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REVIEW

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Advancement and practical applications of rhizobacterial biofertilizers for sustainable crop production in sub-Saharan Africa

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Abstract

Agricultural intensification continues in Africa in attempts to meet the rising food demands of the equally rising population. However, most arable lands in the region are characterized by nutrient deficiency and over-reliance on synthetic fertilizers which consequently contributes to increased production costs, environmental pollution, and global warming. Decades of research on plant–rhizobacterial interactions have led to the formulation and commercialization of rhizobacterial biofertilizers globally for sustainable soil and crop health. Nevertheless, this promising technology has not received much attention in Africa and remains largely unexplored due to several constraints. This article discusses the practical applications of rhizobacterial biofertilizers for sustainable crop production in sub-Saharan Africa. The challenges of soil infertility and the use of conventional synthetic fertilizers in crop production in Africa are critically evaluated. An overview of the potential of rhizobacteria as biofertilizers and alternatives to synthetic fertilizers for soil fertility and crop productivity in the continent is also provided. The advantages that these biofertilizers present over their synthetic counterparts and the status of their commercialization in the African region are also assessed. Finally, the constraints facing their formulation, commercialization, and utilization and the prospects of this promising technology in the region are deliberated upon. Such knowledge is valuable towards the full exploitation and adoption of this technology for sustainable agriculture for Africa's food security.

Keywords: Biofertilizers, Sustainable agriculture, Soil fertility, Rhizobacteria

Introduction

The world's population is growing and projections are that Africa will contribute to about 60% of this increase by the year 2050 and become home to more than 2.5 billion people [1]. Agriculture is one of the pillars for food and economic security in Africa, employing up to 65% of the labor force and contributing to over 30% of the national gross domestic product [2]. Notwithstanding, the continent's agricultural efficiency is largely affected by low soil fertility and nutrient deficiencies [3, 4]. The continuous application of artificial fertilizers in attempts to increase yields continues to elicit numerous concerns worldwide regarding the sustainability of food production systems [5]. The problem is no longer just to produce enough food, but to do so sustainably [6]. Therefore, alternative and sustainable crop fertilization mechanisms should be embraced in Africa.

The exploitation of plant–soil microbe interactions is recognized as an important avenue to achieving sustainable agriculture globally [7]. As such, plant rhizospheres have been the center of focus of researchers for decades worldwide due to their importance in soil and crop health [8]. The bacteria associated with plant rhizospheres are generally termed rhizobacteria [9]. A majority of these bacteria can positively influence plant growth

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and are referred to as plant growth-promoting rhizobacteria (PGPR) [10]. The PGPR can promote plant growth either directly or indirectly, for example through the production of phytohormones and siderophores, solubilization of nutrients, and biological nitrogen (N) fixation (BNF) [11]. Many of these strains can also improve the ability of plants to tolerate abiotic environmental stresses such as soil salinity, acidity, and alkalinity [12]. The beneficial aspects of these bacterial communities have also been demonstrated in several important crops in different African countries (Table 1), demonstrating their immense potential for crop fertilization and productivity.

Biofertilizers or microbial inoculants are living microorganisms that can promote plant growth when directly applied to seeds or soil [13–15]. The use of rhizobacterial biofertilizers is now gathering momentum and many PGPR are presently being used as inoculants to enhance nutrient uptake and crop yields while reducing the use of chemical fertilizers [16]. Although some studies in Africa have proven that PGPR can substantially increase plant

Table 1 Examples of studies documenting plant growth-promoting rhizobacteria in Africa

