SOIL & CROP SCIENCES | RESEARCH ARTICLE

Soil fertility challenges and Biofertiliser as a viable alternative for increasing smallholder farmer crop productivity in sub-Saharan Africa

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Abstract: Low fertility and inefficient management of sub-Saharan African soils have been the major challenges facing productivity among smallholder farmers. Unfortunately, inorganic fertiliser used as major soil nutrient management is unsustainable, causing soil degradation and environmental pollution. Therefore, smallholder farmers may only realise their maximum potential if a more sustainable, low-cost and efficient integrated nutrient management system compatible with their socioeconomic status is practised. Currently, the increasing demand for sustainable agriculture is driving the use of biological fertilisers, which are composed of beneficial microorganisms; ranging from bacteria to blue-green algae and fungi. Biofertilisers such as Rhizobium, Azotobacter, Azospirillum, Pseudomonas and Bacillus have invaluable use in sustainable agriculture owing to their environmentally-friendly, cost-effectiveness and improved productivity benefits. They improve plant nutrition and yield through biological nitrogen fixation, nutrient solubilisation, biocontrol activities and production of plant growth promoting substances. This

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PUBLIC INTEREST STATEMENT

The economic condition of most sub-Saharan Africa countries cannot support the development of commercial agriculture and the use of expensive farm inputs such as inorganic fertilizers, which also damage and render more unproductive, the infertile African soil. This article describes the importance of smallholding and sustainable agriculture as the unlocking strategy in alleviating the food security challenges in sub-Saharan Africa. Importantly, the use of environmentally-friendly and cost-effective biofertilizer was reviewed. Biofertilisers, such as nitrogen-fixing, phosphate solubilizing and plant growth-promoting rhizobacteria play crucial roles in preserving and/or restoring soil nutrient richness. It also protects crops against diseases and pests. Evidently, the use of biofertilizers holds the potential to increase crop productivity. Consequently, it is essential to increase awareness and adoption of biofertilizers among smallholder farmers in sub-Saharan Africa. In addition, government and non-government organisations can help to improve awareness through improved regulatory framework, financial support and quality management strategy development.
review specifically focuses on biofertiliser potential as an efficient integrated nutrient management in increasing smallholder farmer productivity and profitability. It also suggests that increasing biofertiliser awareness and use is an impetus for maintaining and improving ecological stability and alleviating poverty, especially among the rural dwellers. Importantly, efficient biofertiliser strategies by stakeholders will improve adoption of this technology among smallholder farmers.

**Subjects:** Environment & Agriculture; Bioscience; Environmental Studies & Management; Food Science & Technology

**Keywords:** biofertiliser; smallholder farmer; fertility; inorganic fertiliser; sub-Saharan Africa

1. Introduction

The world population is estimated to reach about 9 billion by 2050 and Africa, especially sub-Saharan Africa, has been predicted to contribute to bulk of the increase (Godfray et al., 2010; United Nations, Department of Economic and Social Affairs, Population Division, [UN DESA], 2015). In this context, sub-Saharan Africa needs to increase food production to feed her growing population adequately. This growing population has triggered competition in all forms of resources required for human survival such as land, water, energy and food. Perhaps, the most essential is the food resources that have become insufficient, and consequently, its increased production cannot be compromised (Asenso-Okyere & Jemaneh, 2012). Sadly, many African countries lack political will that can drive agricultural policies, and this has caused low agricultural productivity. The situation is further aggravated by the design of the economy that reflects “dual” economies, where labour productivity is lower in agriculture than in other industries (Rattso & Torvik, 2003). Lack of attention for improving agricultural productivity has degenerated to a more complex situation of food insecurity, which has caused economic, environmental and financial losses in sub-Saharan Africa (Rosegrant, Cline, Li, Sulser, & Valmonte-Santos, 2005; Rukuni, 2002). Therefore, sub-Saharan African nations need to combat food security situation with a scientific, economic and technologically based approach. This is an impetus for increasing agricultural productivity at a rate higher than the population growth rate, which will in turn trigger economic growth and development (Muzari, Gatsi, & Muvhunzi, 2012). Many economic, scientific and technological measures have been designed to support farmers and increase food production in developed countries. However, it is difficult to find evidence of successful implementation of these approaches in many African countries (Abdullah & Samah, 2013). Implementation is usually a problem due to challenges related to financing, technical know-how, policy management, financial misappropriation, as well as climatic and environmental conditions (Poulton, Dorward, & Kydd, 2010).

Considering this fact, the sustainability of commercial agricultural systems in sub-Saharan Africa has been severely hindered leaving the cultivation of land to smallholder farmers, who cultivate small plots of land to sustain their immediate family (Kariuki, 2011; Weis, 2007). The smallholder farmers grow subsistence crops and one or more cash crops, relying almost entirely on family labour. It is apparent that the smallholder farmers have the potential to achieve sustainable food production if supported (Collier & Dercon, 2014). However, most sub-Saharan African nations have little or no economic policy to support them. It is high time that all stakeholders should fashioned new ideas and strategies to encourage the development of smallholders (Dioula, Deret, Morel, Vachat, & Kiaya, 2013; Karuku, 2014). According to Jacobs and Baiphethi (2015), one of the strategies is to consider smallholder farmers as entrepreneurs and significant holders of natural resources (soil, water and plants) with the capability to manage natural assets and contribute to the national and global production grid. In Target 4 of the modern Dutch food security policy, some of the ways to achieve 100% increase in smallholder productivity and income include investing in smallholder agriculture, encouraging and reinvesting in agroecological local production and helping smallholder
farmers to increase soil organic matter. Helping the smallholders to combat weak agricultural production through efficient integrated nutrient management and intervening through scientific and ecological methods were also suggested (Figure 1) (Evert-Jan & Aniek, 2014).

2. Contribution of smallholder farmers to sub-Saharan African economy

Agriculture has been the backbone of African economy and the largest sector on which the economic and social lives of the majority of sub-Saharan African people depend. Interestingly, sub-Saharan African agriculture is primarily driven by smallholder farmers who contribute immensely to the economic growth and development as their roles lead to poverty reduction, rural and social development, as well as food security (Diao, Thurlow, Benin, & Fan, 2012; Vanlauwe et al., 2014). Smallholder farmers exist in a wide range of locations ranging from the deep rural areas to towns (Ahlers, Kohli, & Sood, 2013). It has been estimated that approximately 525 million smallholders exist in the world and support over 2 billion people. About 33 million of these farmers are operating in Africa (International Fund for Agricultural Development [IFAD], 2013; Nagayet, 2005). Usually, smallholders cultivate below 5–10 acres of land and occupy about 10% of the world’s agricultural land while also accounting for over 20% of the total global food supply. In sub-Saharan Africa, smallholder farms account for over 80% of all the farms and contribute up to 90% of agricultural production (Asenso-Okyere & Jemaneh, 2012; Wiggins & Keats, 2013). The synergy between economic development and agriculture suggests that if properly managed, agriculture could improve the gross domestic product (GDP) of many sub-Saharan African countries (Cervantes-Godoy & Dewbre, 2010). For instance, smallholder farmers cultivate major food crops such as millet, cassava, maize, yam, sorghum, rice, sweet potato, vegetables (tomato, carrot, and pepper) and fruits (mango, pawpaw, apples and orange). Cash crops, which include cotton, cashew nuts, tobacco, tea, coffee and cocoa, are also grown. These contribute to food production and export earnings of sub-Saharan African countries. Many examples of such contributions abound in different African nations. Of recent, Ghana, Zimbabwe, Ethiopia and Kenya have become prominent in export trade as a result of smallholder farmers increasing agricultural production, especially in cash crops in the range of 28–65% that significantly improved their export values (Hu & Lee, 2015; Kolavalli & Vigneri, 2011; Koskei, Langat, Koskei, & Oyugi, 2013; Taffesse, Dorosh, & Asrat, 2011). Over 65% of sub-Saharan African labour force is involved in agriculture, generating about 32% of the GDP (Willoughby &
In Rwanda, smallholder agriculture employs about 90% of the total labour force and accounts for about 34% of the GDP. Similarly, two thirds of the entire workforce in Nigeria is employed in agriculture, generating 41% of the GDP. Countries such as Togo, Cote d’Ivoire, Zimbabwe, Mozambique, Zambia, Tanzania, Kenya and Burundi have within 65–90% of the total labour force employed in agriculture (The World Factbook, 2017). Admittedly, harnessing the potentials in smallholder agriculture can lead to social development, sustainable food systems, income equality, decent living conditions and employment opportunities in sub-Saharan Africa, especially among rural dwellers (Dioula et al., 2013; Tschirley & Benfica, 2001).

