to require lesser amount of N_2 compared to other crops like maize. It obtains N_2 from the atmosphere, assimilate it and are released to the soil as the plant die provided that this legume residues are kept in the field. Motis [17] also highlighted that pigeon pea has extensive roots which could grow through hard layers of soil aggregates, increasing soil porosity and aeration which in turn improves soil fertility. This report therefore is to infer that mixed cropping could be beneficial to other crops when pigeon pea is incorporated.

*1.1.5 Common bean (*Phaseolus vulgaris *L.)*

Common bean is one of the most familiarized beans worldwide. The developing countries especially in the sub-saharan regions mainly rely on common bean as a protein source; an alternative to animal protein, which are highly costly and beyond the reach of many low-income earners especially among the rural population.

Ismail et al. [18] recently identified six bacterial and four fungal strains which were isolated from the common bean (*P. vulgaris*) root plant for their growth promoting properties using molecular techniques and all the microbial isolates showed varying activities to produce indole-3-acetic acid and different hydrolytic enzymes such as amylase, cellulase, protease, pectinase and xylase. All the six bacterial endophytes isolates were reported to display phosphate solubilizing capacity. To increase the reliability of measures, each bacterial and fungal were tested twice by conducting a field experiment to evaluate the promotion activity of the metabolites of the most potent endophytic bacterial and fungal strains, in comparison to two exogenous applied hormones; IAA and benzyl adenine (BA) on the growth and biochemical characteristics of the *P. vulgaris*. Base on the results findings of Ismail et al. [18] it was established that both bacterial and fungal endophytic metabolites surpassed the exogenously applied hormone in increasing the plant biomass, photosynthetic pigments, carbohydrates, and protein contents, antioxidants, enzyme activity, endogenous hormones and yield traits. Therefore, it could be deducted that endophytic bacteria *Brevibacillus agri* (PB5) shows promising traits as a stimulator for growth and productivity of the common bean.

2. Role of plant growth promoting microbes in sustainable crop production

PGPR play a pivotal role in promoting plant growth either directly (by enabling resource acquisition of essential nutrients and elements like nitrogen, phosphorus), moderating plant hormone levels, or indirectly serving as biocontrol agents by decreasing the inhibitory effects of various pathogens on plant growth and development [19, 20].

According to Finkel et al. [21], growing crops continuously in agricultural soils can result in pathogen build up as well as bring about the emergence of disease suppressive soils. These soils in the long run convey resistance to plant pathogens and contain biocontrol agents within their resident bacterial community. Hassan et al. [22] points out that plant growth promoting rhizobacteria may affect plant growth, development and disease suppression by one or more direct or indirect mechanisms.

Ahemad and Kibret [23], in their study on the current prospect of mechanisms and application of plant growth promoting rhizobacteria point out that 80% of microorganisms isolated from the rhizosphere of various crops possesses the ability to synthesis and release of auxins as secondary metabolites. Phytohormones like auxins, gibberellins, cytokinin, ethylene and abscisic acid facilitate plant cell enlargement and extension in symbiotic and non-symbiotic roots [24]. It is now well established from a variety of studies that indole acetic acid (IAA) is involved in multiple processes in plant growth and development such as aiding cell division, differentiation and vascular formation which are the three most essential processes involved in nodule formation. Therefore, it was suggested that auxins levels in host legume plants are necessary for nodule formation [23–30]. Supporting this view is the study by Camerini et al. [31] that introducing IAA biosynthesis pathway in the inoculation with *Rhizobium leguminosarum* bv Viciae produced potential nitrogen fixing root nodules containing up to 60-fold more IAA than nodules formed by wild-type counterpart in *Vicia hirsute*. Therefore, drawing from the extensive range of sources, *Rhizobium* sp. have shown to produce IAA.

Gouda et al. [32] claims that plants have always been in symbiotic relationship with soil microbes (bacteria and fungi). The leguminous crops and beneficial microbes create a mutual relationship in the rhizosphere to fix the atmospheric nitrogen into plant available form. Mehmood's et al. [33] work on plant growth promoting rhizobacteria is complemented by Hassan's [22] study of the interactions of rhizo deposits with plant growth-promoting rhizobacteria in the rhizosphere, holds the view that plant release certain exudates such as sugars, sterols, growth factors, etc. which stimulate the movement of beneficial microbes towards plant roots. On reaching the root, the beneficial microbes are known to form nodules.