Crop	PGPR	PGP effects	Place of study	References
Common Beans	*Rhizobium*	285% increase in Fe, 67% increase in Zn	Tanzania	[17]
	Rhizobium spp.	Increased shoot dry weight and nodule weight	Kenya	[18]
	Rhizobium spp.	Increased uptake of nutrients	Tanzania	[19]
	Rhizobium spp.	Improved yields	South Africa	[20]
	Rhizobium	Increased seed yields over control	Kenya	[21]
	Rhizobia	Significant yield increase	Ghana, Kenya, Tanzania, Uganda	[22]
Chickpea	*Rhizobium*	Up to 138% increase in yield	Ethiopia	[23]
Cowpea	*Rhizobia*	Increased yields	Kenya	[24]
	Bradyrhizobium	Improved nodulation, dry matter, and grain yield	Ghana	[25]
Flax	*Azospirillum*, *Azotobacter*	50% reduction in fertilizer use	Egypt	[26]
	Bacillus	Enhanced productivity	Egypt	[27]
Maize	*Paenibacillus alvei*, *B. safensis*, *B. pumilus*, *Lysinibacillus sphaericus*	33% yield increments	South Africa	[28]
	Azotobacter, *Azospirillum*	100% reduction in fertilizer use	Egypt	[27]
	Pseudomonas, *Klebsiella oxytoca*, *Enterobacter sakazakii*	Increased agronomic characteristics	Nigeria, Kenya	[29]
Mung bean	*Bradyrhizobium*	Increased nitrogen fixation and yields	Ethiopia	[30]
Okra	*P. aeruginosa*	Improved growth	Nigeria	[31]
	Azospirillum, *Azotobacter*	100% reduction in fertilizer use	Egypt	[32]
Potato	*Serratia*, *Citrobacter*, *Serratia*	Enhanced nutrient levels in tubers and rhizosphere soils	Kenya	[33]
Rice	*Azolla pinnata*, *A. nilotica*, *A. filiculoides*, *A. caroliniana*	Increased yield and soil N content	Nigeria, South Africa, Ivory Coast, Togo, Senegal, and Kenya	[34]
Soybean	*Rhizobium*	Increased yield by 447 kg ha^{-1}	Nigeria	[35]
	Bradyrhizobium japonicum	Increased yield and micronutrient uptake	Tanzania	[17]
	Rhizobium	Up to 47% increase in yields	Several countries	[36]
	Rhizobium	15–30% increase in yields	Kenya	[37]
	Bradyrhizobium	24% increase in yields	Ghana	[25]
	Bradyrhizobium	Significant increase in dry weight of shoot and grain yield	Kenya	[38]
	Rhizobium	Increased nutrients content in soil	Tanzania	[39]
	Rhizobium	Increased yields	Several countries	[40]
	Rhizobia	Significant yield increase	Ghana, Kenya, Tanzania, Uganda	[22]
Sweet fennel	*Rhizobium*	Enhanced productivity	Egypt	[41]
Tomato	*Bacillus subtilis*, *Pseudomonas aeruginosa*, *Klebsiella pneumonia*, *Citrobacter youngae*	Enhanced seedling height, leaf area, number of leaves	Nigeria	[42]
	P. aeruginosa	Improved growth	Nigeria	[31]

growth (Table 1), the concept of rhizobacterial biofertilizers still seems far-fetched and there is very little applicability.

The present review discusses the advancement and practical applications of rhizobacterial biofertilizers as alternatives to synthetic fertilizers for sustainable agriculture in Africa. The state of soil infertility and the challenges related to the use of synthetic fertilizers for crop production in Africa are evaluated. An overview of the potential of rhizobacteria as biofertilizers and alternatives to synthetic fertilizers for soil fertility and crop productivity is also evaluated extensively.

The benefits offered by these microbial products over their synthetic counterparts, together with the constraints still facing their formulation and commercialization in Africa and the state of their commercialization in the continent are carefully articulated. Finally, the future perspectives and prospects for their advancement, commercialization, and practical applications in Africa are provided. Such knowledge will ultimately increase the understanding of rhizobacterial biofertilizers and provide direction on how to accelerate their utilization for the improvement of the African agroecosystems.

The state of soil infertility in Africa

The worrying state of soil infertility in African countries started over two decades ago [43]. Over the years, African soils have gradually undergone severe nutrient depletion and declining fertility levels [3, 4, 44]. Many African soils are characterized by the deficiency of important plant nutrients like N, phosphorus (P), potassium (K), zinc (Zn), and iron (Fe) [4]. In East African soils, the deficiencies of N, P, and K can be as high as 90, 50, and 50%, respectively [45], resulting in low crop productivity that threatens food security in the region [46]. Older reports document that Ferralsols which occupy a sizeable portion of Africa including Angola, Zambia, Burundi, Uganda, and Cameroon and others have a low capacity to supply essential nutrients to crops [47].

