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Microbial Contributions in Alleviating Decline in Soil Fertility

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Author's contribution

The only author KOWN performed research work, wrote all drafts and approved the final draft of the manuscript.

Review Article

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ABSTRACT

The continued decline in soil fertility, high fertilizer costs and the need to implement environmental friendly agricultural systems are some of the world's major strategic concerns. Soil microorganisms are part of the soil ecosystem and are reported to contribute in soil fertility improvement. This paper is aimed at highlighting their contributions in alleviating soil fertility decline. The *Rhizobium*/legume symbiosis, a well known association contributes substantial amounts of biologically fixed nitrogen to cropping systems and significant benefits on yields of crops that follow in rotation. Soil microorganisms such as bacteria and fungi contribute to plant phosphorus nutrition through solubilization of sparingly soluble Al, Fe and Ca phosphates, and mineralization of phosphorus from organic substances. Solubilization is mainly achieved through production of organic acids, chelation and ligand exchange, and other pH lowering mechanisms whereas mineralization is achieved through production of enzymes such as phytases and phosphatases. Mycorrhizal associations are reported to contribute to plant phosphorus nutrition through increasing root surface area for soil exploration, production of phosphorus solubilizing enzymes and acids. Mycorrhizal fungi and bacteria also solubilize other nutrients such zinc, copper, potassium and calcium from their precipitated or sparingly soluble forms. Microorganisms also contribute to soil fertility improvement through their roles in composting. They are currently isolated, studied and packaged as biofertilizers and used to supplement chemical fertilizers. It can be noted that thorough exploitation of microbial activities can contribute to balanced plant nutrition. However, poor soil management practices limit realization of potential benefits from soil microorganisms whereas biofertilizer technology development in

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developing countries such as Sub-Saharan African countries is derailed because of lack of awareness, infrastructure and human capacity. From this study it can be noted that intensifying soil management practices that maximize microbial activities can go a long way in improving soil fertility with minimal use of chemical fertilizers. On the other hand there is a need to improve both human and infrastructure capacity in poor countries such as those in Sub-Saharan Africa so as to manage research in biofertilizer technologies. Awareness and dissemination of information on the importance of biofertilizers, intensifying effective microbial inoculation where it deemed to give good response and systematic evaluation of economic viability of biofertilizer technologies are other areas that need to be addressed.

Keywords: Soil microorganisms; biofertilizers; nitrogen fixation; mycorrhizae; soil fertility; composting.

1. INTRODUCTION

Soil fertility decline is also described as soil productivity decline and is defined as a deterioration of chemical, physical and biological soil properties [1]. The major processes that contribute to soil fertility decline include soil erosion, decline in soil organic matter and biological activity, degradation of soil structure and loss of other soil physical qualities, reduction in availability of major nutrients (N, P, K) and micronutrients, and increase in toxicity due to acidification and pollution [1,2]. However, both over- and under-application of chemical fertilizers and poor soil management practices have lead to degradation of the soil and environment in general [3]. In the developed countries concerns are mostly associated with over application of fertilizer that lead to negative effects to the environments such as ground water nitrate contamination and eutrophication in water bodies [4,5,6]. On the other hand, in the developing countries there is nutrient mining due to under-replenishment of nutrients and poor management of organic resources [3,7,8]. The problem of nutrient depletion is quite huge in Sub-Saharan Africa (SSA) with earlier studies indicating Kenya, Malawi, Burundi, Ethiopia, Lesotho and Rwanda as countries most affected [9,10]. On average 22 kg of nitrogen (N), 2.5 kg of phosphorus (P) and 15 kg of potassium were reported to be lost annually per hectare of cultivated land in SSA [9]. World Bank [11] indicated a net loss of 700 kg N, 100 kg P and 450 kg K per ha in about 100 million hectares of cultivated land. The decline in soil fertility is a widespread limitation in yield improvement in many maize based-cropping systems throughout East and Southern Africa [12,13] with N and P in most soils of the humid and subhumid tropical areas reported to be the common limiting nutrients to crop growth [14,15]. Low soil fertility is considered as a major factor contributing to low soil productivity, food insecurity and source of inefficiency in the returns to inputs such as fertilizers, improved seed, labour and management committed to smallholder farms in SSA [16,17].

Nutrient depletion can be controlled through a number of ways including nutrient replenishment by applying inorganic fertilizers and organic amendments such as crop residues, animal manure and composts. However, high costs of inorganic fertilizers are a huge challenge for the developing countries [11,18] whereas the worldwide concern on environmental quality is another factor that needs consideration in planning a sustainable agricultural production. The incorporation of farm yard manure, crop residue and composts also faces a challenge of quality or limited amount of nutrients returned to the soil [19,20]. These challenges call for holistic approaches that will provide nutrients for plant growth in a sustainable manner. Integrated nutrient management approach and exploitation of soil microorganisms are some of the important ways that are being researched upon. This paper is not intended to promote any farming system but to highlight the benefits and potentials of exploitating soil microorganisms for soil fertility improvement. Soil microorganisms include bacteria, fungi, and actinomycetes. Other micro-, meso- and macrofauna such as protozoa and earthworms also have very important roles in soil ecology and soil fertility improvement [4,21].

The beneficial functions of soil microorganisms include release of plant nutrients such as P, K and Zn from insoluble inorganic forms [22,23,24]; decomposition of organic residues and release of nutrients [4,25,26]; formation of beneficial soil humus by decomposing organic residues and through synthesis of new compounds [21,27]; production of plant growth promoting compounds [25,28,29,30]; improvement of plant nutrition through symbiotic or mutualistic relationships such as *Rhizobium*/legume association and mycorrhizal association that lead to biological nitrogen fixation and enhanced P uptake respectively [4,21,27]; improvement of soil aggregation, aeration and infiltration [4]; have antagonistic actions against insects, plant pathogens and weeds (biocontrol) and help in pesticide degradation [25]. The benefits of soil microorganisms are realized through soil management practices or cropping systems (for example crop rotation, intercropping, application of organic resources) that maximize their activities in their soil habitat [31], composting and application of effective microorganisms as inoculants or biofertilizers [32].

The paper highlights how important roles of soil microorganisms are exploited in efforts to enhance soil fertility. Although other authors reported in a good number of papers in specific areas [33,34,35,36,37], this paper gives an overview of the concept of biofertilizer, the process of biological nitrogen fixation and its benefits, mycorrhizal association and its role in soil fertility enhancement, microbial solubilization of phosphorus and other nutrients, role of microorganisms in composting and challenges that are encountered in exploiting microbial functions.

2. THE CONCEPT OF BIOFERTILIZERS

The concept of biofertilizer is still new in such that there is no single agreed definition [34]. Usually biofertilizers are considered as low cost renewable sources of plant nutrients which supplement chemical fertilizers [34]. This definition looks rather too broad and to differentiate with other organic inputs, recently it has been proposed that biofertilizers be defined as substances that contain living microorganisms which colonize the rhizosphere or the interior of the plant and promote growth by increasing the availability of nutrients to the target crop, when applied to seed, plant surface, or soil [34,38,39]. Biofertilizers enhance nutrient availability to plants through processes such as biological nitrogen fixation, and solubilization of P, K, S [24,39,40] and micronutrient elements (including Zn and Fe) [23,41]. They can also be used to hasten decomposition processes during compositing [42]. Microbes that produce hormones and anti-metabolites and promote root growth are also considered to carry a biofertilizer function [34]. Examples of microorganisms that are used as biofertilizers include bacteria (*Rhizobium, Bradyrhizobium, Azospirillum, Azobacter, Bacillus,* and *Pseudomonas* species) and fungal species such as those of mycorrhizal fungi, *Penecillium*, *Chaetomium* and *Trichoderma* [34,38]. Some details on how biofertilizers work are included in the sections that follow. These microbes can be isolated from rhizospheres of legumes, their wild relatives or other plant species, cultured in a laboratory and packaged with some carrier material to be used as inoculants or biofertilizers [34,43,44]. Isolation and identification of the effective biofertilizer microorganisms are achieved through traditional cultural techniques such as serial dilutions and plating [34,45,46], morphological, biochemical and molecular techniques such 16S rRNA and rDNA sequencing methods [45,47,48,49]. The biofertilizer microorganisms that are applied to seeds are commonly mixed with carrier materials. Carriers commonly used are sticky materials that are non-toxic to the microbes and seeds and these include gum arabic, methylcellulose, sucrose solutions and vegetable oils [34].