However, many of the smallholder farmers are faced with challenges that have hindered their productivity and development (Collier & Dercon, 2014; Karuku, 2014). One of such is the inefficient government policies that still encourage the importation of food rather than protecting and improving local production. Also, weak infrastructure, environmental, technical expertise and soil fertility challenges have adversely affected smallholder productivity. It has also been emphasised that there is a need to improve on efficiency, management systems and sustainable practice among smallholders (Francis & van Huís, 2016; Tilman, Cassman, Matson, Naylor, & Polasky, 2002). Therefore, improved agricultural input subsidies, government financial support and adoption of new technology are critical for greater productivity among smallholder farmers (Denning et al., 2009; Muzari et al., 2012). One of such essential technologies in integrated nutrient management harnesses the scientific knowledge of the interaction of plant and microorganisms in the rhizosphere (Figure 1). This approach is used in biotechnology and microbiological science for products such as phytostimulator, biopesticides and biofertilisers for improving crop nutrient efficiency (Bhattacharyya & Jha, 2012; Chandler et al., 2011; Rai, 2006). The use of these products has potential in increasing smallholder farmer productivity and economic values through soil fertility enhancement and plant growth promoting abilities (Ahmed & El-Araby, 2012; Banayo, Cruz, Aguilar, Badayos, & Haefele, 2012; Bhardwaj, Ansari, Sahoo, & Tuteja, 2014).

In this review, we assess the nutrient challenges of African soil and different integrated nutrient management for its augmentation. In particular, the importance of biofertiliser application in sustainable agronomic practices and in improving the output of smallholder farmers will be discussed in this review.

3. Status of soil fertility in sub-Saharan Africa

Of the over three billion ha of arable land in tropical Africa, only about half a billion ha is free of physical and chemical constraints with 13% having low nutrient content and about 17% having high soil pH (Ugboh & Ulebor, 2011). In general, 55% of African land is desert and can only support nomadic grazing (Eswaran, Almaraz, van den Berg, & Reich, 1997). Over the years, overgrazing, deforestation and over cultivation without efficient nutrient management have contributed to soil nutrient loss in sub-Saharan Africa (Henao & Baanante, 2006). According to Sanchez (2002), an average of 660 kg N, 75 kg P and 450 kg K per ha has been lost in the last 30 years from an estimated 202 million ha of cultivated land in 37 African countries. The estimated nutrient loss for NPK yearly was 800,000 t for humid central Africa, 600,000 t for North Africa, 1.5 million tons for East Africa and 8 million tons in sub-Saharan Africa (Henao & Baanante, 2006). In fact, an estimated US$ 4 billion is lost in Africa annually due to nutrient mining and about US$ 42 billion in income and 6 billion ha of valuable land lost annually due to land degradation and reduction in crop productivity (Bationo et al., 2012).

In sub-Saharan Africa, the yield gap has continually increased, deteriorating to less than 25% of potential attainable yield while the per capita food production has also continued to decrease over the past 40 years (Sanchez, 2002). With the increase in demand for food and social and economic development, the available agricultural land will continue to decrease. Unfortunately, arable land is being damaged by anthropogenic and environmental factors, coupled with the fact that many of the cultivated soils are naturally infertile. Yet, the low nutrient stock will have to be cultivated (Henao & Baanante, 2006). This suggests the need for efficient integrated soil fertility management (ISFM) to improve productivity (Rashid et al., 2016; Sommer et al., 2013).
3.1. Limiting nutrients of sub-Saharan African soil

Unfortunately, some African soils lack essential nutrients. In Uganda, Kenya and Tanzania low yield of crops was attributed mainly to poor soil fertility (Keino et al., 2015). For instance, Zn is deficient in most West African soils, especially the lowland areas (Abe, Buri, Issaka, Kiepe, & Wakatsuki, 2010) while plant viable P is unavailable in the iron-rich tropical soils of Africa due to low pH and high level of iron and aluminium oxides (de Valença & Bake, 2016). In fact, 80% of smallholder farmlands for maize cultivation in Kenya are extremely deficient in P (Tittonell, Shepherd, Vanlauwe, & Giller, 2008). Ferrosol soils, which have low capacity to supply essential nutrients to crops, occupy a sizeable part of central Africa-Angola, Zambia, Burundi, Uganda and Cameroon (Deckers, 1993). Low fertile soil mostly characterises West African countries such as Liberia and Sierra Leone and part of Madagascar. The soil lacks Ca, Mg and K, and when acidic, has a high level of free Mn, which is toxic to crops. According to Bühmann, Beukes, and Turner (2006), some South African soils are deficient in K and P, making it unsuitable for cultivation. Similarly, East African soils have up to 90% N, 50% P and 50% K as limiting nutrients (Bekunda, Nkonya, Mugendi, & Msaky, 2002).

The average nutrient required by various crops for an increased yield are presented in Table 1. In sub-Saharan Africa, the total NPK requirement per ha per year range from 24.5 to 176 kg NPK/ha (Henao & Baanante, 1999). It is worthy to note that neither crop quality nor adequate nutrient supply will cause an increase in yield where a third factor is limiting.

3.2. Low fertiliser usage in sub-Saharan Africa

Organic and inorganic fertilisers are the major categories of fertilisers used by smallholder farmers. The inorganic fertilisers are in the form of ammonium nitrate, urea, rock phosphate, potassium chloride and potassium sulphate (Morris, Kelly, Kopicki, & Byerlee, 2007). The majority of the inorganic fertilisers in Africa are imported, and the bulk of it is primarily used in commercial agriculture. According to Food and Agricultural Organisation (FAO) (2015), 2013 fertiliser statistics, South Africa and Nigeria had the highest quantity of N fertiliser imported while Uganda and Cameroon had the lowest amount (Figure 2). However, Africa has lower fertiliser consumption when compared to other regions of the world. In 2002, sub-Saharan Africa had about 8 kg/ha of fertiliser consumption which increased to 12 kg/ha in 2010 and 18 kg/ha in 2013 (Sommer et al., 2013). This is far below that of other regions of the world such as North America, South Asia, and East Asia and Pacific which were estimated at 127.9 kg/ha, 151.8 and 337.0 kg/ha respectively (World Bank Fertiliser Consumption, 2013).

Low fertiliser usage in sub-Saharan Africa is attributed to lack of financial incentives, weak fertiliser policies, high product price and low fertiliser demand and supply (Liverpool-Tasie, Omonona, Sanou, & Ogunleye, 2015; Minde, Jayne, Crawford, Ariga, & Govereh, 2008). Unfortunately, when demand is low, economies of scale among manufacturers is affected and the consequence is the high cost of operation that is reflected in the product price (Yanggen, Kelly, Reardon, & Naseem, 1998). Besides, many African countries do not have favourable business environment; investors are discouraged with exorbitant taxes and fees, unnecessary regulations and high rental costs. These have hindered full commercialisation of fertilisers (Druilhe & Barreiro-Hurlé, 2012). Moreover, inconsistency in foreign exchange rates, demand and supply have made fertiliser profitability unpredictable, which often presents a risk and substantial impediments to fertiliser use among smallholders (Yanggen et al., 1998).