It is documented that 80% of plant available nitrogen comes from biological nitrogen fixation (BNF), while remaining 20% is contributed by other non-symbiotic organisms [34]. Nitrogen fixing organisms are generally categorized as symbiotic N_2 fixing bacteria including members of the family rhizobiaceae which forms symbiosis with leguminous plants (e.g. *rhizobia*) [28]. Non-leguminous trees (e.g. Frankia) and non-symbiotic (free living, associative and endophytes) nitrogen fixing forms such as cyanobacteria (*Anabaena*, *Nostoc*), *Azospirillum*, *Azotobacter*, and symbiotic nitrogen fixing bacteria provide only a small amount of the fixed nitrogen that the bacterially-associated host plant requires [29]. On a global scale, BNF provides the largest input of nitrogen to agricultural soils. Inoculation of these efficient plant beneficial rhizo-microbe species usually increases plant's productivity. If *Rhizobium* is inoculated as biofertilizer in the crops such as groundnut, pigeon pea, soybean, etc., it can supply ~19–22 kg ha^{-1} which can raise the production by ~17–33% [34]. Gouda et al. [32] in a similar study on 'revitalization of plant growth promoting rhizobacteria for sustainable development in agriculture' reported that plant growth promoting rhizobacteria fix atmospheric nitrogen in the soil including the strains of *Azoarus* sp., *Beijinrinka* sp., *Pantoea agglomerans* and *Klebsiella pneumoniae*. Symbiotic nitrogen fixing rhizobia within the rhizobiaceae family (a-proteobacteria) infect and establish symbiotic relationship with the roots of leguminous plants. On the other hand, arbuscular mycorrhizal fungi (AMF) were similarly reported to improve growth, nodulation and nitrogen fixation in legume-Rhizobium symbiosis [26].

2.1 Phytohormone production

Plant hormones or plant growth regulators are a wide range of microorganisms within the rhizosphere involved in secretions of substances known as exudates that regulate growth and development of organic materials [32]. They are also referred to as organic compounds that influence physiological changes in the plant at low concentrations [35]. Like Shah et al. [35] and Gouda et al. [32] hold the view that at a minimum concentration (<1 mM), growth hormones/regulators can promote, inhibit, or modify growth and development of plants. Similarly, Kumar et al. [36] maintain that hormones are the basic chemical signals that influence plant's ability to respond to the environment even at a low concentration of these active organic compounds [33]. Surprisingly, these growth regulators (also known as exogenous plant hormones) can be induced or activated by certain microbes, such as PGPR in plants [22, 37].

Organic plants hormones are classified into five (5) groups; auxins, ethylene, cytokinins, gibberellins and abscisic acid [23, 32, 33, 35, 36]. Microbial synthesis of the phytohormone; auxin (indole-3-acetic acid/indole acetic acid (IAA)) has a long history. According to Ahemad and Kibret [23], 80% of microorganisms isolated from various crop rhizospheres have the ability to synthesis and release auxins as secondary metabolites. Auxins are a group of plant hormone relevant in the advancement of root formation which in turns leads to increase in absorption of essential nutrients by the roots of plants [34]. IAA has been implicated in almost all aspects of plant growth and development, likewise in defense responses.

Generally, IAA is a commonly produced phytohormone associated with cell division, cell enlargement, cell extension, cell differentiation; stimulates seeds and tuber germination; increases the rate of xylem and root development and adventitious root formation and initiation; controls vegetative growth process; mediates responses to light, gravity and fluorescence; affect photosynthesis, pigment formation, biosynthesis of various metabolites and resistance to stressful conditions. It was also reported that rhizobacterial IAA could increase root exudation by loosening the plant root cell walls, which in turn helps the rhizobacterial colonization and growth [38]. IAA produced by PGPR is also reported to modifying plant morphological functions to uptake more nutrients from the soil [23, 33–35].

Gibberellins can also alter the plant morphology by elongation of stem tissues [34–36]. Ethylene generally is an essential metabolite for the development of plants [23].

According to Sarkar et al. [34]; cytokinin has similar functions as gibberellins in stimulating lateral shoot development, leading to advance plant development. In addition to that, cytokinin encourages tissue expansion, cell division and cell enlargement, enhanced root hair formation, inhibition of root elongation, shoot initiation, or specific physiological responses in plants [35, 39]. Ethylene is the only gaseous hormone [36]. Kumar et al. [36] also referred to it as "wounding hormone" because its production can be induced by physical or chemical disturbance of plant tissues. Ethylene has many effects on plant growth and development, such as rapid seedling death and deprived growth when secreted in excess [33].