3. BIOLOGICAL NITROGEN FIXATION

Nitrogen is the most critical nutrient element needed in the largest amounts and commonly limiting plant growth [20,50]. Although nitrogen is the most limiting plant nutrient, there is a lot of it in the atmosphere constituting 78% of the air and is in a form of dinitrogen (N_2) gas with a strong triple bond that makes it inert and unavailable for plant uptake [51]. The only cheaper way through which N_2 is converted to available forms is through biological nitrogen fixation (BNF). Biological nitrogen fixation is a biochemical process that converts N_2 gas of the atmosphere to reactive N, ammonia (NH_3) that becomes available to all forms of life through the N cycle [4,21]. It is catalyzed by a biological catalyst called nitrogenase that is commonly produced only by certain microorganisms including several species of *Rhizobium*, actinomycetes and cyanobacteria [4]. These organisms fix nitrogen in a symbiotic or mutualistic relationship with plants. The common mutualistic relationship is the association between rhizobia and roots of legume plants where N_2 is converted to NH_3 in the legume plant nodules. The biochemistry of BNF is well illustrated by Giller [52] and Cheng [53].

The terminology of rhizobia is broadly used to refer to special microorganisms that can form symbiotic relationship of legumes resulting in BNF. There are many genera of rhizobia including *Allorhizobium, Azorhizobium, Bradyrhizobium, Mesorhizobium, Rhizobium* and *Sinorhizobium* [21,52]. In most soils there are indigenous rhizobial species that nodulate legumes and their efficiency depends on compatibility of the legume and the rhizobial species, and the environmental factors such as soil pH, soil temperature, soil moisture, and availability of other plant nutrients such as P and Molybenum (Mo) [4,54].

The NH_3 produced in this interaction benefits the plant as it is assimilated into various compounds while the *Rhizobium* microsymbiont benefits from the protected environment and the supply of photosynthates [21]. Significant amounts of N are fixed in mutualistic relationships between *Rhizobium* and roots of legumes [4,21,52,55]. Table 1 illustrates estimated amounts (by different methods) of N fixed by different grain legumes.

The substantial soil fertility benefits of BNF are mainly through the residues that are incorporated in the soil for the growth of the crops such as cereals grown in rotation with the legume [56,57]. Several studies have shown positive residual effects (improved soil fertility and increased yields) attributed to BNF [56,57,58,59,60,61,62,63,64].

Table 1. Estimates of the amount of nitrogen biologically fixed by some grain legume (Modified from [52])

Grain legume	N fixed Kg ha^{-1}	Time period (days)	Country	Method
Groundnuts (*Arachis hypogea*)	152 – 189	118 - 137	India	NA/Diff
	101	-	Ghana	Diff
Pigeon pea (*Cajanus cajan*)	150 – 166	-	India	ID
	13 – 163	120	Malawi	NA
Chickpea (*Cicer arietinum*)	67 – 85	170	Australia	NA
	35 – 80[C]	-	Nepal	NA
Soybean (*Glycine max*)	85 – 154	110	Brazil	ID
	15 – 170	-	Nepal	NA
Common bean (*Phaseolus vulgaris*)	25 – 65	60 - 90	Brazil	ID
	8 – 26[C]	75	Tanzania	ID
Cowpea (*Vigna unguiculata*)	9 – 51	110	Brazil	ID
	47 – 105	66	Nigeria	ID/Diff

All legumes were planted with small amounts of N-fertilizers and generally adequate amounts of phosphorus were applied; ID means 15N Isotope dilution; NA means 15N Natural abundance; Diff stand for N difference; [C] Measurements in experiments on farmers' fields or in farmers' crop.

4. PHOSPHORUS SOLUBILIZATION BY BACTERIA AND FUNGI

Phosphorus is the common limiting major nutrient element after nitrogen. It is a component of key molecules such as nucleic acids, phospholids, sugar phosphates, proteins and energy rich adenosine triphosphate (ATP) in plants and other organisms [4,21,65]. It is associated with vital functions such as root development, stalk and stem strength, flower and seed formation, crop maturity, nitrogen fixation in legumes, crop quality and resistance to diseases [4,33,55]. Phosphorus is taken up in the form of orthophosphate. However, it is less available for plant uptake because the inorganic P is easily fixed by the Al, Fe and Mn oxides in predominantly acidic soils and precipitated by Ca in alkaline soils [4, 66]. Organic P forms (inositol phosphate, phospholipids, nucleic acids) contribute a large amount of soil P [67]. Yadav and Tarafdar [68] reported that 68% of organic P is present as phytin which is not directly available to plants.

Microorganisms play critical roles in soil P dynamics including mineralization and immobilization of organic P. The positive influences of soil microorganisms are on mineralization of organic P and solubilization of P from its fixed or precipitated forms including P from rock phosphate [48,67,69,70,71]. Microorganisms that are commonly involved in P solubilization and mineralization are bacteria and fungi [33,67]. Bacteria commonly reported for P solubilizing ability include species of *Pseudomonas, Bacillus, Rhizobium, Enterobacter, Arthrobacter, Serratia, Rhodococcus, Phyllobacterium, Flavobacterium, Aerobacter* and *Azospirillum* [33,43,48,72]. Fungi commonly reported to effectively solubilizing phosphorus include species of *Aspergillus* (*candidus, niger, parasiticus, rugulosus, terreus*), *Penecillium, Pseudeurotium, Trichoderma* and some mycorrhizal fungi [34,73].

Microorganisms solubilize P through production of low molecular weight organic acids in which hydroxyl and carboxyl groups chelate cations that are associated with complexed forms of P (Ca, Al and Fe) thus rendering phosphate soluble in both basic and acid soils [33,46,67,73] or through ligand exchange [74] and directly dissolve mineral phosphates from Al-P and Fe-P complexes as a result of anion exchange of PO_4^{3-} with acid anion [67,75]. The organic acids and proton release mechanisms by microorganisms also decrease the pH in basic soils and thus solubilize P from the calcium phosphate (Ca-P) [33,67]. Substantial amounts of P solubilized by some selected microbial species/strains as reported by a number of authors are presented in Table 2.