Estimates of the financial implication of soil infertility in Africa reveal that close to US$ 4 billion and 6 billion ha of land are lost annually due to nutrient mining and land degradation [48]. Earlier predictions also showed that with the ever-increasing population and demand for food, the available arable lands will continue to shrink and worsen the already low nutrient stocks in them [49]. Incomplete re-accumulation of nutrients in soils due to increasing cropping frequencies and shorter fallow intervals is also anticipated [50].

According to Sanchez [43], averages of 660 kg N, 75 kg P, and 450 kg K ha^{-1} were lost in 37 African countries in the last 30 years alone, from approximately 202 million ha of cultivated land. The annual loss of N, P, and K (NPK) was approximated at 800,000 t for humid central Africa, 600,000 Mt for North Africa, 1.5 Mt for East Africa, and 8 Mt for sub-Saharan Africa (SSA) [49]. Soils in some African countries like Liberia and Sierra Leone and Madagascar are reportedly characterized by low fertility soils while some South African soils are also deficient in K and P [51]. Both regional and national estimates of N balances are also negative for most SSA countries [52]. Similarly, the inability of African soils to supply adequate amounts of N for crop cultivation is well documented, yet N is the most important nutrient for plant growth.

The computation of African N budgets indicates that the soils are extremely deficient in N [53], threatening food production and security [43, 44]. Most of the N deficiencies in African soils result from mining through harvested crops, overgrazing, leaching, erosion, and volatilization which altogether surpass what can be supplied in N fertilizer inputs [54]. According to Ugboh and Ulebsor [55], out of over 3 billion ha of arable land in SSA, only about half a billion is free of physical and chemical constraints while 17% is acidic and affects the availability of nutrients to plants [56]. The P deficits in most African countries are so huge that it would require doubling of the global production of potash fertilizers to sustain the demand [44]. Up to 80% of smallholder maize farmlands in Kenya are extremely deficient in P [57]. Such extreme P deficiencies are probably due to the low soil pH levels and high levels of Fe and aluminum oxides in the soils [58]. Potassium deficiency is similarly common in many African soils even though the most important food and cash crops in Africa such as sugarcane, bananas, and cocoa are extremely K-demanding and withdraw a lot of K from soil [1, 44].

Although micronutrients are needed by plants in very small quantities, their deficiencies can severely limit plant growth and reduce yields [59]. Generally, the existing fertilization programs in African countries are often focused on NPK with little regard to the multiple micronutrient deficiencies [53, 58]. Consequently, the micronutrient deficiencies not only reduce crop productivity, but also cause widespread malnutrition from the production of food with poor nutritional quality [60].

Challenges related to the use of synthetic fertilizers for crop production in Africa

Fertilizers are vital inputs for sufficient food production systems in Africa [61] since they can increase crop productivity multi-fold by up to 50 or 100% [44]. The annual average fertilizer consumption in African countries is estimated to range between 8.3 kg ha^{-1} [62] and 42.5 kg ha^{-1} [63]. Such rates are reportedly the least globally due to the high prices, untimely availability, and inadequate supply of fertilizers [44, 64]. Past and recent

recommendations are that Africa should increase its fertilizer usage to increase crop production and food security [65]. Predictions are that the growth rate of synthetic fertilizer usage in Africa will be the highest globally by the year 2030 [66]. According to forecasts from "The African Green Revolution" as reported by the African Development Bank, fertilizer consumption in Africa is expected to increase from the current usage of just about 8 kg y^{-1} ha^{-1} to reach approximately 50 kg y^{-1} ha^{-1} in the next few years [67]. Nevertheless, the costs and benefits of the continued usage of these artificial fertilizers continue to elicit a lot of debate. Here, we discuss the challenges related to the dependency on these fertilizers for food production in Africa, but it should be noted that some of these challenges are global.

The eutrophication of surface water bodies in SSA has largely been associated with chemical nutrient leaching and runoffs from agricultural fields [18]. These chemicals may also destabilize natural ecosystems and affect the microflora in plant rhizospheres which are extremely important for soil health and fertility [68]. Chemical fertilizers also lead to environmental pollution [69], and their long-term application may also have negative impacts on human health [13] since they can contain heavy metals, inorganic acids, and other pollutants that build up in soils and contaminate agricultural food products [70].