Sub-Saharan Africa fertiliser market lacks basic infrastructure for sustainability, efficient pricing and competition (Sommer et al., 2013). Consequently, the market has been positioned in the hands of monopolists who are in the business only to make profits (Morris et al., 2007). A good fertiliser policy would be one of the strategies to resuscitate the collapsing market and poor price incentives (Minde et al., 2008). Several policies to encourage the use of inorganic fertiliser in sub-Saharan Africa have either not been formulated or where in place, have been ineffective and inconsistent (Sommer et al., 2013). A genuine implementation strategy of effective input subsidy policy would make fertiliser affordable and thus increase usage among the smallholder farmers. The recent introduction of
Table 1. Illustrative information for average nutrients absorbed by crops causing a medium to high crop yield under fertile soil conditions. Soil testing was considered in arriving at the figures and the units are in kg of Nutrient per hectare

| Crops         | Scientific name       | N   | P   | K   | Ca  | Mg  | S   | Fe  | Zn  | Mn  | Cu  | B   | Cl  | Mo  | Si  | Yield tonne/ha |
|---------------|-----------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|----------------|
| Wheat         | Triticum aestivum     | 128 | 46  | 219 | 27  | 19  | 22  | 1.8 | 0.5 | 0.5 | 0.15 | -   | -   | -   | -   | 4.6 tonnes     |
| Rice          | Oryza sativa L.       | 20  | 11  | 30  | 7   | 3   | 3   | 0.15| 0.04| 0.675| 0.18 | 0.15| -   | -   | 0.002| 1.0 tonne      |
| Maize         | Zea mays L.           | 191 | 89  | 235 | 57  | 73  | 21  | 2.13| 0.38| 0.34| 0.11 | 0.24| 0.081| 0.009|-   | 9.5 tonnes      |
| Chickpea      | Cicer arietinum L.     | 91  | 14  | 60  | 39  | 18  | 9   | 1.3 | 0.057| 0.011| 0.017| -   | -   | -   | -   | 1.5 tonnes     |
| Pigeon pea    | Cajanus cajan         | 85  | 18  | 75  | 32  | 25  | 9   | 1.44| 0.038| 0.128| 0.031| -   | -   | -   | -   | 1.2 tonnes     |
| Groundnut     | Arachis hyphogaea     | 58.1| 19.6| 30.1| 20.5| 13.3| 7.9 | 2.284| 0.109| 0.093| 0.036| -   | -   | -   | -   | 1.0 tonne       |
| Soybean       | Glycine max           | 146 | 25  | 53  | 28  | 22  | 5   | 0.476| 0.104| 0.123| 0.041| 0.055| -   | 0.013| -   | 1.0 tonne       |
| Oilsseed rape | Canola                | 32.8| 16.4| 41.8| 42  | 8.7 | 173 | 1.123| 0.1  | 0.095| 0.017| -   | -   | -   | -   | 1.0 tonne       |
| Sunflower     | Helianthus annuus     | 131 | 87  | 385 | 210 | 70  | -   | 0.732| 0.348| 0.412| 0.059| 0.396| -   | -   | -   | 3.5 tonnes of seeds |
| Potatoes      | Solanum tuberosum     | 135 | 21  | 157 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | 34 tonnes of tubers |
| Sweet potato  | Ipomoea batatas       | 51.6| 17.2| 71.0| 6.3 | 6.1 | -   | 0.8 | -   | -   | -   | -   | -   | -   | -   | -   | 14 tonnes biomass |
| Cassava       | Manihot esculenta     | 198 | 70  | 220 | 43  | 47  | 19  | 0.96| 0.66| 1.09 | 0.08 | 0.2 | -   | -   | -   | -   | 37 tonnes tubers |
| Sugar cane    | Saccharum officinarum | 0.8 | 0.3 | 1.32| 0.42| 0.5 | 0.25| 0.031| 0.005| 0.011| 0.002| 0.002| 0.00001| -   | -   | 1.0 tonne       |
| Sugar beet    | Beta vulgaris         | 50  | 20  | 70  | 15  | 15  | 5   | -   | -   | -   | -   | -   | -   | -   | -   | 10 tonnes      |
| Cotton        | Gossypium spp.        | 156 | 36  | 151 | 168 | 40  | 10  | 2.96| 0.116| 0.25 | 0.12 | 0.32 | -   | -   | -   | 2.5 tonnes     |
| Jute          | Corchorus olitorius   | 35.2| 20.3| 63.2| 55.6| 13.3| 0.368| 0.119| 0.139| 0.018| -   | -   | -   | -   | -   | 1.0 tonne dry fibre |
| Bean          | Phaseolus vulgaris    | 155 | 22  | 100 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | 2.4 tonnes     |

Source: Adapted from: Roy et al. (2006)
input support program in some African countries such as Malawi, Kenya, Zambia, Ghana and Nigeria has indicated hope for better fertiliser usage among smallholders (Mwangi, 1996; Ngetich, Shisanya, Mugwe, Mucheru-Muna, & Mugendi, 2012).

Inorganic fertiliser has been suggested to be the short-term solution for increasing crop yield in Africa, and the present fertiliser consumption needs to be increased by 10–18% annually to reach this target (Sommer et al., 2013; Wallace & Knausenberger, 1997). However, the long-term solution would be an approach that is not only based on improving soil nutrient level and plant management; it must also guarantee risk-free incentives for farmers to invest in. Similarly, the approach should lead to sustainable economic growth in smallholder agriculture, as well as ecological sustainability (Sommer et al., 2013). In addition, a very small percentage of sub-Saharan African farmers are also concerned about the adverse environmental impacts of inorganic fertiliser while a larger percentage of farmers consider the benefits and access to other efficient nutrient management system such as organic fertilisers as a good alternative.

3.3. Challenges in the use of organic fertilisers in sub-Saharan Africa

One of the major nutrient management, which has been in use for centuries, is organic fertiliser. It is made from natural materials of either plant or animal matter and includes animal manure (cow dung and poultry manure), household wastes, crop residues and compost (Ngetich et al., 2012). Aside from supplying nutrients, organic fertilisers also improve the physical structure and biochemical activity level of the soil. Another advantage of organic fertiliser is that it releases nutrients into the soil through gradual decomposition of the organic matter. This slow decomposition of organic matter regulates the rate at which organic matter is added and builds up in the soil, thereby balancing soil organic matter content (Morris et al., 2007). However, the challenge of its availability, management and cost have decreased its use among sub-Saharan African smallholder farmers (Svotwa, Baipai, & Jiyane, 2009; Trewavas, 2001). The quantity of available organic manure is inadequate to supply the actual nutrient needs of crops in any African region. Unfortunately, the little produced are wasted due to minimal technical expertise (Abbas, 2016). In South Africa for example, 3 million tons of animal manure produced annually is enough to supply about 13.3% N, 27.6% P and 9.9% K of the soil nutrient need. However, only 25% is used on the soil while the remaining is unexploited due to management constraints (Harris, 2002; Okorogbona & Adebisi, 2012).
addition, the nutrient ratio of organic fertilisers varies for the same product from different sources; this has made soil-plant-nutrient need application ratio very difficult (Rowell & Hadad, 2004).

Majority of sub-Saharan African countries have poor road networks that increase the cost of transportation and coupled with the extensive labour requirement for truck loading, the cost of organic manure has become increasingly high, making it uneconomical for smallholders (Rosen & Bierman, 2005). Furthermore, the pungent smell associated with some of the organic fertilisers (animal manure), has made it difficult to work with. In many instances, cow dung, poultry waste, and compost have been reported as a potential haven for pathogenic microbes (Heinonen-Tanski, Mohaibes, Karinen, & Koivunen, 2006) and heavy metal contaminants (Cd, Hg, Pb, and Ni) in agricultural soil. These cause diseases to plants and animals, hence creating more troubles than its benefits (Moreno-Caselles, Moral, Perez-Murcia, Perez-Espinosa, & Rufete, 2002). Organic fertilisers have relatively low nutrient content and an uncontrollable decomposition rate due to variability in soil moisture, temperature and biodiversity. This fluctuation in nutrient supply has made organic fertiliser uneconomical for growing plants with urgent and substantial nutrient needs (Pang & Letey, 2000).