Table 2. Some amounts of P solubilized by selected species of microorganism

Amount of P solubilized (mg/L)	Microbial species/strains	Mechanism	References
524	*Acinetobacter* sp. (BR-25)	Decrease in pH observed suggesting production of organic acids	[76]
519.7	*Arthrobacter* sp. (CC BC03	Production of organic acids (citric acid and lactic acid)	[48]
479	*Pantoea* sp.	Production of organic acids; phosphatase activity noted	[45]
421.8	*Serratia marcescens* (CC-BC14)	Production of organic acids (citric acid, gluconic acid, succinic acid, lactic acid)	[48]
400	*Aspergillus niger*	Production of organic acids	[44]
395	*Klebsiella* sp.(BR-15)	Decrease in pH observed suggesting production of organic acids	[76]
336.2	Bacterial strain (TSP-B4)	Production organic acid; phosphatase activity noted	[45]
293	*Enterobacter cloacae*	Production of organic acids; phosphatase activity noted	[45]
289.8	*Chryseobacterium* sp.	Production organic acids (citric acid)	[48]
211	*Bacillus* sp. (AF507879)	Production of acids; phosphatase activity noted	[77]
206	*Enterobacter* sp. (BR-26)	Decrease in pH observed suggesting production of organic acids	[76]
179.9	*Pantoea ananatis* (AF364846.1)	Production of acids; phosphatase activity noted	[77]
167.2	*Burkholderia* sp. (AY224513.1)	Production of acids; phosphatase activity noted	[77]

In brackets are accession numbers for the strains

Microorganisms use enzymes such as phosphatases and phytases in hydrolyzing P containing organic compounds and release P into the soil solution [72,73,78,79]. Production of organic acids and siderophores is also important in influencing release of P from organic compounds. Table 3 shows some fungal species that effectively solubilize organic P and their efficiencies.

Table 3. Efficiency of fungal mat of different fungi to hydrolyze different organic P compounds (Adapted from [73])

Efficiency μg P release * min^{-1}			
S. No.	**Fungal species**	**Phytin**	**Glycerophosphate**
1	*Aspergillus candidus*	2.72	4.72
2	*Aspergillus niger*	1.72	2.46
3	*Aspergillus parasiticus*	3.21	5.12
4	*Aspergillus rugulosus*	0.98	1.82
5	*Aspergillus terreus*	3.09	4.98
6	*Penecillium rubrum*	2.16	2.90
7	*Penecillium simplicissimum*	2.21	2.99
8	*Pseudeurotium zonatum*	2.59	3.62
9	*Trichoderma harzianum*	3.54	5.89
10	*Tichoderma viride*	3.32	5.46
	LSD (p<0.05)	0.64	0.71

**Initial P added 500 ppm either as phytic acid or as Na-glycerophosphate in all the replications*

5. MYCORRHIZAL FACILITATED SOIL FERTILITY IMPROVEMENTS

The term mycorrhiza is used to describe symbiotic or mutualistic association between roots of plants and fungal hyphae [4,21]. Mycorrhizae exist in diverse morphological, functional and evolutionary categories [80]. Recent studies classify mycorrhizae into a number of categories including vesicular arbuscular mycorrhizae (VAM) which are also called arbuscular mycorrhizae (AM), ectomycorrhizae (ECM), orchid and ericoid mycorrhizae [21,81]. Over 82% of higher plants are capable of forming mycorrhizal associations [80] with VAM as the most common root fungal associations [81]. The VAM fall under a phylum *Glomeromycota* [82], order *Glomales* [83] and belong to the group traditionally called endomycorrhiza [84]. The vesicular arbuscular name is derived from their morphological characteristics that include formation of vesicles for storage of substances and arbuscules which are structures for transportation of materials [4,85].

The mutualistic association between the VAM fungi and plant roots provides the fungi with carbon nutrition [86] while the plant obtains many benefits including water and nutrient uptake from the soil; and protection from some diseases, weeds, heavy metals and induced oxidative tissue stresses [87]. VAM fungi also contribute to soil aggregation and soil structure improvement through a network of hyphae and the gluing effect of their glycoprotein product, glomalin [88,89].

The involvement of VAM in plant acquisition of P is its commonest known positive contribution in plant nutrition. VAM fungi are also involved in acquisition of other nutrients such as N, K, Ca, Cu, Zn and Fe [21,90,91,92]. The external hyphae of VAM was reported to deliver up to 80% of plant P, 25% of plant N, 10% of plant K, 25% of plant Zn and 60% of plant Cu [36]. More examples of nutrient uptake enhancement by VAM are reported in recent studies [87,93,94]. The enhancement of uptake of nutrients such as P, and micronutrients improves nitrogen fixation in legumes [87,88]. The process of plant nutrient acquisition enhancement by VAM involves different mechanisms. The common mechanism is that VAM enhance nutrient acquisition by enabling exploration of a larger soil volume [95,96]. Mycorrhizal fungi are also reported to produce organic acids and phosphatase enzymes that solubilize sparingly soluble P in forms of Ca, Fe and Al phosphates [96,97,98]. VAM has also shown synergistic interactions with other phosphate solubilizing microorganisms including bacteria [71,99]. Table 4 presents effects of mycorrhiza on P uptake.

Table 4. Effects of mycorrhizal inoculation and pH on P concentration in shoot and root, and total P uptake of different forage grass species [100]

	P concentration in shoot		P concentration in root		Total P uptake	
	-AM[1]	+AM[1]	-AM	+AM	-AM	+AM
	(g/kg)		(g/kg)		(mg/pot)	
Species						
BB[2]	0.37Bc[3]	1.27Aa	0.44Bab	0.88Aa	0.86Bb	3.60Aa
BD	0.48Ba	1.05Aab	0.48Ba	0.86Aa	0.91Bb	2.91Aa
HU	0.47Bab	1.20Aa	0.44Bab	0.92Aa	1.53Ba	3.24Aa
PM	0.41Bbc	0.89Ab	0.38Bb	0.73Aa	1.29Ba	3.34Aa
Soil pH						
Low	0.43[4]	0.96[4]	-	-	0.07Bc	0.70Ac
Medium	0.42Ba	1.16Aa	0.45Ba	0.93Aa	1.06Bb	3.42Ab
High	0.44Ba	1.04Aa	0.42Ba	0.77Ab	2.32Ba	5.70Aa
Mean	0.43	1.10	0.44	0.85	1.15	3.27

[1] *Treatment: -AM = no mycorrhiza applied, +AM = mycorrhiza applied.*
[2] *Abbreviations for grass species: BB = B. Brazantha; BD = B. decumbens; HU = B. humidicola; PM = P. maximum.*
[3] *Parameters within the same column (lower case) or row (upper case) followed by the same letters are not significantly different at 5% level.*
[4] *root and shoot samples were mixed for each grass species.*

6. CARRIER MATERIALS AND METHODS OF APPLYING BIOFERTILIZERS

Most biofertilizers are prepared as carrier-based inoculants containing effective microorganisms [34]. Carrier materials enable easy-handling, long term storage and high effectiveness of the biofertilizers [34]. Materials that are usually used as carriers for inoculants include peat, coal, composts, farm yard manure, soybean oils, perlite, vermiculite, ground rock phosphate and alginate beads, and can be dispersed as powders, slurries, granules or liquids [34,101,102]. The common methods of applying inoculants include: application to the seed, application to the soil and seedling dipping [34]. Seed inoculation involves coating the seeds evenly with an inoculant paste or powder with an adhesive such as sucrose solutions, gum Arabic, methylcellulose, vegetable oils and honey [34,103]. The seeds are dried in the shade, usually, for less than an hour and planting of the inoculated seeds is done within 24 hours [104]. Soil inoculation involves granular or inoculants mixed with farm yard manure applied in the furrow alongside the seed [34]. This method is considered necessary when legume seeds are planted in hot, dry or adverse weather conditions [105]. Seedling dipping is considered when seedlings are transplanted and liquid inoculants are used for dipping roots of the seedling [34].

7. ROLE OF MICROORGANISMS IN COMPOSTING

7.1 Involvement of Microorganisms in the Composting Process

Composting is a controlled decomposition of organic residues or waste to a state in which the composted material can be safely handled, stored and/or applied to land without adverse effects to the environment [106]. It is a process that creates humus like organic materials outside the soil by mixing, piling, or otherwise storing organic materials under conditions conducive to aerobic decomposition and nutrient conservation [95]. Compost is considered as an organic fertilizer as it adds nutrients and organic matter to the soil [107].