Perhaps the biggest challenge is that fertilizer recommendations in Africa are often generalized by region. Such 'blanket' recommendations do not always produce the desired effects since environmental and management factors differ even over short distances [71]. Furthermore, the fertilizers are generally composed of the major plant-limiting nutrients without consideration of the specific requirements and appropriate products for African soils [44, 45]. Most crops also exhibit low fertilizer use efficiency or respond differently to fertilizer applications in different areas [44]. According to Le Mire et al. [72], only about 10–40% of all applied N in crop fields is effectively used by plants, while approximately 60–90% escapes into the environment from the agricultural fields by nitrate leaching or NH_3 volatilization. Similarly, only about 5–25% of applied P is taken up by plants while the remaining 75–95% persists in soil in insoluble forms [73]. Zinc fertilizers also dissolve very slowly in soils at rates that cannot adequately supply sufficient Zn as required by plants [74].

Synthetic fertilizers contribute to climate change and global warming through the emission of greenhouse gases (GHG) like nitrous oxide (N_2O) from N fertilizers [75]. This continues to raise concerns worldwide especially since the global warming effect per unit weight of N_2O is 300 times that of CO_2 [76]. According to Campbell et al. [77], N fertilizers alone are responsible for more than 30% of agricultural-related N_2O emissions. Moreover, the carbon footprint of N fertilizers is higher than those of P and K by at least one order of magnitude [78]. The production of synthetic N fertilizers also relies heavily on fossil fuels to generate the high temperatures needed to catalyze the artificial dinitrogen (N_2)-fixation process [79]. This results in the depletion of natural resources and global warming [80].

The production of artificial fertilizers is energy-intensive and extremely expensive for African countries [81]. For instance, the amount of energy required to produce 1 kg of N, P, and K fertilizers is 11.2, 1.1, and 1.0 kW h^{-1}, respectively [82]. Although the demand for these fertilizers can be met by imports, the global fertilizer industry is largely dominated by international companies [83], and the cost of acquiring these fertilizers is often prohibitive for many African farmers, especially due to transportation overheads [44, 52, 81]. A very recent survey indicates that the cost of these fertilizers in the African market can be 2–6 times higher than in the United States of America due to transportation costs [18], importation duties, and storage costs alone [44]. In an analysis of the cost of acquiring urea fertilizers for maize production in East Africa and the corresponding prices of the produce by Guo et al. [84], the costs incurred for fertilizers were shown to increase with increasing market distances while the prices of maize and value-cost ratios decreased. Given that the consumption of these fertilizers exceeds their production in Africa, most countries rely on imports to supplement their demands [85], and the high costs involved are often prohibitive [86].

Perhaps the greatest problem associated with the usage of synthetic fertilizers is the looming depletion of natural resources required for their production. Research shows that the costs of synthetic P fertilizers will continue to rise due to the depletion or scarcity of rock phosphates that are used to produce them [66]. These resources are rapidly diminishing and are predicted to be completely exhausted by 2030 [87] or 2033 [88].

The potential roles of rhizobacteria as biofertilizers for soil fertility and crop productivity

Most important plant nutrients such as N, P, K, Zn, and Fe occur as bound organic molecules which are inaccessible to plants [89]. Several rhizobacteria can fix atmospheric N using the nitrogenase enzyme-mediated reduction of N_2 into ammonia (NH_3) [90], which is one of the N forms that can be assimilated by plants [91]. Such rhizobacteria can be exploited as alternative N biofertilizers for crops [92]. *Rhizobium* and *Bradyrhizobium* are the most popular N_2-fixing rhizobacteria [93], and their potential for increasing the yield of legumes has also been demonstrated in Africa [30, 94]. Reports show that

Rhizobium biofertilizers alone can supplement about 50% of the fertilizers needed by crops in the arid and semiarid N-deficient croplands in Zimbabwe, Tanzania, and Kenya [95]. Similarly, about 48–300 kg N ha^{-1} can be fixed by BNF in legume plots [95–97]. Relatively recent estimates suggest that the N_2-fixing *Azolla* in African countries such as Nigeria, South Africa, Ivory Coast, Togo, Senegal, and Kenya can be used to increase soil N content and yield of rice plantations [34]. Cognizant of this, the application of rhizobacteria has an enormous potential in Africa to sustainably maintain soil fertility.