There is an increasing concern in the inefficient management of organic manure, which causes emissions of gasses (ammonia, nitrous oxide, carbon dioxide and methane) and eutrophication in rivers and lakes (Pacanoski, 2009). During the last decade, Africa has witnessed an increase in the emission of greenhouse gasses (GHG), especially CO₂ and N₂O from the application of manure for crop production (FAO, 2015; Hristov et al., 2013; Tubiello et al., 2013). Emission of GHG remained highest in Eastern Africa followed by Western and Northern Africa while the lowest amount was reported in the Middle and Southern Africa. In 2012, the rate of emission in East Africa increased by 12.8% over the previous year. This may be due to the increased use of organic manure without efficient management (FAO, 2015).

The challenges in the use of inorganic and organic fertilisers have caused the need to intensify more on best management practices and efficient integrated nutrient management in order to achieve a more sustainable and economical way of nutrient management. This will not only benefit the smallholders but will also lead to ecological sustainability (Ngetich et al., 2012). Such efficient nutrient management has emphasised the practice of sustainable agriculture. Sustainable agriculture ensures resource efficiency by integrating biochemical, economic and physical sciences to develop new practices that are safe, cost-effective and environmentally friendly. It also supports an ecosystem that accommodates and provides for the development of all classes of plants and animals (Gupta, Kalia, & Kapoor, 2007; Lichtfouse et al., 2009; Vejan, Abdullah, Khadiran, Ismail, & Nasrulhaq Boyce, 2016).

4. Biofertiliser

An approach that guarantees biosafety, nutrient-rich yield and efficient nutrient utilisation, as well as increased productivity, will support sustainable agriculture (García-Fraile, Menéndez, & Rivas, 2015; Lesueur, Deaker, Herrmann, Bräu, & Jansa, 2016). One of such approaches involves the use of microbial technology in the production of biological fertilisers, generally called biofertiliser (Agsani, 2013; Ahsan, Ali, & Ahmed, 2012).

4.1. What are biofertilisers?

The idea of biofertiliser (“bio” which means life and fertiliser which means substances used to deliver plant nutrients in usable form) was first initiated in 1834 when a French agricultural chemist named J. B. Boussingault reported soil nitrogen build-up through legume cultivation (Bhattacharyya, 2014). Hellriegel and Wilfarth (1886) and, Beijerinck (1888), a Dutch scientist, further established the concept of biological nitrogen fixation. Subsequently, Noble F. and Hiltner L. (who produced the first rhizobium biofertiliser, Nitragin in 1896), and other scientists have made various contributions and discoveries that have led to full biofertiliser commercialization and use in sustainable agriculture (Bhattacharjee & Dey, 2014; Boraste et al., 2009). Many biofertiliser products exist in sub-Saharan Africa with major producers from South Africa and Kenya (Table 2).
Table 2. Microbial composition of commercial biofertilisers and their function

| Biofertiliser       | Active component                                      | Manufacturer                                      | Possible Functions                                                                 | References                                                                 |
|---------------------|-------------------------------------------------------|---------------------------------------------------|-------------------------------------------------------------------------------------|-----------------------------------------------------------------------------|
| MycoApply root dip gel | Arbuscular mycorrhizal fungi                         | Mycorrhizal Applications Inc., Grants, US         | Solubilise Zn, Cu, Fe & P; Improve plant tolerance                                  | Garg and Chandel (2011), Tawaraya, Naito, and Wagatsuma (2006)               |
| Mycoroot superGro   | Arbuscular mycorrhizal fungi                         | Mycoroot (Pty) Ltd, South Africa                  |                                                                                     |                                                                              |
| Mycoroot Super Booster | Arbuscular mycorrhizal fungi                      | Mycorrhizal Applications Inc., Grants, US         |                                                                                     |                                                                              |
| Mycoroot green       | Arbuscular mycorrhizal fungi                         | Mycorrhizal Applications Inc., Grants, US         |                                                                                     |                                                                              |
| MycoApply endo       | Arbuscular mycorrhizal fungi (3 spp.)                | Mycorrhizal Applications Inc., Grants, US         |                                                                                     |                                                                              |
| Twin N              | Azorhizobium sp., Azotarcs sp., Azospirillum sp.     | Mapleton Ltd., UK                                 | Fix N, P solubilisation, gibberel lin, IAA, kinetin & siderophore production         | Rodrigues et al. (2008), Reinhold-Hurek et al. (1993)                        |
| Mazospirflo         | Azospirillum brasiliense                             | Soygro (Pty) Ltd, South Africa                    |                                                                                     |                                                                              |
| Azo- N              | Azospirillum brasiliense, Azospirillum lipoferum     | BioControl Products SA (Pty) Ltd                  |                                                                                     | Ahmad et al. (2005), Verma, Kukreja, Pathak, Sunja, and Narula (2001)         |
| Azo-N Plus          | Azospirillum brasiliense, Azospirillum lipoferum, Azotobacter chroococcum |                                                                 |                                                                                     | Parmar and Sindhu (2013), Mohammadi and Sohrabi (2012), Karadeniz, Topcuoglu, and Inan (2006) |
| Rhizostim           | Azospirillum sp.                                     | Soygro (Pty) Ltd, South Africa                    |                                                                                     |                                                                             |
| Bio-N               | Azotobacter spp.                                     | Nutri-Tech Solution, Australia                    | Fix N, solubilise P, produce IAA, gibberellin, kinetin and siderophore               |                                                                             |
| LifeForce           | Bacillus sp.                                         | Microbial solution (Pty) Ltd, South Africa        | Solubilise P and K, produce gibberellin, auxin and cytokinin                       |                                                                             |
| Firstbase           | Bacillus sp.                                         |                                                                                     |                                                                                     | Parmar and Sindhu (2013), Mohammadi and Sohrabi (2012), Karadeniz, Topcuoglu, and Inan (2006) |
| BioStart            | Bacillus sp.                                         |                                                                                     |                                                                                     |                                                                             |
| Landbac             | Bacillus sp.                                         |                                                                                     |                                                                                     |                                                                             |
| Waterbac            | Bacillus sp.                                         |                                                                                     |                                                                                     |                                                                             |
| Composter           | Bacillus sp.                                         | BioControl Products SA (Pty) Ltd                  |                                                                                     |                                                                             |
| Organo              | Bacillus spp. Enterobacter spp., Pseudomonas, Stenotromonas, Rhizobium | Amka Products (Pty) Ltd, South Africa             | Solubilise P and K, produce gibberellin, auxin and cytokinin, siderophore           | Parmar and Sindhu (2013), Mohammadi and Sohrabi (2012), Karadeniz, Topcuoglu, and Inan (2006) |
| Bac up              | Bacillus subtilis                                    | Biological control product Ltd, South Africa     |                                                                                     |                                                                             |
| B-RUS               | Bacillus subtilis                                    | Ag-Chem Africa (Pty) Ltd, South Africa           |                                                                                     |                                                                             |
| EXTRASOL            | Bacillus subtilis                                    |                                                                                     |                                                                                     |                                                                             |
| Soil Vital Q        | Bacillus subtilis, Bacillus thuringiensis, Azotobacter chroococcum, lactobacillus sp., Pseudomonas florescens | Biological Control Products SA (Pty) Ltd         |                                                                                     |                                                                             |