The most important point of emphasis in this section is that composting mainly happens because of microbial activities [107]. Microbes decompose organic materials through production of various extracellular enzymes such as peptidases, cellulases, hemicellulases and pectinases [21,27]. Microbial activities in the compositing process are in turn affected by a number of factors including residue/waste composition, for instance cellulose, hemicelluloses and lignin contents but also the C/N ratios, and environmental factors such as pH, temperature, moisture and aeration. Composting is carried out by both aerobic and anaerobic microorganisms but aerobes are known to be efficient decomposers and therefore aeration accelerates the process [4]. On the other hand, predominantly anaerobic composting is less efficient and leads to production of malodorous compounds such as hydrogen sulphide, dimethyl sulphide and dimethyl disulphide [106,108,109].

There are a number of methods of composting including composting in pits, trenches, or compost heaps (indore, Bangalore and block methods) [107]. Detailed information on processes and methods of composting are presented in a book by Inckel et al. [107]. Common features of all these methods are that they undergo stages of temperature change and each stage is associated with certain categories of microbial species. The thermophilic stages (heating, > 40^{o}C) are associated with microbes like thermophilic bacteria (*Bacillus stearothermophilus*, *Bacillus informis* and *subtilis)*; actinomycetes (*Nocardia* spp.*, Streptomyces rectus, S. thermofuscus, S. thermovulgaris and Thermomonospora* spp.); and fungal species (*Absidia, Mucor, Thermophilum, Dactylomyces, Talaromyces (Penecillium); Basidiomycetes- Coprinus, Aspergillus* and *Humicola*) and mostly fungi dominate the later stages when the material remaining is more of recalcitrant cellulose or lignin [4,27,95]. The mesophilic stages (20-40ºC) are associated with species of *Pseudomonas, Azotobacter, Serratia, Azobacter, Azospirillum and Bacillus* [110,111]. Efforts are being made to isolate and identify some effective microorganisms that can decompose recalcitrant materials at an accelerated rate and these can be used as inoculants to composts [111]. Some studies have already shown promising results [112,113,114]. Some of the microorganisms that have been used as inoculants in composting include *Aspergillus niger, Azotobacter chrooccum, Stenotrophomonas maltophila,* and *Scedosporium apiospermium* [115].

7.2 Contributions of Composting to Soil Fertility and Crop Yield

Composting is very beneficial in improving soil properties, crop yields and ensuring clean environments [4,116]. Soil fertility and crop yield benefits from both traditional/conventional composting and composting with inoculants of specific effective microorganisms have been reported by various authors. Increases in wheat yields by 9-25%, and soil carbon and soil N by 27% and 13-16% respectively were reported from a 9 year study in Pennsylvania, USA due to compost application [117]. Increases in maize yields due to compost have also been reported from other studies [118,119]. Compost inoculated with cellulolytic fungi, *Trichoderma harzianum* and nitrogen fixing bacteria, *Azotobacter* sp. increased mungbean nodulation, plant height and biomass yield by 250, 29 and 86% respectively as compared to the control treatment [113]. Inoculation with thermophilic cellulolytic bacterium, *Anoxybacillus* sp. was reported to accelerate degradation of municipal solid waste [37]. A comprehensive analysis of several benefits of compost application including nutrient availability enhancement, improving soil structure, soil water infiltration and retention capacity, increasing soil biodiversity and nutrient cycling, reducing susceptibility to soil erosion and suppressing soil borne diseases is presented in a review paper by Amlinger et al. [116]. Table 5 presents results of the impacts of compost use on yields of different crops in Ethiopia.

Table 5. Average yields by treatment in kg/ha for 9 crops in Tigray, 2000-2006 inclusive (Adapted from [120])

Crop type	Average yields (kg/ha)					
	Check		Compost		Fertilizer	
	Grain	Straw	Grain	Straw	Grain	Straw
Barley	1115 (n=56)	2478 (n=52)	2349 (n=57)	4456 (n=55)	1861 (n=36)	3739 (n=35)
Durum wheat	1228 (n=73)	2342 (n=67)	2494 (n=61)	3823 (n=57)	1692 (n=48)	3413 (n=45)
Finger millet	1142 (n=16)	2242 (n=16)	2652 (n=14)	4748 (n=13)	1848 (n=8)	3839 (n=7)
Hanfets	858 (n=31)	2235 (n=31)	1341 (n=31)	3396 (n=31)	1199 (n=29)	2237 (n=29)
Maize	1760 (n=31)	3531 (n=20)	3748 (n=41)	4957 (n=31)	2900 (n=25)	3858 (n=13)
Sorghum	1338 (n=14)	2446 (n=13)	2497 (n=11)	3662 (n=10)	2480 (n=5)	4433 (n=5)
Teff	1151 (n=106)	2471 (n=94)	2143 (n=75)	3801 (n=66)	1683 (n=71)	3515 (n=68)
Faba bean	1378 (n=20)	2121 (n=17)	2857 (n=23)	4158 (n=24)	2696 (n=3)	3783 (n=3)
Field pea	1527 (n=9)	1201 (n=9)	1964 (n=9)	1625 (n=9)	0	0

'hanfets is a mixuture of barley and durum wheat
(n = number records for each treatment and crop)

8. CHALLENGES FACED IN EXPLOITING SOIL MICROORGANISMS

Many benefits that can be obtained from soil microbial activities are hindered by the failure to fully exploit them. There are a number of factors that derail maximization of beneficial microbial activities. In some parts of the world including SSA, there is still a challenge as far as building soil organic matter stocks is concerned. Apart from climatic factors, there are a number of anthropogenic or social factors that affect biological functions and soil productivity in general. Use of crop residues as mulch or soil incorporation creates a dilemma for some farmers on whether to use them as fodder for animals or soil improvement [121], addition of manure faces a challenge of labour and transport costs [122], while other challenges are malpractices such as burning of crop residues and uncontrolled movement of livestock that destroy crop residues [118]. Therefore these challenges affect soil biodiversity.

Microorganisms proliferate in soils with sufficient organic matter as they depend on it as substrate [4,25].

Literature shows that there are a number of challenges that are faced in SSA in implementing biofertilizers technologies. This can be attributed to a number of reasons including lack of development in this technology and awareness to most of the farmers on use of biofertilizers. Opperman [124] noted that in Southern Africa apart from the Republic of South Africa, very few farmers use inoculants for soybean and this is attributed to lack of awareness and accessibility. Infrastructure and capacity/expertise in soil microbiology is also a big challenge in Sub-Saharan Africa where institutions are lacking enough technocrats in soil management fields [123]. Recent advances in microbial ecology whereby effective soil microorganisms studies are being conducted, the advanced techniques such as isotopic and PCR based methods are employed and this may also not be easy in poor countries including those in SSA. Chianu et al. [125] noted the following as some of the main challenges faced in SSA in the use of inoculants with reference to soybean production:

- Absence or very weak institutions, policy and budgetary support for biotechnology research and lack of its integration into wider agricultural and overall development objectives in SSA.
- Limited knowledge of inoculation responses of both promiscuous and specifically nodulating soybean varieties as well as the other factors that inhibit BNF, hence a weak basis for decision-making on biotechnology issues in SSA.
- Limited capacity and lack of sustainable investment.
- Poorly developed marketing channels and infrastructure, and limited involvement of the private sector in the distribution of inoculants.
- Limited farmer awareness about and access to inoculants.