Although N_2-fixation potential is widely investigated among the symbiotic legume–*Rhizobium* interactions, reports show that nitrogenase genes occur in diverse bacterial taxa [98], and non-leguminous plants can also host N_2-fixing bacterial strains [33, 99, 100]. This implies that other plant–microbe interactions can similarly be important. The use of N_2-fixing biofertilizers in Africa is quickly gathering momentum, especially for legume crops and subsequent crops in rotation [53], and is critical for improving soil fertility [101]. These alternative N fertilization mechanisms present a new front in crop production especially due to the high cost of N fertilizers and their apparent negative effects on the ecosystem [102]. However, information on African Rhizobia is still limited despite the potential they hold for improving legume production systems [103].

Apart from N_2-fixation, some rhizobacteria can greatly improve plant nutrient uptake through nutrients solubilization [89, 104]. Evidence suggests that P solubilization and mobilization which are mediated by most rhizobacteria are invaluable at increasing P availability in agricultural soils [105, 106].

Phosphate-solubilizing bacteria (PSB) can mediate the solubilization of inorganic P like tricalcium phosphate and rock phosphate to monobasic ($H_2PO_4^-$) and dibasic (HPO_4^{2-}) ions which are the only P forms that can be used by plants [107]. The solubilization of organic P by phosphatases and phytases by PSB is referred to as mineralization [104] and may constitute up to 5% of total P in soil [108]. Examples of some commonly studied PSB are *Azotobacter*, *Bacillus*, *Beijerinckia*, *Burkholderia*, *Enterobacter*, *Erwinia*, *Flavobacterium*, *Microbacterium*, *Pseudomonas*, *Rhizobium*, and *Serratia* [67]. These rhizobacteria, therefore, present a great potential towards P nutrition for plants.

Potassium solubilizing biofertilizers (KSB) can solubilize K from insoluble K-bearing minerals using organic ligands and enzymes [104]. The ability of KSB to effectively solubilize K depends on soil types, microbial strains, and the form of K compounds [109]. Most KSB species belong to *Pseudomonas*, *Burkholderia*, *Acidothiobacillus*, *Bacillus*, and *Paenibacillus* genera [110]. Different mechanisms implicated in K solubilization such as acidolysis, chelation, exchange reactions, and production of organic acids [104] are extensively reviewed by Sarratt et al. [7]. The application of such organisms can be useful for increasing K availability to plants and should be considered as an attractive strategy for eco-friendly crop production [7].

The supply of micronutrients in agricultural soils is rapidly gaining recognition in African not only due to their important roles in crop productivity, but also the provision of essential micronutrients in food [3]. Zinc-solubilizing biofertilizers (ZSB) have the potential to improve plant Zn utilization [111]. Such bacteria are documented to solubilize insoluble Zn sources such as Zn Oxide (ZnO), Zn carbonates ($ZnCO_3$), and Zn phosphates [$Zn(PO_4)_2$] which are commonly present in soils but unavailable to plants [112]. Some rhizobacteria produce siderophores which have a high affinity for binding Fe and are useful in enhancing plant Fe nutrition [113]. Besides, siderophores can also be involved in the inhibition of plant pathogens and plant bio-protection through Fe starvation and competitive exclusion in Fe-limited soils [104]. Rhizobacterial biofertilizers with this capacity can, therefore, enhance Fe acquisition by plants in Fe-limiting soils by chelating Fe from available complexes [113].

Some beneficial rhizobacteria produce plant growth regulators that influence various plant physiological processes at very low concentrations [104]. These hormones may also be indirectly involved in enhancing the tolerance of plants to abiotic environmental stresses [11]. The two most studied plant growth regulators are indole-3-acetic acid (IAA) and gibberellic acid (GA) [94]. While IAA is important for root elongation, differentiation, and extension [114], GA is known to induce shoot elongation, flowering, stem elongation, and fruit setting [115]. Generally, rhizobacteria-mediated soil fertility and plant health improvement is a net result of multiple processes that may occur simultaneously and all aforementioned attributes make rhizobacteria important candidates for soil fertility and plant health [116]. The use of rhizobacterial biofertilizers could be the ultimate strategy for enhancing and maintaining soil fertility and agricultural sustainability [64].