(Continued)
| Biofertiliser | Active component | Possible Functions | Manufacturer | References |
|-------------|----------------|-------------------|--------------|------------|
| Liquidjama | Bradyrhizobium elkanii | Fix N, solubilise P, produce siderophore | Microbial solution (Pty) Ltd, South Africa | Antoun, Beaufrano, Soussard, Chabot, and Mukhongo (2016) |
| Nodura | Bradyrhizobium elkanii | Fix N, solubilise P, produce siderophore | ITA, Nigeria | Arloum et al. (2015) |
| Nespy | Bradyrhizobium elkanii | Fix N, solubilise P, produce siderophore | Syngro (Pty) Ltd, South Africa | Becker Underwood, USA |
| SoilX | Bradyrhizobium elkanii | Fix N, solubilise P, produce siderophore | Biocor Products SA (Pty) Ltd | |
| Sifin | Bradyrhizobium elkanii | Fix N, solubilise P, produce siderophore | BASF South Africa (Pty) Ltd | |
| N-Soy | Bradyrhizobium elkanii | Fix N, solubilise P, produce siderophore | BASF South Africa (Pty) Ltd | |
| Vault NP | Bradyrhizobium elkanii | Fix N, solubilise P, produce siderophore | BASF South Africa (Pty) Ltd | |
| N-Soy | Bradyrhizobium elkanii | Fix N, solubilise P, produce siderophore | BASF South Africa (Pty) Ltd | |
| SoilFix | Bravibacillus laterosporus, Paenibacillus chitinolyticus, lysinibacillus sphaericus, Sporolactobacillus laevolacticus | Solubilise P | Biocor Products SA (Pty) Ltd | BioControl Products SA (Pty) Ltd |
| Ectovit | Glomus intraradices | Uptake of Zn, Cu, Fe & P, improve salinity tolerance | SymbioLind Ltd., Czech Republic | Antoun, Beauchamp, Goussard, Chabot, and Lalande (1998), Tairo and Ndakidemi (2014) |
| MycoApply | Glomus intraradices | Uptake of Zn, Cu, Fe & P, improve salinity tolerance | Mycorrhizal Applications Inc., Grant, US | Garg and Chandel (2011) |
| Rhizatech | Glomus mosseae, G. etunicatum, G. intraradices | Uptake of Zn, Cu, Fe & P, improve salinity tolerance | Duddu Tech, Narabali, Kenya | Garg and Chandel (2011), Tawaraya et al. (2006) |
| Rhodovit | Mycorrhiza fungi (Not specified,) | Solubilise Zn, Cu, Fe & P, improve water stress tolerance | SymbioLind Ltd., Czech Republic | Wu and Xia (2006) |
| BIOFIX | Not specified | Fix N | MEA Fertiliser Ltd, Kenya | Martinez-Romero (2008) |
| N-Bean | Rhizobium phaseolus | Fix N and produce IAA and siderophore | BioControl Products SA (Pty) Ltd | Berraho, Lesueur, Diem, and Sasson (1997), Ghosh, Kumar De, and Maiti (2015) |
| Legume fix | Nitrosaciflua (Lucerne) | Fix N and produce IAA and siderophore | Biocor Products SA (Pty) Ltd | Legume Tech (UK) |
| Nitrasac | Nitrosochromum mellorum | Fix N | Microbial solution (Pty) Ltd, South Africa | Villegas et al. (2006) |

Source: Adapted from Herrmann, Atieno, Brau, and Leuwer (2015); Mukhongo et al. (2016).
Biofertilisers are substances containing live microorganisms, which when applied to plant surfaces, seeds, roots or soil; colonize the rhizosphere or the interior of plants and help to improve soil fertility while also stimulating plant growth by increasing the availability of plant nutrients and growth substances to the host crops (Figueiredo, Seldin, de Araujo, & Mariano, 2011; Suyal, Soni, Sai, & Goel, 2016; Vessey, 2003). The term biofertiliser is sometimes used interchangeably with “microbial inoculant, bioinoculant, inoculum or bioformulation” (Gupta et al., 2007; Hassen, Bopape, & Sanger, 2016; Suyal et al., 2016) or effective microorganisms (Megali, Schlau, & Rasmann, 2015). Biofertilisers comprised of bacteria, blue-green algae (BGA) and fungi (separately or in combination), and can be made in solid, powdered, granular carrier materials or liquids. The carrier materials sustain the microbial inoculants and allow the product to be stored for longer period (Boraste et al., 2009; Rashid et al., 2016). The beneficial microbes may be rhizospheric; colonising the surface or intercellular spaces of the plant roots, or endophytic; where they colonise the tissue or apoplastic space within the host plants (Gupta, Panwar, Akhtar, & Jha, 2012; Malusá, Pinzari, & Canfora, 2016).

Biofertilisers should not be misunderstood for organic fertilisers such as compost, animal manure and plant manure or extracts (Carvajal-Muñoz & Carmona-Garcia, 2012; Malusá, Sas-Paszt, & Ciesielska, 2012; Vessey, 2003). However, whether the beneficial microbes improve crop accessibility to nutrients (Egamberdiyeva, 2007; Mujawar, 2014) or replenish soil nutrients (Shridhar, 2012; Thamer, Schädler, Bonte, & Ballhorn, 2011), if the overall nutrient condition of crop and soil has been improved, such substances containing the beneficial microorganisms are considered as biofertilisers (Vessey, 2003).

4.2. Types of biofertiliser
Biofertilisers are classified based on their microbial composition and functional characteristics established during their interactions with plants in the rhizosphere (Lucy, Reed, & Glick, 2004; Malusá et al., 2012). It has been suggested that the classification of biofertiliser be based on the ability to perform at least two major functions (Gupta et al., 2012; Lesueur et al., 2016). Major classifications include N-fixing, phosphate and micronutrient solubilising and plant growth promoting rhizobacteria biofertilisers (Figure 3).

4.2.1. Nitrogen-fixing biofertilisers
Nitrogen is abundant in the atmosphere, making up about 80% (approx. 10^{15} tonnes) of the atmospheric gasses. It is so stable that it is inaccessible by living organisms except when converted to compounds that can be assimilated by plants (Bernhard, 2010; Thamer et al., 2011). The inert N_2 is recycled through different transformations involving various soil microorganisms (Figure 4). In N deficient soil, diazotrophs fix N gas from abiotic to biotic environments through biological nitrogen fixation (BNF) process using the enzyme called nitrogenase. This oxygen-sensitive enzyme complex, which is composed of dinitrogenase reductase and dinitrogenase, is responsible for reducing the atmospheric N_2 into reactive forms such as ammonia (Dighe et al., 2010). Diazotrophs are usually in symbiotic or non-symbiotic relationships with the host plants. The symbiotic relationship is common in *Rhizobium*, *Bradyrhizobium* and *Sinorhizobium*, which inhabit the root nodules of most leguminous crops such as groundnut, soybean and cowpea (Martínez-Romero, 2009; Oldroyd, Murray, Poole, & Downie, 2011). The non-symbiotic free-living N-fixers include *Azotobacter*, *Beijerinckia* and *Clostridium* while associative N-fixers include *Azospirillum* and *Entorhobacter* species (Shridhar, 2012; Wagner, 2012). Other bacteria that can fix N and as well produce plant growth promoting substances are *Azorarcus* sp., *Klebsiella pneumonia*, *Rhizobium* sp., and *Ponntoa agglomerans* (Riggs, Chelius, Iniguez, Kaeppler, & Triplett, 2001; Yanni et al., 2001).

Another important N biofertiliser of considerable economic importance to smallholder farmers is cyanobacteria (Benkeblia & Francis, 2014). It is made up of Anabaena (or Nostoc) in association with Azolla and used mainly for rice cultivation. Azolla is a heterosporous water fern and in association with Anabaena, can fix N in the range of 40–100 kg/ha when used for wet-rice cultivation (Paudel, Pradhan, Pant, & Prasad, 2012; Wagner, 2012).
Figure 3. Types of biofertilisers based on functional attributes.

Source: Adapted from Tamil Nadu Agricultural University, Agritech Portal (2014).

Figure 4. Nitrogen cycle.

Source: Adapted from: The University of Waikato (http://www.waikato.ac.nz/__data/assets/image/0013/151033/NitrogenCycle.jpg).
4.2.2. Solubilising and mobilising biofertiliser

Soil P and K couple with elements like iron, aluminium and calcium to form stable compounds, which are not readily available for plant use (Mohammadi, 2012; Richardson, Barea, McNeill, & Prigent-Combaret, 2009). This has resulted in limiting nutrients, especially for P. Therefore, solubilisation and mobilisation, which are exhibited by the phosphate-solubilising and mobilising microbes are important aspects of P cycle (Mohammadi, 2012; Sundara, Natarajan, & Hari, 2002).