9. CONCLUSIONS AND RECOMMENDATIONS

From this review it is noted that soil microorganisms have a huge contribution in alleviating the decline in soil fertility. This is achieved through a number of ways. The commonly reported *Rhizobium*/legume symbiosis contributes substantial amounts of biologically fixed nitrogen to cropping systems and significantly benefits crops that follow in rotation. Soil microorganisms such as bacteria and fungi contribute to plant phosphorus nutrition through solubilization of fixed or precipitated phosphorus from complexes with Al and Fe in acidic soils and calcium complexes in alkaline soils. Solubilization is mainly achieved through production of organic acids, chelation and ligand exchange, and other pH lowering mechanisms. They also contribute to the release of P from organic substances through mineralization processes. Mycorrhizal associations are reported to contribute to plant phosphorus nutrition through increasing root surface area for soil exploration, production of phosphorus solubilizing enzymes and organic acids. Mycorrhizal fungi and bacteria also solubilize other nutrients such as zinc, copper, and calcium. Microorganisms also contribute to soil fertility improvements through their roles in composting. Soil microorganisms are currently isolated, studied and packaged as biofertilizers and used to supplement chemical fertilizers. It can be noted that thorough exploitation of microbial activities can contribute to balanced fertilization. However, biofertilizers' technology development in developing countries such as Sub-Saharan African countries is derailed because of lack of awareness, infrastructure and human capacity.

From this review the following can be recommended:

- There is need to encourage and intensify soil management practices that maximizes microbial activities. These include crop rotation, intercropping, and application of organic resources.
- There is a need to improve in both human and infrastructure capacity in poor countries such as those in Sub-Saharan Africa so as to manage research in biofertilizer technologies.
- Improvement in access, awareness and dissemination of information on the importance of biofertilizers is needed.
- There is need to intensity inoculation with the available inoculants where it deemed to give good response. More research with an integrated approach whereby effective microorganisms and small doses of inorganic fertilizer need to be encouraged.
- There is need for systematic evaluation of economic viability of biofertilizer technologies.

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COMPETING INTERESTS

The author declared that no competing interest exists.

REFERENCES

1. Food and Agricultural Organization of the United Nations (FAO). Soil fertility management in support of food security in Sub-Saharan Africa. FAO, Rome; 2001.
2. Lal R. Degradation and resilience of soils. Phil. Trans. R. Soc. Lond. B. 1997;352:997-1010.
3. Gruhn P, Goletti F, Yudelman M. Integrated nutrient management, soil fertility, and sustainable agriculture: current issues and future challenges.International Food Policy Research Institute. Washington DC. Food, Agriculture and Environment Discussion Paper 32; 2000.
4. Brady NC, Weil RR. The Nature and Properties of Soils. Revised 14th ed. Pearson Prentice Hall. New Jersey, USA; 2008.
5. Environmental Protection Agency (EPA). Inventory of US greenhouse gas emissions and sinks: 1990-2011; 2013.
6. Dubrovsky NM, Burow KR, Clark GM, Gronberg JM, Hamilton PA, Hitt KJ, et al. The quality of our Nation's waters. Nutrients in the Nation's streams and groundwater, 1992-2004: U.S. Geological Survey Circular 1350; 2010. Available: http://water.usgs.gov/nawga/nutrients/pubs/circ1350.
7. Food and Agricultural Organization (FAO). Assessment of Soil Nutrient Balance: Approaches and Methodologies. FAO Fertilizer and Plant Nutrition Bulletin 14. FAO, Rome; 2003.
8. Sanchez PE. Soil Fertility and Hunger in Africa. Science. 2002;295:2019-2020.

9. Stoorvogel JJ, Smaling EMA. Assessment of soil nutrition depletion in sub-Saharan Africa: 1983-2000. Report No. 28. Winand Staring Centre, Wageningen, Netherlands; 1990.
10. Henao J, Baanante C. Nutrient depletion in the agricultural soils of Africa. A 2020 vision for food, agriculture and environment. 2020 Brief; 1999.
11. World Bank. Natural resource degradation in Sub-Sahara Africa. Restoration of soil fertility. Africa Region. World Bank. Washington D.C; 1996.
12. Buresh RJ, Sanchez PA, Calhoun F. Replenishing soil fertility in Africa. Soil Science Society of America; 1997. SSSA Special Publication Number 51.
13. Mekuria M, Waddington S, Siziba S. Breaking the “fertilizer poverty” and food insecurity traps in smallholder maize based systems in southern Africa: Experiences and lessons from Soil Fertility Network/Economics and Policy Working Group. 2004. Available: http://www. ageconsearch.umn.edu/bitstream/9515/1/cp04me01.pdf.
14. Ahlawat IPS, Sigh A, Saraf CS. Effects of winter legumes on nitrogen economy and productivity of succeeding cereals. Exp. Agr. 1981;17(1):57-62.
15. Ndakidemi PA, Dakora FD, Nkonya C, Ringo D, Mansoor D. Yield and economic benefits of common bean (Phaseolous vulgaris) and Soybean (Glycine max) inoculation in northern Tanzania. Aust. J. Exp. Agr. 2006;46(4):571-577.
16. Bationo A, Kimetu J, Ikerra S, Kimani S, Mugendi D, Odendo M. et al. The African Network for Soil Biology and Fertility: New challenges and opportunities. In: Bationo A, editor. Managing Nutrient cycles to Sustain Soil Fertility in Sub-Saharan Africa TSBF-CIAT. Academy Science Publishers. Nairobi. 2004;1-24.
17. Mekuria M, Waddington SR. Initiatives to encourage farmer adoption of soil fertility technologies for maize-based cropping systems in southern Africa. In: Barrett, CB, Place F Aboud AA. editor, Natural Resources Management in African Agriculture: Understanding and Improving Current Practices. Wallingford: CAB International. 2002;219-233.
18. Druille Z, Barreto-Hurle J. Fertilizer subsidies in sub-Saharan Africa. Agricultural Development and Economics Working Paper No.12-04. FAO. Rome; 2012.
19. Palm CA, Myers RJK, Nandwa SM. Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. In: Buresh RJ, Sanchez PA. Calhoun F, editor. Replenishing Soil Fertility in Africa. Soil Science Society of America, Madison, Wisconsin. 1997; SSSA Special Publication Number 51:151-192.
20. Giller KE, Cadish G, Ebaliostis C, Adams E, Sakala WD, Mafongoya PL. Building nitrogen capital in Africa. In: Buresh RJ, Sanchez PA. Calhoun F, editor. Replenishing Soil Fertility in Africa; 1997; SSSA Special Issue Publication No. 51:151-192.
21. Sylvia DM, Fuhrmann JJ, Hartel PG, Zuberer DA. Principles and applications of soil microbiology. 2nd ed. Pearson Education Inc., New Jersey; 2005.
22. Hu X, Chen J, Guo J. Two phosphate and potassium solubilizing bacteria isolated from Tianmu Mountain, Zhejiang, China. World J. Microbiol. Biotech. 2006;22(9):983-990. DOI: 10. 1007/s11274-006-9144-2.
23. Saravanan VS, Subramoniam SR, Raj SA. Assessing in vitro solubilization potential of zinc bacterial solubilizing isolates. Braz. J. Microbiol. 2003;34:121-125.
24. Parmar P, Sindhu SS. Potassium solubilization by rhizosphere bacteria: influence of nutritional and environmental conditions. J. Microbiol. Res. 2013;3(1):25-31. DOI: 10.5923/j.microbiology.20130301.04.
25. Kennedy AC, Stubbs TL, Schillinger WF. Soil and crop management effects on soil microbiology. In: Magdoff F, Weil RR, editors. Soil Organic Matter in Sustainable Agriculture. CRC Press. 2004;295-326.
26. Plaster EJ. Soil Science and Management. 5th ed. Delmar Cengage Learning. New York. 2009.