The commercialization, utilization, and practical application of rhizobacterial biofertilizers in Africa

Although many reports exist on the formulation, commercialization, and application of rhizobacteria all over the world, very few of these report on their commercialization and applications in African countries (Table 2).

A literature search revealed that in Africa, most rhizobacterial biofertilizers are commercialized in South

Table 2 Examples of commercialized biofertilizers in some African countries

Rhizobacteria	Product name	Company	Country	References
Rhizobium	SeedQuestR	Soygro Ltd	S. Africa[a]	[122]
Azospirillum brasilense	Mazospirflo, Azo-N	Soygro Ltd	S. Africa[a]	[123]
Bacillus sp.	LifeForce, Biostart, Waterbac, FirstBase	Microbial solution Ltd	S. Africa[a]	[124, 125]
Bacillus sp., *Enterobacter* spp., *Pseudomonas*, *Rhizobium*	Organo	Microbial solution Ltd	S. Africa[a]	[124]
B. subtilis	B-RUS, Extrasol	Ag-Chem Africa Ltd	S. Africa[a]	[124]
Bradyrhizobium elkanii	Likuiq Semia	Microbial Solution Ltd	S. Africa[a]	[17, 125]
B. japonicum	Histick	BASF South Africa Ltd	S. Africa[a]	[17]
Azospirillum spp.	Azo-N	BioControl Products	S. Africa[a]	[125]
Bacillus sp., *Pseudomonas* sp., *Rhizobium*, *Azotobacter*	Organico	Amka Products	S. Africa[a]	[125]
Bradyrhizobium	Nodumax	IITA[b]	Nigeria	[17]
Bacillus subtilis	Bac up	BioControl Product SA	S. Africa[a]	[105]
Bradyrhizobium japonicum	Soyflo, Vault N Soy	Soygro Ltd	S. Africa[a]	[17]
Azotobacter sp., *Lactobacillus* sp., *Pseudomonas fluorescens*	Soil Vital Q	BioControl Products SA	S. Africa[a]	[126]
Bravibacillus, *Paenibacillus*, *Sporolactobacillus*	SoilFix	BioControl Products SA	S. Africa[a]	[127]
Not revealed	Biofix	MEA Fertilizer Ltd	Kenya	[128]

[a] South Africa

[b] The International Institute of Tropical Agriculture

Africa, with little or no evidence of their commercialization and/or usage in other African countries. Zimbabwe has also invested considerably in biofertilizer usage for soybean production [117]. Adesemoye and Egamberdieva, [118] articulate some of the reported uses and prospects of microbes and PGPR in the African region. These prospects are also reported for Kenya [29], South Africa [119], Nigeria [31], Egypt [120], and Ethiopia [121]. These studies evidence the capacity of rhizobacterial bio formulations in African agriculture for crop productivity.

Advantages of rhizobacterial biofertilizers over conventional fertilizers

Rhizobacterial biofertilizers present numerous advantages over their chemical counterparts from a global perspective. For instance, they offer environmentally friendly, low cost and efficient methods of increasing crop yields [129]. The use of biofertilizers by resource-poor farmers can increase crop yields and reduce the production costs through reduced need for chemical inputs [14]. For Africa, reports show that the cost of rhizobacterial biofertilizers is far much lower than that of synthetic fertilizers needed to deliver the same quantity of nutrients in soil. For instance, the cost of NoduMax biofertilizer in Zimbabwe and other West African countries is only \$5 ha^{-1} compared to about \$100 cost ha^{-1} for urea fertilizers [130]. In this regard, rhizobacterial biofertilizers are an economically viable technology for increasing sustainable crop production in Africa.