P-solubilising microorganisms (PSM) comprise mainly bacteria and fungi (Mohammadi, 2012; Sundara et al., 2002). According to Pindi and Satyanarayana (2012), most efficient P solubilisers include the following genera: Bacillus, Pseudomonas, Aspergillus, and Penicillium. They mineralize organic P through enzymatic hydrolysis by secreting phosphatase enzymes (Figure 5). This can save up to 30–50 kg/ha of P₂O₅ fertiliser (Richardson et al., 2009; Singh, Srivastava, Sharma, & Sharma, 2014). PSM also secrete organic acids such as oxalic, citric, gluconic and lactic acids to solubilise soil inorganic P e.g. tricalcium phosphate and rock phosphate to monobasic (H₂PO₄⁻) and dibasic (HPO₄²⁻) ions (Adeleke, Nwangburuka, & Oboirien, 2017; Mohammadi, 2012; Rai, 2006). Their efficiency is dependent on the soil carbon and nitrogen source, as well as the soil buffering ability. Azotobacter chroococcum, Bacillus circulans, Pseudomonas chlororaphis, P. putida and Rhizobium leguminosarum have been used as phosphate solubilising biofertilisers (PSB) on various crops like potato, tomato, wheat and pulse (Malusà & Ciesielska, 2014).

Another technique used by most plants to arrest P limiting situation is the plant-fungi symbiotic relationship (ectomycorrhiza and endomycorrhiza). Plants develop increased root growth by the extension of the existing root systems through mycorrhizal association or hormonal stimulation (phytostimulation) effect (Richardson & Simpson, 2011). Here, fungi hyphae are able to mobilise and make P available to the plants (Mujawar, 2014; Ramasamy et al., 2011). According to Adeleke, Cloete, Bertrand, and Khosa (2010), ectomycorrhizal fungi such as Pisolithus tinctorius, Paxillus involutus, Phialocephala fortinii and Suillus tomentosus have potential to mobilise substantial amount of P and K from different minerals under different conditions. The arbuscular mycorrhizal fungi (AMF) increase its exploitation of soil nutrients through specialised structures known as vesicles and arbuscules (Leigh, Hodge, & Fitter, 2009). In addition, P is mobilised through the changes in sorption balance of soil solution caused by microbial biomass turnover in the rhizosphere. This leads to an increased mobility and uptake of organic P or orthophosphate ions (Adeleke et al., 2017). Microbial

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**Figure 5.** Soil microbes mediate phosphorus (P) availability for plant growth through solubilisation of inorganic P and mineralisation of organic P.

Source: Adapted from Richardson and Simpson (2011).
metabolic processes can also directly solubilise and mineralise inorganic and organic P through the efflux of protons, organic ions and siderophore production (Figure 5) (Richardson & Simpson, 2011).

Potassium Solubilising Biofertiliser (KSB) solubilises K from compounds such as mica, muscovite, illite, orthoclase and biotite by producing organic ligands, hydroxyl anions, enzymes and biofilms (Bahadur, Meena, & Kumar, 2014; Shanware, Kalkar, & Trivedi, 2014). The ability to solubilise potassium effectively depends on the soil type and microbial strain, as well as the form of K compounds (Sangeeth, Bhai, & Srinivasan, 2013). KSB include *Pseudomonas*, *Burkholderia*, *Acidithiobacillus*, *Bacillus*, and *Paenibacillus* genera (Ahmed & El-Araby, 2012; Liu et al., 2010; Yasin, Munir, & Faisal, 2016). This biofertiliser is important in areas experiencing high rate of potassium loss found in West Africa (Nigeria and Guinea Bissau) and East Africa (Burundi, Malawi, Kenya, Swaziland, Uganda and Rwanda) (Bationo et al., 2012).

4.2.3. Micronutrient biofertiliser
Micronutrients (Zn, Fe, Mn, Cu and Mo) form insoluble complexes in the soil, which are not readily accessible by crops. According to Mahdi et al. (2010), 75% of applied Zn forms insoluble complexes while plants use only about 1–4% of total available Zn in the soil. However, *Rhizobium*, *Bradyrhizobium*, *Pseudomonas*, *Thiobacillus*, *Saccharomyces*, *Penicillum* and *Bacillus* can improve the uptake and availability of micronutrients in the soil (Adeleke, Cloete, & Khasa, 2010; Ahsan et al., 2012; Esitken et al., 2010). In Fe immobilised soils, for example, bacteria siderophores solubilise and chelate Fe into complexes that can be easily absorbed by the plant roots (Mathew, Eberl, & Carlier, 2014; Radzki et al., 2013). *Trichoderma harzianum*, a fungal specie, can solubilise minerals such as metallic Zn and MnO₂ by chelating and reducing mechanisms (Altomare, Norvell, Björkman, & Harman, 1999). Vesicular Arbuscular Mycorrhiza (VAM) are also able to solubilise Zn, Fe, Mn, and Cu in agricultural soil (Martino, Perotto, Parsons, & Gadd, 2003; Pal, Singh, Farooqui, & Rakshit, 2015).

4.2.4. Plant growth promoting rhizobacteria (PGPR)
This is made up of heterogeneous group of beneficial rhizospheric microbes that can stimulate plant growth and development through one or more mechanisms (Roy, Finck, Blair, & Tandon, 2006). The growth promoting substances may increase plant growth directly or indirectly (Hayat, Ali, Amara, Khalid, & Ahmed, 2010; Soltani et al., 2010). They may indirectly control diseases by producing antimicrobial metabolites such as hydrogen cyanide, phenazines and tensin. PGPR interaction with the plant roots may also elicit plant defense against bacterial, fungal and viral pathogens. This is termed induced systemic resistance (Ahemad & Kibret, 2014; Vacheron et al., 2013). This group has multiple modes of action, which may include N-fixation, nutrient solubilisation and phytostimulation (Table 2) (Beneduzi, Ambrosini, & Passaglia, 2012; Bhattacharyya & Jha, 2012; Gururani et al., 2013; Hassan et al., 2016). PGPR include the genera *Azotobacter*, *Bacillus*, *Azospirillum*, *Burkholderia*, *Erwinia*, *Flavobacterium*, *Pseudomonas* and *Serratia*. Others include the *Mesorhizobium*, *Bradyrhizobium*, *Rhizobium*, and *Azorhizobium*, which are intracellular bacteria (Ahemad & Kibret, 2014; Bhattacharyya & Jha, 2012).

5. Contribution of biofertiliser in smallholder agriculture
The profitability benefit of biofertiliser can be deduced from biofertiliser benefit-cost analysis, which is based on the ratio of the obtainable value of benefit compared to the actual cost of the inoculum at a particular time. An enterprise will be profitable when the benefit to cost ratio exceeds 1 after discounting the gross cost and benefit. According to Mulongoy, Gianinazzi, Roger, and Dommergues (1992), the benefits from legume inoculants is usually based on the N fixed. For instance, the benefit-cost ratio for white clover was found to be 416, fixing 200 kg of N/ha while that of soybean was 17, fixing 100 kg of N/ha from inoculation when the cost of fixed N is considered as 50 cents per kg (Mulongoy et al., 1992). Some significant contributions of biofertiliser in smallholder agriculture are discussed below.
5.1. Increased yield and nutrient availability

Legume yield among smallholder farmers can be increased by using N-fixing biofertilisers such as *Rhizobium* and *Bradyrhizobium* (Hassen et al., 2016). For example, inoculation of soybean causes an increase in yield, improves soil organic matter while also fixing about 80% of soybean N need (Chianu, Nkonya, Mairura, Chianu, & Akinnifesi, 2010; Giller, Murwira, Dhliwayo, Mafongoya, & Mpepereki, 2011). Rose et al. (2014) reported that biofertiliser could replace about 52% of N-fertiliser and cause an increase in rice yield over the control. *Rhizobium* biofertiliser alone can supplement about 50% of the fertiliser need of crops in most arid and semiarid marginal lands of Zimbabwe, Tanzania, and Kenya, which are deficient in N (Chianu et al., 2010; Mugabe, 1994; Nkonya et al., 2008). Ronner et al. (2016) also found that crop yield increased by 447 kg/ha over the control due to inoculation in northern Nigeria. Azolla soaked in 50 ppm of superphosphate when inoculated in a paddy field fixed about 40–55 kg N/ha, 15–20 kg P/ha and 20–25 kg K/ha in a month per 1 kg of Azolla applied, bringing the yield of flooded paddy to about 10–20% over the control (Wagner, 2012). Different *Azolla* species—*A. pinnata*, *A. nilotica*, *A. filiculoides* and *A. caroliniana* found in African countries such as Nigeria, South Africa, Ivory Coast, Togo, Senegal and Kenya can be used on rice plantation to increase yield and soil N content (Diniz, Teixeira, & Carrapico, 2015).