27. Paul EA. Soil Microbiology, Ecology, and Biochemistry. 3rd. Elsevier Inc. Amsterdam; 2007.
28. Tsavkelova EA, Klimova SY, Cherdyntseva TA, Netrusov AI. Microbial producers of plant growth stimulators and their practical use: A review. Appl. Biochem. Microbiol. 2006;42:117–126.
29. Thuler DS, Floh EIS, Handro W, Barbosa HR. Plant growth regulators and amino acids released by Azospirillum sp in chemically defined media. Lett. Appl. Microbiol. 2003;37:174–178.
30. UmaMaheswari T, Aubukkarasi K, Hemalatha T, Chendrayan K. Studies on phytohormone producing ability of indigenous endophytic bacteria isolated from tropical legume crops. Int. J. Curr. Microbiol. App. Sci. 2013;2(6):127-136.
31. Magdoff F, Weil RR, editors. Soil organic matter in sustainable agriculture. CRC Press. New York; 2004.
32. Mohammadi K, Sohrabi Y. Bacterial biofertilizers for sustainable crop production: A review. ARPN Journal of Agricultural and Biological Sciences. 2012;7(5):307-316.
33. Khan AA, Jilani G, Akhtar MS, Naqvi SMS, Rasheed M. Phosphorus solubilization: Occurence, mechanisms and their role in crop production. J. Agr. and Biol. Sci. 2009;1(1):48-58.
34. Muraleedharan H, Seshadri S, Perumal K. Biofertilizers (Phosphobacteria). Shri AMM Murugappa Chettiar Research Centre, Taraman, Chennai; 2010.
35. Yadav BK, Verma A. Phosphate solubilization and mobilization soil through microorganisms under arid ecosystems. In: Ali M, editor. The functioning of ecosystems. In Tech Europe. 2012;93-108.
36. Marschner H, Dell B. Nutrient uptake in mycorrhizal symbiosis. Plant and Soil. 1994;159(1):89-102.
37. Ghaffari S, Sepahi AA, Razavi MR, Malekzadeh F, Haydarian H. 2011. Effectiveness of inoculation with isolated anoxybacillus sp. MGA110 on municipal solid waste composting process. Afr. J. Microbiol. Res. 2011;5(30):5373-5378. DOI: 10.5897/AJMR11.864
38. Kaechai S, Soyton K, Hyde KD. Mycofungicides and fungal biofertilizers. Fungal Diversity. 2009;38:25-50.
39. Mohammadi K, Sohrabi Y. Bacterial biofertilizers for sustainable crop production: A review. ARPN J. Agr. Biol. Sci. 2012;7(5):307-316.
40. Zarjan JK, Aliasgharzad N, Oustan S, Emadi M, Ahmad A. Isolation and characterization of potassium solubilizing bacteria in some Iranian soils. Arch. Agron. Soil Sci. 2013;59:1-11. DOI:10.1080/03650340.2012.756977.
41. Vega NWO. A review on beneficial effects of rhizosphere bacteria of soil nutrient availaility and plant nutrient uptake. Rev.Fac.Nal.Agr.Medellín. 2007;60(1):3621-3643.
42. Boraste A, Vamsi KK, Jhadav A, Khaimar Y, Gupta N, Trivedi S, et al. Biofertilizers: A novel tool for agriculture. Int. J. Microbiol. Res. 2009;1(2):23-31.
43. Ramachandran K, Srinvasan V, Hamza S, Anandaraj M. Phosphaste solubilizing bacteria isolated from the the rhizosphere soil and its growth promotion of black pepper (*Piper nigrum* L.) cuttings. Dev. Plant Soil Sci. 2007;102:325-331. DOI: 10.1007/978-1-4020-5765-6_51.
44. Vazquez P, Holgium G, Puente ME, Lopez Cortes A, Bashan Y. Phosphate solubilizing microorganisms associated with the rhizosphere of mangroves in semi-arid coastal lagoon. Biol. Fertil. Soils. 2000;30:460-468.
45. Park J, Bolan N, Mallavarapu M, Naidu R. Enhancing the solubility of insoluble phosphorus compounds by phosphate solubilizing bacteria. 19^{th} World Congress of Soil Science, Soil Solutions for a Changing World 1-6 August 2010. Brisbane, Australia. 2010:65-68.

46. Sharma S, Kumar V, Tripathi RB. Isolation of phosphate solubilizing microorganisms from soil. J. Microbiol. Biotech. Res. 2011;1(2):90-95.
47. Brodie EL, Desantis TZ, Joyner DC, Baek SM, Larsen JT, Andersen GL et al. Application of high density oligonucleotide microarray approach to study bacterial population dynamics during uranium reduction and reoxidation. Appl. Env. Microbiol. 2006;72:6288-6298.
48. Chen YP, Rekha PD, Arun AB, Shen FT, Lai WA, Young CC. Phosphate solubilizing bacteria from subtropical soil and their tricalcium phosphate solubilizing abilities. Appl. Soil Ecol. 2006;34(4):33-41.
49. Tallapragada P, Seshachala U. Phosphate solubilizing microbes and the occurrence in the rhizospheres of *Piper befel* in Kanataka, India. Turk J. Biol. 2012;36:25-35.
50. Saka AR. Nitrogen Movement , Retention and Uptake in the Corn (*Zea mays* L.) Root Zone as Influenced by Cultivation and Water Management. PhD Thesis. University of Florida. Gainsville, Florida: University of Florida; 1984.
51. Taiz L, Zeiger E. Plant physiology. 4th ed. Sanderland: Sinauer Associates, Inc., Publishers; 2006.
52. Giller KE. Nitrogen Fixation in Tropical Cropping Systems. CABI International. Wallingford. UK; 2001.
53. Cheng Q. Perspectives in biological nitrogen fixation research. J. Integrat. Plant Biol. 2008;50(7):784-796.
54. Mohammadi K, Shohrabi Y, Gholamreza H, Khalesro S, Majidi M. Effective factors on biological nitrogen fixation. Afr. J. Agric. Res. 2012;7(12):1782-1788.
55. Havlin JL, Beaton JD, Tisdale SL, Nelson WL. Soil Fertility and Fertilizers: An introduction to nutrient management. 7th ed. Pearson Prentice Hall. New Jersey; 2005.
56. Hayat R, Ali S, Siddique MT, Chatha TH. Biological nitrogen fixation of summer legumes and their residual effects on subsequent rainfed wheat yield. Pak. J. Bot. 2008;40:711–722.
57. Mpepereki S, Pompi S. Promoting BNF Technologies among smallholder farmers: A success Story from Zimbabwe. In Waddington SR, editor Grain Legumes Green Manures for Soil Fertility and in Southern Africa.Takin g Stock of Progress. Proceedings of a Conference held 8-11 October 2002 at the Leopard Rock Hotel, Vumba Zimbabwe. Soil Fert Net and CIMMYT-Zimbabwe, Harare, Zimbabwe; 2002.
58. Egbe OM, Idoga S, Idoko JA. Preliminary investigation of residual effects of pigeon pea geonptypes intercropped with maize in Southern Guinea savanna of Nigeria. J. Sust. Dev. Agr. Environ. 2007;3:58-75.
59. Svubure O, Mpepereki S, Makonese F. Sustainability in maize-based cropping systems in rural areas of Zimbabwe: an assessment of the residual soil fertility effects of grain legumes on maize (Zea mays [L.]) under field conditions. Int. J. Engin., Sci. Tech. 2010;2(7):141-148.
60. Mafongoya PL, Bationo A, Kihara J, Waswa BS. Appropriate technologies to replenish soil fertility in Southern Africa. Nutr Cycl Agroecosyst. 2006;76:137-151. DOI: 10.1007/s10705-006-9049-3.
61. ICRISAT/MAI. Cost-effective soil fertility options for smallholder farmers in Malawi. Bulawayo, Zimbabwe: ICRISAT; and Lilongwe, Malawi: Ministry of Agriculture and Irrigation; 2000.
62. Chamango AMZ. Improving maize grain yield of smallholder cropping systems: a farmer participatory research (FPR) approach with legumes for soil fertility improvement in central Malawi. Seventh Eastern and Southern Africa Regional Maize Conference. 2001:413-417.