Apart from enhancing plant growth and yields by increasing soil fertility and nutrient availability, the use of rhizobacterial biofertilizers also reduces the environmental pollution caused by chemical fertilizers and protects plants against many soil-borne pathogens [131]. These bio-products can also alleviate abiotic stresses in plants [132]. Additionally, they are safer to apply and their activities are more specific and effective in small quantities and they can survive to the next cropping seasons, unlike their artificial counterparts. For instance, the continuous use of these biofertilizers is advanced to enable the beneficial microbial populations to build up in soils, thus constantly maintaining soil fertility [133].

Unlike synthetic fertilizers where up to 50% of the applied fertilizers are lost by leaching and/or fixation in soil, biofertilizers are not prone to leaching and fixation in soil, and have over 90% efficiency [72]. Biofertilizers also undergo natural decomposition, hence, there is no risk of their persistence in the environment and to human health [134]. In this context, rhizobacterial biofertilizers offer a promising, sustainable, and environmentally friendly approach to soil fertility and plant health [134], not only for Africa but the entire world at large.

Constraints of formulation, commercialization, and practical application of rhizobacterial biofertilizers in Africa

Despite the benefits offered by biofertilizers as alternatives to synthetic fertilizers, their potential remains largely untapped in Africa [95, 135]. Here we identify

some of the reasons why their formulation, commercialization, and utilization in Africa are not developing as fast as in other parts of the world. Some of these constraints may, however, be global. Even though a large number of biofertilizers are known and patented for PGP in Africa, these are still not commercially available for utilization due to several reasons. Inadequacy of effective regulations in the region is recognized as the main hindrance to their adoption, thus many of these products have not been registered because of lengthy procedures and the high costs involved [136]. The regulation of formulated products and the formalities involved in the registration process by environmental protection agencies are often very stringent and the costs involved are also prohibitive. This is often unaffordable to industrialists trying to venture into their commercialization, thus, laboratory developments do not always end up as practical applications.

The commercialization of PGPR formulations to boost crop productivity is also greatly limited by the variability and inconsistency of laboratory, greenhouse, and field results [73, 137]. Soil is an unpredictable environment and the intended results are not often accomplished. Climatic variations also have a large impact on the effectiveness of PGPR [138]. Consequently, rhizobacteria which function optimally in laboratories may not produce similar results as field formulations [139]. This calls for innovative solutions.

Considering the distribution of inoculants to remote farms in less developed countries, it is obvious that inoculants cannot always be stored under ideal conditions but may be exposed to high temperatures, humidity, or light [140]. To increase acceptance by farmers, formulations should also be compatible with their conventional practices, be applicable with standard machinery, not associated with additional work steps, and be compatible with traditional techniques such as seed treatments [141]. The commercialization of non-sporulating bacterial inoculants is even more challenging due to their susceptibility to loss of viability during production, storage, and handling. This implies that sensitive bacterial strains, albeit displaying strong plant-beneficial aspects, hardly find their way into the market. Herein lies the challenge for formulation development and the prospect of utilizing highly potent bacterial strains.

Farmers are not always keen on alternative crop fertilization technologies in most developing countries [142]. The main reason for this skepticism relates to their variable efficacy in the field compared to conventional synthetic fertilizers [143]. Additionally, inoculants must overcome the loss of viability during storage and possess long shelf lives. Farmers are seeking products with repeated positive results, ease of handling, and reasonable prices. In this regard, the disadvantages associated with rhizobacterial biofertilizers such as low shelf life, temperature-sensitive storage conditions, and bulkiness are the main reasons why the biofertilizer technology is not yet satisfactory and popular as alternative means of soil fertilization [144]. Some biofertilizers may require storage by refrigeration which is not ideal in Africa where temperatures are often high and power is costly [136]. Furthermore, there is low demand for this technology due to the lack of awareness and understanding [145].

Other challenges relate to the lack of proper distinction between potential biofertilizer agents and opportunistic human pathogens. There still is lack of clarity in distinguishing between biofertilizers and related opportunistic pathogens which promotes the lack of acceptance and challenges in convincing policymakers, environmental protection bodies, and other stakeholders about technology transfer and adoption [146].

Prospects and future perspectives

Although there are great prospects for rhizobacterial biofertilizers for sustainable crop production and food security in Africa, the use of these products in the continent is still limited and grossly inadequate. Their production, distribution, and consumption require a lot of emphasis. Since their commercialization and utilization are greatly dependent on shelf life, there is need to improve this aspect during formulation [137]. The successful application of rhizobacterial biofertilizers in African agriculture will similarly require market stimulation through investments and strategies that can promote their understanding, access, and use [143]. Along with this, well-defined regulations and quality standards will also facilitate their registration [147].