The use of biofertilisers leads to separate accumulation of N, P and K in the soil, thereby maintaining soil nutrient balance (Adesemoye, Torbert, & Kloepper, 2008; Egamberdieva, 2007). Sundara et al. (2002) observed an increased sugarcane and sugar yield when the plant was inoculated with PSB, *Bacillus magisterium* var. *Phosphaticum*. Similarly, the use of biofertilisers with cheap rock phosphate increased crop yield by 74% over the control, while peanut and sunflower plants inoculated with PSB recorded a significant yield over the control (Ahmed & El-Araby, 2012).

KSB such as *Pseudomonas* and *Burkholderia* has been reported to cause a decrease in plant growth and yield in wheat and pepper (Sangeeth et al., 2012; Shanware et al., 2014), while *Bacillus*, a KSB and PSB caused a yield increase in cucumber and pepper (Garcia-Fraile et al., 2015). Han and Lee (2005) reported an increase in NPK uptake, photosynthesis and yield of eggplant cultivated on P and K limited soils when KSB and PSB were co-inoculated with direct application of rock P and K. *Bradyrhizobium japonicum* inoculation causes an increase in yield and micronutrient uptake in soybean plant (Tairo & Ndakidemi, 2014). According to Bambara and Ndakidemi (2010), the concentrations of Fe, Cu and Zn in the rhizosphere of *Phaseolus Vulgaris* when inoculated with *Rhizobium* increased by 28, 20 and 67% respectively compared to the control. A similar result was obtained in the case of *Originum vulgare* L. where AMF inoculum induced a significant increase in shoot nutrient content (Mg, Fe, Cu, Mn, N, P, & K) (Khalil & El-Noemani, 2015). Guimarães, Neves, Bonfim-Silva, and Campos (2016) cultivated cowpea plants with four *Rhizobium* strains. The result showed that biofertiliser treatment gave a better yield with an increase in soil nutrient quantity such as N and P over the control. This could be due to the role of biofertiliser in improving soil nutrient content and nutrient uptake of the plant (Guimarães et al., 2016).

5.2. Plant growth promoting rhizobacteria as biofertiliser

Various species of beneficial microorganisms grow in the rhizosphere, participating in nutrient cycling and the production of plant growth promoting substances. Hence, are called plant growth promoting rhizobacteria (PGPR) (Ahemad & Kibret, 2014; Beneduzi et al., 2012; Bhattacharyya & Jha, 2012). Some of the PGPR are considered biofertiliser due to their biofertilization potential (Vessey, 2003). Similarly, bacteria such *Bacillus* and *Paenibacillus* have been found to cause an increase in plant-mycorrhizal colonisation, therefore, are referred to as mycorrhizal helper bacteria (MHB) (Adeleke & Dames, 2014). Some biofertilizing-PGPRs produce phytohormones such as indole acetic acid, gibberellins and cytokinins that cause an increase in plant foliage, root elongation, fruit yield and plant-microbe symbiosis (Hassen et al., 2016; Vacheron et al., 2013). Indole acetic acid (IAA) affects plant root architecture; leading to increased root surface area and root tip elongation (Ahmad, Ahmad, & Khan, 2005; Lu et al., 2015) while gibberellic acid induces increased flowering, stem and internode elongation, fruit setting and growth in plants (Kumar, Biswas, Singh, & Lal, 2014;
Zalewska & Antkowiak, 2013). Therefore, beneficial microbes that promote root development have an immense impact on nutrient uptake ability (Vessey, 2003).

In a trial study by Swain, Naskar, and Ray (2007), Dioscorea rotundata inoculated with Bacillus subtilis, an IAA producing strain, had an increased tuber length and number of sprouts compared to uninoculated plants. Maize and rice cultivated with giberellic acid producing PGPRs had a significant increase in growth and yield (Vacheron et al., 2013). Similarly, root hair, surface area and total biomass increase in tomato plants inoculated with Azospirillum sp. producing IAA-mediated ethylene (Ribaudo et al., 2006). Siderophore is another important plant growth promoting substances. According to Egamberdiyeva (2007), siderophore produced by PGPR stimulates the growth of maize under iron-poor soil. More so, increase in yield of many crops (maize, rice, wheat, soybean, and bean) was reported in the work of Pérez-Montaño et al. (2014) when the crops were inoculated with biofertilisers.

5.3. Low cost of nutrient supply

Biological nitrogen fixation (BNF), a natural process of fixing N in the soil, has been put at different values. Galloway (1998) estimated the annual BNF to be about 90–130 Tg N year⁻¹ while Boyer et al. (2004) reported it to be roughly 107 Tg N year⁻¹. Bhattacharyya (2014) estimated BNF on land to be 140 Tg N year⁻¹. Interestingly, the energy bill of this process is fully paid by nature. Similarly, it has been reported that about 48–300 kg N/ha can be fixed by BNF on a grain legume plot in a season (Ngetich et al., 2012). This low-cost method of supplying nutrient to the soil has made the use of biofertiliser economical for smallholder farmers. In addition, the quantity of biofertiliser required to achieve the same amount of nutrients supplied by inorganic fertiliser is relatively lower. The cost of peat-based rhizobium inoculants is as low as US$ 0.24 ha⁻¹ for white clover and US$ 6.46 ha⁻¹ for Vicia faba. Rhizobium biofertiliser sufficient for 1 ha cost US$ 5.20 in Zimbabwe and US$ 4.50 in Rwanda (Mulongoy et al., 1992). These prices are far below the cost of mineral fertiliser needed for the same quantity of nutrients supplied. In West Africa, NoduMax, like other biofertilisers, is economically profitable costing only $5 per ha in application as opposed to $100 per ha cost of urea fertiliser needed to supply the same quantity of nutrients (N2Africa, 2015).

The production process of mineral fertiliser is faced with energy challenges, which makes it more expensive, compared to biofertilisers. In fact, about 60% of smallholder farmers in Africa cannot afford the high priced inorganic fertiliser (Chianu et al., 2010). The energy requirement for producing 1 kg of inorganic fertiliser has been estimated to be 80 MJ (11.2 kWh) for N, 12 MJ (1.1 kWh) for P and 8 MJ (1 kWh) for K. This is rather uneconomical and unsustainable, considering the challenges of power generation in many of the sub-Saharan African countries (Bhattacharyya, 2014). In addition, phosphorus reserves are likely to be exhausted in the next few decades (Rosemarin, De Bruijne, & Caldwell, 2009; Sutton et al., 2013). Although this has been discredited, as enough P deposits that can last for the next 400 years have been reported (Cho, 2013; Van Kauwenbergh, Stewart, & Mikkelsen, 2013). However, the major issue is that P is lost in the soil when applied. Crops take up an estimated 20% of P while about 40% is lost during processing and mining, and over 50% is wasted in the agricultural soil (Cho, 2013; Schröder, Cordell, Smit, & Rosemarin, 2010). This, if not effectively managed, will cause an increase in the cost of P products (Sutton et al., 2013).