63. Osunde AO, Bala A, Gwam MS, Tsado PA, Sanginga N, Okugum JA. Residual benefits of promiscuous soybean to maize (*Zea mays* L.) grown on farmers' fields grown around Minna in the Southern Guinea savanna zone of Nigeria. Agr. Ecosyst. Environ. 2003;100(2):09-220.
64. Njira KOW, Nalivata PC, Kanyama-Phiri GY, Lowole MW. Effects of sole cropped, doubled-up legume residues and inorganic nitrogen fertilizer on maize yields in Kasungu, Central Malawi. Agr. Sci. Res. J. 2013;3(3):97-106.
65. Uchida R. Essential nutrients for plant growth: Nutrient functions and deficiency symptoms. In: Silva JR, Uchida R. Plant nutrient management in Hawaii's soils: Approaches for tropical and subtropical agriculture. University of Hawaii. Manoa; 2000. Available: http://www.ctahr.hawaii.edu/oc/freepubs/pdf/pnm3.pdf
66. Mahdi SS, Hassan GI, Hussain A, Rasol F. Phosphorus availability issue, its fixation and role of phosphate solubilizing bacteria in phosphate solubilization. Res. J. Agric. Sc. 2011;2(1):174-179.
67. Yadav BK, Verma A. Phosphate solubilization and mobilization in soil through microorganisms under arid ecosystems. In: Ali M, editor. The functioning of ecosystems. In Tech; 2012. Available: http://www.intechopen.com/books/the-functioning-ofecosystems/phosphate-solubilization-and-mobilization-in-soil-through-microorganisms-under-arid-ecosystems
68. Yadav BK, Tarafdar JC. Ability of *Emericella rugulosa* to mobilize unavailable P compounds during pearl millet (*Pennisetum glaucum* L.) crop under arid condition. Indian J. Microbiol. 2007;41(1):57-63.
69. Hameeda B, Harini G, Rupela OP, Wani SP, Reddy G. Growth promotion of maize by phosphate solubilizing bacteria isolated from composts and macrofauna. Microbiol. Res. 2008;163:234-242.
70. Chabot R, Beauchamp CJ, Kloepper JW, Antoun H. Effect of phosphorus on root colonization and growth promotion of maize by bioluminescent mutants of phosphate solubilizing *Rhizobium leguminosarum* biovar *phaseoli.* Soil Biol. Biochem. 1998;30(2):1615-1618.
71. [Yousefi AA, Khavazi K, Moezi AA, Rejali F, Nadian HA. Phosphate solubilizing bacteria and arbuscular mycorrhizal fungi impacts on inorganic phosphorus fractions and wheat growth. World Appl. Sci. J. 2011;15(9):1310-1318.
72. Rodriguez H, Fraga R. Phosphate solubilizing bacteria and their role in plant growth promotion. Biotech. Adv. 1999;17:319-339.
73. Aseri GK, Jain N, Tarafdar JC. Hydrolysis of organic phosphate forms by phosphatase and phytase producing fungi of arid and semi-arid soils of India. Am-Euras. J. Agric. Environ. Sci. 2009;5(4):564-570.
74. Whitelaw MA. Growth promotion of plants inoculated with phosphate solubilizing fungi. Adv. Agron. 2000;69:99-151.
75. Khan MS, Zaidi A, Wani PA. Role of phosphate solubilising microorganisms in sustainable agriculture: A review. Agron. Sustain. Dev. 2007;27:29-43.
76. Islam MT, Deora A, Hashidoko Y. Isolation and identification of potential phosphate solubilising bacteria from the rhizoplane of *Oriza sativa* L. cv BR29 of Bangladesh. Verlag der Zeitschrift fur Naturforschung. 2007;62:103-110.
77. Oliveira CA, Alves VMC, Mariel IE, Gomez EA, Scoffi MR, Carneiro NP et al. Phosphate solubilising microorganisms isolated from the rhizosphere of maize cultivated in an Oxisol of the Brazillian Cerrado biome. Soil Biol. Biochem. 2009;41:1782-1787.

78. Tarafdar JC, Claassen N. Organic Phosphorus Compounds as a Phosphorus Source for Higher Plants through the Activity of Phosphatases Produced by Plant Roots and Microorganisms. Biol. Fertil. Soils. 1988;5(4):308-312.
79. Tarafdar JC, Bareja M, Panwar, J. Efficiency of Some Phosphatase Producing Soil-Fungi. Indian J. Microbiol. 2003;43(4):27-32.
80. Brudrett MC. Coevolution of roots and mycorrhizas of land plants. New Phytol. 2002;154:275–304.
81. Brundrett MC. Diversity and classification of mycorrhizal associations. Bio Rev. 2004;79:473-495.
82. Achubler A, Schwartzoth D, Walker C. A new fungal phylum, the *Glomeromycota* phylogeny and evolution. Mycol. Res. 2001;12:1413-1421. DOI: http:dx.doi.org/10.1017/s0953756201005196.
83. Morton JB, Benny GL. Revised classification of arbuscular mycorrhizal fungi (Zygomycetes): a new order glomales, two new suborders, *Glomineae* and *Gigasporineae*, and two new families, Acaulosporaceae and Gigasporaceae, Mycotaxon. 1990;37:471-491.
84. Jeffries P. Use of mycorrhize in Agriculture. CRC. Crit. Rev. Biotech. 1987;5:319-348.
85. Smith SE, Smith FA, Jakobsen I. Mycorrhizal fungi can dominate phosphate supply to plants irrespective of growth responses. Plant Physiol. 2003;133:16-20.
86. Pfeffer PE, Douds Jr. DD, Becard G, Shachar-Hill Y. Carbon uptake and the metabolism and transport of lipids in an arbuscular mycorrhiza. Plant Physiol. 1999;120:587-598.
87. Makoi HJR, Ndakidemi PA. The agronomic potential of vesicular-arbuscular mycorrhiza (VAM) in cereals-legume mixtures in Africa. Afr. J. Microbiol. Res. 2009;3(11):667-675.
88. Lupwayi NZ, Kennedy AC, Chirwa RM. Grain legume impacts on soil biological processes in sub-Saharan Africa. Afr. J. Plant Sci. 2011;5(1):1-7.
89. Singh PK. Role of glomalin related soil protein produced by arbuscular mycorrhizal fungi: A review. Agr. Sci. Res. J. 2012;2(3):119-125.
90. Cruz C, Egsgaard H, Trujillo C, Ambus P, Requena N, Amelia M, et al. Enzymatic evidence for the role of argentine in nitrogen translocation by arbuscular mycorrhizal fungi. Plant Physiol. 2007;144:782-792.
91. Barea JM, Jeffries P. Arbuscular mycorrhizas in sustainable soil plant systems. In: Varma A, Hock B, editors. Mycorrhiza: Structure, Function, Molecular Biology and Biotechnology. Springer-Verlag, Berlin. 1995;53(374):521–560.
92. Liu A, Hamel C, Hamitton RI, Ma BL, Smith DL. Acquistion of Cu, Zn, Mn and Fe by mycorrhizal maize (*Zea mays* L.) grown in soil at different P and micronutrient levls. Mycorrhiza. 2000;9:331-336. DOI: 10.1007/s00720050277.
93. Dania SO, Fagbola O, Dania MI. Response of maize-pigeon pea intercrop to arbuscular mycorrhizal fungi in nutrient depleted soil. Ann. Rev. Res. Biol. 2013;3(3):232-245.
94. Sharma A. Yadav S. Review of role of VAM fungi and crop plant-soil system. International Journal of Agricultural Science and Research. 2013;3(1):17-24.
95. Brady N, Weil RR. The nature and properties of soils. 2nd ed. Pearson Education, Inc. New Jersey; 2002.
96. Bolan NS. A critical review on the role of mycorrhizal fungi in the uptake of phosphorus by plants. Plant and Soil. 1991;134(2):189-207. DOI: 10.1007/BF00012037.
97. Song YC, Li XL, Feng G, Zhang FS, Christie P. Rapid assessment of acid phosphatase activity in the mycorrhizosphere and in arbuscular mycorrhizal fungal hyphae. Chin. Sci. Bull. 2000;45:1187–1190.