Research to improve the agricultural application of biofertilizers is still in infancy in most SSA countries [148], and is largely derailed by the absence of supportive regulatory and policy frameworks [135, 149]. Proper regulation and quality control of biofertilizers can ensure their conformity to prescribed standards, product safety, and efficacy [150]. In the same context, effective quality control and regulations can ensure that rhizobacterial biofertilizers compete favorably with proven technologies to promote fair trade and market expansion [151].

Nitrogen fixation is widely studied for legume application in Africa. However, the focus should now shift to N_2-fixation in non-leguminous plants which are also important for food security [136]. Similarly, the biodiversity of N_2-fixing rhizobacteria other than Rhizobia should be investigated for applicability [99]. The efficacy of rhizobacterial fertilizers is known to vary widely from one geographical location to another [152], and without extensive research, it will be impossible to develop formulations that can cater for the spatial and temporal

differences across the African continent [153]. The consistency of biofertilizers can greatly be enhanced through the development of compatible cocktails or consortia of beneficial microbes for increased performance. Other approaches that can enhance the performance of rhizobacterial biofertilizers include genetic engineering of effective PGPR strains or the isolation and formulation of multi-trait PGPR strains. Through genetic engineering, the development and introduction of single bacteria with multiple PGP traits into plant rhizospheres can be achieved for increased performance.

Increased awareness of biofertilizers should be targeted through information dissemination to facilitate acceptance by African farmers [149]. Demonstrations and field trials can similarly enhance their acceptance as has been evidenced in Vietnam, for instance [154]. There is increasing evidence that biofertilizers can enhance plants' tolerance to abiotic environmental stresses [12] which is extremely important especially in the wake of climate change and prolonged droughts. However, many challenges remain to be overcome before they can fully and widely be accepted in Africa [72]. The integration of biofertilizers into agricultural practices is pegged on their economic and functional relevance relative to the conventional and contemporary practices [142]. In this regard, further research is needed to comprehend the environmental parameters that affect their efficacy and the selection of multi-trait PGP strains. It is also essential that the formulation of biofertilizers employs cheap raw materials like agricultural or industrial wastes to keep the costs of production low.

With intensive efforts in research and awareness creation, the credibility, acceptance, and utilization of rhizobacterial fertilizers will eventually increase [155]. Globally, the biofertilizer market is predicted to continue expanding due to the growing concerns over GHG emissions, increasing awareness, calls for sustainable agriculture, and rising consumer demands for organically produced foods [156]. With this, their formulation, commercialization, distribution, and utilization in Africa may similarly increase. Ultimately, the much-needed agricultural revolution may be witnessed both in Africa and globally through biofertilizers.

Conclusions

The intensification of agricultural activities is increasing more than ever, and with even greater impacts on the environment. Africa and the rest of the world are faced with a double challenge of producing more food to ensure food security but without further environmental degradation. Rhizobacterial biofertilizers possess multifarious PGP functions that can be exploited and harnessed for eco-friendly and sustainable agricultural systems worldwide. However, the use of these promising technology is still grossly inadequate in Africa, and a lot of emphasis is required on their production, promotion, commercialization, consumption, and distribution. As Africa's population continues to expand, and more and more food must be produced to meet the equally rising food demand, and these biofertilizers can be the critical link to sustainable agriculture and Africa's food security.

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Authors' contributions
BNA, ERM, and BAM participated in the conception of the study, literature review, and drafting of the manuscript. BAM, BNA, JBT were involved in manuscript preparation and substantially revised the final manuscript. JBT reviewed the manuscript during the first and second revisions and participated in the acquisition of funds towards the publication (article processing fees) of the manuscript. ERM and BAM were involved throughout the manuscript preparation and revision. All authors reviewed the final manuscript, approved its submission to *Agriculture & Food Security*, and agree to be personally accountable for questions relating to the accuracy and integrity of the work. All authors read and approved the final manuscript.

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The authors declare that they have no competing interests.

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