Ethylene production in excess can inhibit root growth. Mode of action of some PGPR involves the production of 1-aminocyclopropane-1-carboxylate (ACC), a deaminase enzyme which significantly improves growth parameters. In the same view, Dutta et al. [38] report that ACC deaminase production of PGPR brings about growth and advancement by decreasing the levels of ethylene, inducing salt tolerance [23] and reducing drought stress in plants. ACC is a predecessor of ethylene in the biosynthesis pathway of ethylene in plants [36].

Therefore, it was reported that although ethylene being an essential metabolite for plant growth and development, under different stress conditions such as drought or salinity stress, the ethylene level drastically increases, this could negatively influence plant growth [23, 35]. In a nutshell, several forms of stress are relieved by decreasing ethylene production [40]. Through ACC deaminase producers such as effects of phytopathogenic microorganisms (viruses, bacteria, fungi, etc.), and resistance to stress by polyaromatic hydrocarbons, heavy metals, radiation, wounding, insect predation, high salt concentration, drought, extremes of temperature (hot/cold), high light intensity and flooding.

The major noticeable effects of seed/root inoculation with ACC deaminase-producing microbe are root elongation, promotion of shoot growth and enhancement in rhizobial nodulation and N, P and K uptake as well as mycorrhizal colonization in various crops [23, 33, 38].

Kachroo and Kachroo [41] make an interesting contribution with regards to the impact of salicylic acid (SA) and jasmonic acid (JA) in plant defense mechanism. It is a widely held view that many phytohormones are now well known to mediate induced defense signaling, SA and JA are two major players that have been traditionally attributed roles in regulating plant defenses. SA and JA activate specific signaling pathways, which can act individually, synergistically or antagonistically, depending upon the pathogen involved. In addition to plant defense, SA and JA also regulate various developmental processes including flowering, root growth, floral nector secretion, senescence, development, cell growth, trichome development and thermogenesis. JA is an important regulator of plant responses to both biotic and abiotic stresses and is particularly well known for its role in plant defense against insects and herbivores. Febble's [11] work on *C. ensiformis*, complemented by Ruiz-Santiago's [14] study of *P. lunatus* taken together these studies provide important insights into the role of legumes in defense against herbivorous insects due to the activities of the vital phytohormones. **Table 1**

Phytohormones	Crops	PBRMs
Gibberellin	Alder	*Bacillus* sp.
	Soybean	
	Soybean	
Cytokinin	Soybean	*Pseudomonas fluorescens*
	Lettuce and rapeseed	*Rhizobium leguminosarum*
	Wheat	*Paenibacillus polymyxa*
Indole acetic acid (IAA)	Soybean	*Bradyrhizobium japonicum*
	Soybean	*Bradyrhizobium amyloliquefaciens*
	Wheat	*Azospirillum brasilense*
	Radish	*Bradyrhizobium* sp.
	Rice	*Enterobacter cloacae*
	Rice	*Aeromonas veronii*
	Lettuce	*Agrobacterium* sp.
	Lettuce	*Alcaligenes piechaudii*
	Lettuce	*Comamonas acidovorans*
Jasmonic acid (JA)	Soybean	*B. japonicum*
	Soybean	*Bradyrhizobium amyloliquefaciens*
Salicylic acid (SA)	Soybean	*B. japonicum*
	Soybean	*Bradyrhizobium amyloliquefaciens*

Adopted from [34].

Table 1.
Plant beneficial rhizosphere microorganisms (PBRMs) as an efficient phytohormone producer in various plants.

summarizes the essential phytohormones in certain crop species and the associated plant growth promoting rhizomicrobes.

2.2 Role of plant growth-promoting bacteria (PGPR) and fungi (PGPF) in sustainable agriculture

In a comprehensive literature review on role of Plant Growth-Promoting microorganisms in Sustainable Agriculture and Environmental Remediation [42], highlighted the most influential accounts of soil microorganisms, particularly the rhizobacteria that have the potential to influence growth, yield and nutrient uptake by crops either directly or indirectly as well as maintain soil fertility and health.