5.4. Other beneficial properties of biofertilisers

5.4.1. Prevention of plant pests and diseases

Some biofertilisers prevent plant diseases by directly inhibiting pathogens through their metabolic activities or indirect competition (García-Fraile et al., 2015; Rudrappa, Czymmek, Pare, & Bais, 2008). The nodule-forming symbiotic association of legumes with Rhizobium has been established to enhance the synthesis of cyanogenic defence substances, which increases plant resistance to herbivore attack (Mazid, Khan, & Mohammad, 2011; Megali et al., 2015; Thamer et al., 2011). Bacterial and fungal attacks are major factors affecting smallholder productivity, especially in sub-Saharan Africa (Strange & Scott, 2005). Therefore, using biofertilisers producing antifungal and antibacterial...
substances such as chitinases and β-glucanases assists in suppressing diseases attack. *Fusarium* wilt of pigeon pea and soft rot of potato caused by *Fusarium udum* Butler and *Erwinia Carotovora* can be controlled by *Pseudomonas fluorescens* and *sinorhizobium*, both producing chitinase and β-glucanases (Guo, Rasool, & Li, 2013; Kumar, Bajpai, Dubey, Maheshwari, & Kang, 2010). *Bacillus* sp. inhibit important pathogens such as *Rhizoctonia solani* in tomatoes and *Phytophthora capsici* in pepper (Akgül & Mirik, 2008; Arora, Khare, Oh, Kang, & Maheshwari, 2008; Solanki et al., 2012).

Some biofertilisers produce siderophore, a Fe-chelating agent, which limits the available Fe in the soil. This indirect competition for nutrients suppresses the pathogen’s ability to cause diseases (Arora, Khare, & Maheshwari, 2010; Solanki et al., 2014). Siderophores produced by *Pseudomonas* and *Bacillus* attack the popular fusarium wilt of potato and maize, thereby increasing potato and maize yield of smallholder farmers (Beneduzi et al., 2012). Similarly, *Pseudomonas aeruginosa* is used against bacterial blight caused by *Xanthomonas oryzae pv. oryza*, and *Rhizoctonia solani*, which are major rice diseases in West Africa (Mali, Senegal, Nigeria, Niger etc.) (Nga et al., 2013).

### 5.4.2. Volatile organic compounds (VOCs)

VOCs are part of the normal metabolic activities of microorganisms and play important roles in stimulating plant growth and as signals in plant-microbe interactions (Insam & Seewald, 2010). Though plants produce VOCs, soil microbial synthesised VOCs, which include acetone, 3-butanediol, terpenes, jasmonates and isoprene are good source of natural compounds that can increase crop productivity. VOCs from rhizobacteria cause an increase in the biosynthesis of essential oil and growth parameters in *Mentha piperita* (Peppermint) (Santoro, Zygadlo, Giordano, & Banchio, 2011).

### 5.4.3. Bioremediation

Rhizobacteria in consortium with AMF are now being employed to increase the solubility and clean-up of heavy metals in contaminated agricultural soil, thereby increasing the available arable land for smallholder farmers (Khan, 2014; Singh, Pandey, & Singh, 2011). El-Kabbany (1998) evaluated the economic importance of beneficial microbes in bioremediation of major pesticides (organophosphate, carbamate, and chlorinated organic compounds) in Egypt. It was reported that PGPRs are potential remediation agent for pesticide-contaminated soil. Similarly, Bello-Akinosho, Adeleke, Swanevelder, and Thantsha (2015) in a laboratory study on degradation of Polycyclic Aromatic Hydrocarbon (PAH) isolated *Pseudomonas* sp. strain 10–1B from artificially polluted soil. This strain is useful in bioremediation and biofertilization due to its ability to degrade PAH compounds and improve soil fertility.

Bioremediation technology has been successfully used in many sub-Saharan African countries. For instance, in crude oil contaminated soil of Ogoni land, in Delta state, Nigeria (Zabbey, Sam, & Onyebuchi, 2017) and in creosote-contaminated soil in South Africa (Atagana, 2004). The technology has also been proposed for the clean-up of the pesticide-contaminated soil in Tanzania (Kishimba et al., 2004). Biofertilisers such as cyanobacteria (J. Singh, Kumar, Rai, & Singh, 2016), *Azospirillum* and *Burkholderia* (Mathew et al., 2014), *Pseudomonas, Bacillus* (Adeleke, Cloete, & Khasa, 2012), *Rhizobium and Enterobacter* (Jain & Khichi, 2014) and *Aspergillus and Penicillium* (Abdel-Aziz, 2004) have also been found useful in bioremediation. The dual functions of these beneficial organisms in bioremediation and soil fertilisation have made them a significant ISFM technology (Bello-Akinosho et al., 2016).

### 5.4.4. Water stress resistance

Many African countries, especially the arid and semi-arid areas, have long drought season and this has caused limitation to plant growth (Falkenmark & Rockström, 2008). In this situation, biofertilisers, which enhance plant water-stress tolerance, is of immeasurable importance (Dimkpa, Weinand, & Asch, 2009; Hassen et al., 2016). The production of auxins, cytokinins, gibberellins and 1-aminocyclopropane-1-carboxylate (ACC) deaminase by some biofertilisers has been reported to improve plant water stress tolerance (Khalil & El-Noemani, 2015; Mayak, Tirosh, & Glick, 2004). Gururani et al. (2013) observed an increase in water stress tolerance of potato plants when inoculated with *Bacillus*
sp. that enhanced ACC deaminase activity, phosphate solubilisation, and siderophore production. Similarly, Aroca and Ruiz-Lozano (2009) and Mayak et al. (2004) reported an increase in water resistance of pepper and tomato plant grown on water deficient soil when inoculated with PGPRs. Essentially, under water-stressed conditions, AMF with their hyphae make available substantial amounts of ammonium and nitrate to the host plant (Wu & Xia, 2006). Therefore, biofertiliser has a great economic importance in improving the productivity of smallholder farmers in seasons of drought, especially in drought-prone sub-Saharan African countries such as South Africa, Kenya, Uganda, Ethiopia and Somalia (Kaushal & Wani, 2016).

6. Conclusion
This review highlighted soil fertility challenges and the huge economic importance associated with the use of biofertilisers in improving crop productivity among smallholder farmers in sub-Saharan Africa. From the different literature reviewed, the use of biofertiliser has been established to increase plant growth and yield, as well as improve soil quality. In addition, biofertiliser could also protect the natural environment and soil biodiversity. Certain biofertilisers produce metabolites that protect plants from pest and disease attack. The environmentally friendly property of biofertiliser, as well as its great potential in sustainable agriculture, have accentuated the need to reduce, if not replace, the use of agrochemical inputs with biofertilisers.

The resource-poor farmers who cultivate on nutrient-poor sub-Saharan African soil need a cost-effective and efficient technology to increase yield and profitability. It is uninteresting that the intensification in the use of chemical fertilisers has mainly focused on productivity with little or no concern about the increasing cost and ecological damage. This review revealed that the cost-benefit ratio in using biofertiliser is higher than any other nutrient management practice especially the inorganic fertilisers. It is, therefore, important to introduce smallholder farmers to biofertiliser technology through extension education and agronomic training such as on-site training. The production process of biofertiliser technology is simple and requires less capital, technology and workforce, unlike inorganic fertiliser production that requires huge energy, high capital base and a significant amount of manpower. Substituting inorganic fertilisers with biofertiliser will not only increase productivity and profitability of smallholder farmers, it will ultimately build a robust agricultural economy in Africa devoid of any known environmental challenges.

In conclusion, there is an urgent need to improve the awareness and use of biofertiliser among sub-Saharan smallholder farmers. Research studies on efficient microbial strain production, optimisation of product design and biofertiliser business management as well as extension programs and product-marketing strategies are essential to achieving these objectives. It is pertinent to emphasise that sub-Saharan African government have crucial roles to play in ensuring biofertiliser technology is fully adopted as the first choice in our quest to address soil fertility challenges. Their support can be in the form of subsidy or materials to farmers. Apart from training the smallholder farmers, the accessibility of the product is also essential.

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Competing Interests
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