98. Feng G, Zhang FS, Li XL, Tian CY, Tang C, Rengel Z. Improved tolerance of maize plants to salt stress by arbuscular mycorrhiza is related to higher accumulation of soluble sugars in roots. Mycorrhiza. 2002;12:185–190.
99. Babana AH, Antoun H. Effect of Tilemsi phosphate rock-solubilizing microorganisms on phosphorus uptake and yield of field-grown wheat (*Triticum aestivum* L.) in Mali. Plant and Soil. 2006;287:51-58.
100. Kanno T, Saito M, Ando Y, Macedo MCM, Nakamura T, Miranda CHB. Importance of Arbuscular mycorrhiza for growth and phosphorus uptake in tropical forage grasses growing on acid, infertile soil from the Brazilian savannas. Tropical Grasslands. 2006;40:94-101
101. Basham Y. Inoculants of plant growth-promoting bacteria for use inagriculture. Biotech. Adv. 1998;16(4):729-770.
102. Rebah FB, Prevost D, Yezza A, Tyagi RD. Agro-industrial waste materials and wastewater sludge for rhizobial inoculants production: A review. Biores. Tech. 2007;98:3535-3546.
103. Ajeigbe H A, Dashiell K, Woomer PL. Biological nitrogen fixation and grain legume enterprise: Guidelines for N2Africa Lead Farmers. TSBF Institute of CIAT. Nairobi; 2010.
104. Ministry of Agriculture, Irrigation, and Food Security (MoAIFS). Guide to Agriculture and Natural Resource Management, Agricultural Communications Branch, Lilongwe, Malawi; 2005.
105. Food and Agriculture Organization of the United Nations (FAO). Legume inoculants and their use. FAO Fertilizer and Plant Nutrition Service. Rome. Italy; 1984.
106. Cooperband L. The art and science of composting: A resource for farmers and compost producers. Centre for Integrated Agricultural Systems. University of Wisconsin-Madison. Extension Booklet; 2002.
107. Inckel M, Smet P, Tersemette T, Veldkamp T. The preparation and use of compost. 7th ed. Agromisa Foundation. Wageningen. Netherlands; 2005.
108. Van Durme GP, McNamara BF, McGinley CM. Bench-scale removal of odour and volatile organic compounds at a composting facility. Wat. Environ. Res. 1992;64:19-27.
109. Pagans E, Font X, Sanchez A. Emission of volatile organic compounds from composting of different solid wastes: Abatement by biofiltration. J. Haz. Mat. 2006;131:179-186.
110. Rebollido R, Martinez J, Aguilera Y, Melchor K, Koener I, Stegmann R. Microbial populations during composting process of organic fraction of municipal solid waste. Appl. Ecol. Env. Res. 2008;6(3):61-67.
111. Hubbe MA, Nazhad M, Sanchez C. Composting as a way to convert cellulosic biomass and organic waste in high-value soil amendments: A review. BioResources. 2010;5(4):2808-2854.
112. Kim TI, Jeong KH, Ham JS, Yange B, Chung IB, Kim MK, et al. Isolation and characterization of cellulase secreting bacterium from cattle manure: application to composting. Compost Sci. Utilizat. 2004;12(3):242-248.
113. Espriritu BM. Use of compost with microbial inoculation in container media for mungbean (*Vigna radiata* L. Wilckzek) and pechay (*Brassica napus* L.). J. ISSAAS. 2011;17(1):160-168.
114. Rashad FM, Saleh WD, Moselly MA. Bioconversion of rice straw and certain agro-industrial wastes to amendments for organic farming systems: composting quality, stability, and maturity indices. Biores. Technol. 2010;101(15):5952-5960.

115. Patidar A, Gupta R, Tiwari. Enhancement of biodegradation of bio-solids via microbial inoculation in integrated composting and vermicomposting technology. Open Access Sci. Rep. 2012;1(5):1-4.
116. Amlinger P, Peyr S, Geszti J, Norticliff S. Beneficial effects of compost application on fertility and productivity of soils. Lebensministerium.at; 2007. Available: www.lebensministerium.at/dms/lmat/...-/CompBenefits%5B1%5D.pdf
117. Hepperly P, Lotter D, Ulsh CZ, Seidel R, Reider C. Compost manure and synthetic fertilizer influences crop yields, soil properties, nitrate leaching and crop nutrient content. Compost Sci. Utilizat. 2009;17(2):117-126.
118. Lehrsch GA, Kincaid DC. Compost and manure effects on fertilized corn silage yield and nitrogen uptake under irrigation. Comm. Soil Sci. Plant Anal. 2007;38:2131-2147. DOI: 10.1080/00103620701548977.
119. Okoko ENK, Makworo S. Evaluation of the effects of compost and inorganic fertilizer on maize yield in Nyamira district, South West Kenya. Kenya Agricultural Research Institute. 2000. Available: www.kari. Org/fileadmin/publications/legume-project/….2000/3.pdf
120. Edwards S, Asmelash A, Araya H, Egziabh TBG. The impact of compost use in crop yields in Tigray, Ethiopia, 2000-2006 inclusive. FAO, Rome; 2007. Available: http://betuco.be/compost/Impact%20of%20Compost%20Use%20on%20Crop%20Yields%20in%20Tigray,%20Ethiopia.pdf
121. Giller KE, Witter E, Corbeels M, Tittonell P. Conservation agriculture and smallholder farming in Africa: the heretics" view. Field Crops Res. 2009;114:23-24.
122. Ajayi OC, Akinifesi FK, Sileshi G, Chakeredza, S. Adoption of soil fertility replenishment technologies in southern Africa: Lessons learnt and the way forward. Natural Resources Forum. 2007;31:306-317.
123. Sanginga N, Woomer PL. editors. Intergrated Soil Fertility Management in Afirica: Principles, Practices and Development Process. Nairobi: Tropical Soil Biology Institute of the International Centre of Tropical Agriculture; 2009.
124. Opperman C. Soybean value chain. Technical Report. USAID Southern Africa. Gaborone. Botswana; 2011.
125. Chianu JN, Nkonya EM, Mairura FS, Chianu JN, Akinifesi FK. Biological nitrogen fixation and socioeconomic factors for legume production in Sub-Saharan Africa: a review. Agron. Sustain. Dev. 2011;31(1):139-154. DOI: 10.1051/agro/2010004.

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