PGPR can enhance the plant tolerance by promoting the plant growth, even in poor growth conditions and increase agricultural produce of different crops under stressful environment [43–45]. Apart from the above-mentioned facts, recent reports suggest that application of PGPRs also improves nutritional quality and antioxidant status of the crops [46, 47]. Harnessing the above-mentioned plant-microbe interactions can also help in reclamation of degraded lands, reduction in usage of chemical fertilizers and agrochemicals [48]. A prominent agricultural symbiotic association exists between the rhizosphere bacteria and roots of the legumes by the formation of root nodules. Previous studies showed that plant-fungal associations are much older than the rhizobia-legume interaction. In various plant-fungal interactions fungi help in phosphate acquisition and make it available to plants [49]. Some reports also indicate that the DMI-2 protein is required for the initiation of the plant-arbuscular mycorrhizae interaction, which helps in phosphate solubilization. Although, the underlying mechanism of the PGPR and PGPF interactions with the plants are quite different, some studies showed a similarity between them. In *Medicago truncatula*, a type of arbuscular mycorrhizal fungi (AMF), the interaction releases some small diffusible factors to activate the similar genes by the rhizobacterial nod factor [50]. This confirms the analogy of the PGPR and PGPF to some extent and needs further clarification from cutting-edge research on the topic. Supporting this view [51], stated that plants use receptor-like kinases to monitor environmental changes and transduce signals into plant cells. The study further added that *M. trancula* DOES NOT MAKE INFECTION 2 (DMI2) protein functions as a co-receptor of rhizobial signals to initiate nodule development and rhizobial infection during nitrogen-fixing symbiosis. However, the mechanisms regulating DMI2 protein level and folding associated with arbuscular mycorrhizae are still unknown.

Mutualistic association (co-inoculation) of PGPR and PGPF (arbuscular mycorrhizae fungi) increases the growth, nutrient uptake potential, and yield of the plants [52]. PGPF can directly enhance the nutrient uptake (P, Zn) and water use efficiency of the inhabiting plant by increasing the root surface with hyphal network. With increased water use efficiency, AMF also controls the N_2O emission, which is a potent greenhouse gas emitted from agricultural fields [53]. AMF alone or in combination with certain PGPR enhances plant growth indirectly by inhibiting growth of root pathogens and optimizing soil structures [54]. Apart from this PGPF can also regulate soil health and fertility by improving the overall soil nutrient dynamics [55].

The negative effect of climate change is also mitigated by AMF through maintenance of proper soil aggregation and thereby providing another major advantage to agricultural crop production. More and more studies show that the mycorrhizae can play an essential role in plant growth by enhancing plant vigor in poorly performing soils, and through their ability to store large amounts of carbon, which in turn may improve some of the effects of climate change. In conclusion, we can say that application of PGPR and PGPF in combination or alone can negate the hazardous effect of chemical fertilizers, improve soil health, reduce environmental stresses and promote sustainable agriculture [56–58]. The interaction of AMF and rhizobacteria thus can promote plant growth by improving soil structural properties as well as the enhanced availability of nutrients and reduce disease progression in a sustainable manner [43].

3. Soil health, rhizosphere microbes and sustainable crop growth

The concept of soil health has a long history. Attention was much given to soil health in well developed countries initially. This may probably be due to increasing concern of global food security in terms demand for high quality food and feed as a result of exponential growth in population and to keep in check the state of the soil health in general.

According to some studies, some authors are of the opinion that SH has to have inherent components before it can be termed as healthy soil, considering the biological physical and chemical qualities. Health of the soil is a function of its environmental sustainability [59, 60]. There are certain properties to look out for to determine 'healthy soil'. One of the inherent elements of a healthy soil is the ability to be adapted to diverse ecological resources in an optimally balanced condition. It also has to be self-purifying from soil pollutants through elution or biotransformation and thirdly, it has to be suppressive of harmful biota (phytophytogenic) maintaining beneficial soil microbes [60].

While a variety of definitions to the term 'soil health' have been suggested, this chapter will use the definition suggested by Semenov et al. [60] that, soil fertility was traditionally defined as the ability of soil to provide plants with mineral elements, water, air and overall ability to live in favorable physical and chemical environment. Organic fertilizers when used solely, serves as biological control against harmful organisms. Similarly, exclusion of chemical pesticides and using genetically modified organisms in organic farming system offers improved physical and chemical soil properties. The report established that organic farming increases soil health and microbial biodiversity by limiting mass development of pathogenic microbes.

According to Soil Science Society of America (SSSA), soil quality is the ability of the soil to function within the limits of the ecosystem to preserve its biological productivity and quality, ensuring healthy plants and animals. It was further established that methods and parameters have been developed, including portable devices and sets of tools (Environmental Box Kit Soil quality) for the determination of the quality of the soil. These kits are essential in determining soil conductivity, its pH, resistance during plowing, density, organic carbon, carbon microbial biomass, humidity, moisture capacity, nitrate content, soil respiration rates, etc.

Increasing agricultural production to feed the snowballing population in sub-Saharan Africa (SSA) is very challenging [59]. These results due to poor soil quality resulting from soil degradation, unsustainable management practices, and available arable land for mass production to feed the ever-increasing population of subsistence farmers and non-agricultural population. Han et al.'s [61] report on organic and inorganic/chemical fertilizers established that both have their positives and negatives on plant growth and soil in general. Chemical fertilizers/inorganic fertilizers according to their study are reasonably affordable, very rich nutrient contents, and could easily be assimilated by plants. Despite these beneficial effects, chemical fertilizers when used excessively could affect both the plant and the soil community through nutrient loss, surface water and groundwater contamination, soil acidification or basification, reductions in useful microbial communities, and increased sensitivity to harmful insects.

On the other hand, organic manure similarly has several positive effects owing to the stable supply of both essential nutrients and micronutrients, improved microbial activity due to amplified nutrient availability resulting from breakdown of harmful elements, improved soil structure and root development and sufficient soil water for physiological activities [61]. Organic manure is said to be produced from the decomposition of animal byproducts which are utilized to overcome environmental degradation and low plant productivity resulting from excessive utilization of chemical fertilizers. Organic manure is cost-effective and environmentally friendly particularly when waste from livestock industries is recycled which in turn promote agricultural productivity.

In a recent development, Fasusi et al. [45] have shown that nodule formation is enhanced by the low availability of nitrogen, but microorganisms that produce an enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase, have the potential to degrade 1-aminocyclopropane-1-carboxylate before its conversion to ethylene and may also enhance the formation of a nodule. Such formation is part of a common strategy developed by leguminous plants and Rhizobiaceae bacteria to decrease the concentration of oxygen to which the nitrogenase is exposed due to the inhibitory effect of oxygen on nitrogenase activity.

4. Conclusion

This study set out to review in detail the available information on enzymatic processes in pigeon peas and related legumes like the allelopathic inhibition of nitrifying microorganisms by root exudation of phenolic compounds, legumes' tolerance to drought stresses, high biomass productivity, relationship between plant growth promoting bacteria (PGPB) and plant growth promoting rhizofungi (PGPF) and general soil health towards sustainable crop production. This study has examined the peer reviewed literature on pigeon pea among others legumes as having huge untapped potential for improvement of both in quantity and in quality of production in Africa. The most obvious finding to emerge from this study is that pigeon pea requires lesser amount of nitrogen (N_2) compared to other crops like maize. Secondly, pigeon pea has extensive roots which could grow through hard layers of soil aggregates, increasing soil porosity and aeration which in turn improves soil fertility. Taken together, these findings suggest a role for pigeon pea in promoting crop yield. The present study is important in furthering our understanding of the role pigeon pea and related legumes play in boosting yield when mixed cropping is practiced. This is the first study to report an association between underutilized African legumes, enzymatic processes involved in mutualistic association of PGPR (rhizobacteria) and PGPF (arbuscular mycorrhizae fungi) and nodule formation to bring about increases in growth, nutrient uptake potential, and yield of the plants. The study is limited by the lack of information on pigeon pea and accurate state-of the art about the enzymatic processing of pigeon pea seed in promoting its techno-functional potentials. The strengths of the study included the in-depth analysis of Role of Plant Growth-Promoting Bacteria (PGPR) and Fungi (PGPF) in Sustainable Agriculture, Neglected and Underutilized Legumes in Sub-Saharan Africa and general Soil Health for Sustainable Crop Growth. Further research should be undertaken to explore how the mechanism of enzymatic processing of pigeon pea works for sustainable food security.

5. Challenges and future research perspectives

Role of Rhizosphere Microbes in Soil Fertility and Sustainability 'Zero Hunger Challenge' is the major goal of human efforts. This goal can be achieved by sustainable increment in the arena of agricultural productivity to satisfy the demands of abruptly spreading human population. Growing more and more foods from less and less farm holdings is a demand feature of our economy. The time of action is now. There is growing realization that agriculture must diversify. NUS more especially legumes have an important role to play in advancing agricultural development beyond the Green Revolution model of improving and raising the yields of staple crops.

NUS are local and traditional but are globally significant and thus require scientific and political attention beyond the local and national levels. Some of the major challenges to the sustainable use of NUS are neglected by agronomic researchers and policy-makers, genetic erosion, loss of local knowledge, marketing and climate change. The main purpose for the review is to encourage scientists and policy-makers to optimize and promote the benefit of NUS and to create links between scientific and traditional knowledge by establishing interdisciplinary research networks to identify suitable material for NUS breeding by means of strengthening cooperation among stakeholders and creating synergies at local, regional, national and international levels.

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Conflict of interest

The authors declare that they have no known competing financial or personal relationships that could have appeared to influence the work reported in this paper.

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