Efficacy of Biofertilizers: Challenges to Improve Crop Production

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Abstract

Different kinds of soil microorganisms belonging to several taxa of the bacteria, fungi, and possibly, protozoa kingdoms, colonizing the rhizosphere or the plant tissues and promoting plant growth (PGPM), can be utilized for the production of microbial-based fertilizers (biofertilizers). However, their application in agricultural practice is still hindered by several factors. The main reasons derive from the unpredictability of results, problems to identify and track inoculated strains in the field, the poor understanding of the interrelationships between microorganisms and plants, and the technology of production. After describing in brief which microorganisms have been utilized up until now to improve plant productivity through enhanced nutrition, we mention for possible exploitation of new groups of microorganisms (e.g. non-mycorrhizal fungi). Furthermore, we review the factors affecting the efficacy of biofertilizers on crop productivity, from the point of view of the farmers, who appraise their application on the base of their efficacy. In particular, we consider the factors related to the production process (including quality and marketing standards), the persistence and traceability of inoculants, the relations between plant, soil conditions and microorganisms, as well as the effect of farmers' practices (fertilization, soil management practices, application method). In conclusion, it emerges that biofertilizers could allow obtaining a crop productivity similar to that obtained with mineral fertilizers, but with a significant reduction of their use. Therefore, biofertilizers can play a key role to develop an integrated nutrient management system, sustaining agricultural productivity with low environmental impact.

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2.1 Introduction

Exploiting microbial-based fertilizers can be traced back to ancient times—already Classical Greek and Roman writings (namely Virgil's *Georgics* or Pliny the Elder's *Naturalis Historiae*) described agricultural practices for improving yield, that we can today link to microbiological activity (e.g. rotation with legumes or use of animal manure); the ancient Maya were managing water in the Mexico wetlands to support a complex mixture of algae, cyanobacteria, and other microorganisms also with the purpose of increasing the content of nutrients in the soil (Morrison and Cozatl-Manzano 2003). However, a conscious use of microorganisms for soil fertilization started in the late nineteenth century, when patenting and marketing of microorganisms for fertilization purposes began (Kilian et al. 2000; Nobbe and Hiltner 1896, cited in Bashan 1998). Since then, particularly in the last couple of decades, the development and use of microbial-based fertilizers has gained significance in the effort of reducing the negative environmental effects generated by the excessive and/or improper application of chemical fertilizers. However, despite the huge amount of studies and findings of beneficial strains, the application of microbial-based fertilizers in agricultural practice is still hindered by several factors. The main reasons derive from the unpredictability of results, problems to identify and track inoculated strains in the field, the poor understanding of the interrelationships between microorganisms and plants, and the technology of production (Bashan et al. 2014; Lucy et al. 2004; Owen et al. 2015). In this chapter, we aim to describe which factors we consider as mostly affecting a widespread exploitation of microbial fertilizers. Moreover, we want to foster actions by the different stakeholders interested in this sector that could promote a wider practical application of these products. We also briefly describe which microorganisms have been utilized up until now to improve plant productivity through enhanced nutrition, also providing information about new groups of microorganisms not widely exploited yet.

2.2 Microorganisms for Biofertilizers

Different kinds of soil microorganisms belonging to several taxa of the bacteria, fungi, and possibly, protozoa kingdoms, colonizing the rhizosphere or the plant tissues and promoting plant growth (PGPM), can be utilized for the production of biofertilizers (Lucy et al. 2004; Smith and Read 2008; Vessey 2003). Their contribution to plant nutrition can be limited to a single nutrient element, as in the case of N-fixing bacteria, or to a variety of elements, such as for arbuscular mycorrhizal fungi (AMF) (Bardi and Malusà 2012, and references therein). However, they can have a remarkable impact on the yield and quality of plants, increasing the nutrient uptake capacity and the use efficiency of applied chemical or organic fertilizers. Rhizobia, the best known N_2-fixing bacteria symbionts of legume plants, are able to provide up to 90 % of the N requirements of the host through atmospheric N_2 fixation (Franche et al. 2009), but they can also behave as plant growth promoting rhizobacteria (PGPR) with non-legumes such as maize, wheat, rice, and canola (Hayat et al. 2010; Yanni et al. 2001). Non-symbiotic free-living N-fixing bacteria species have been proved to enhance N uptake of plants (Bardi and Malusà 2012; Lucy et al. 2004; Okon and Labandera-Gonzalez 1994), which can derive nitrogen from biological nitrogen fixation in 7–58 % range in cereals (Baldani et al. 2000; Malik et al. 2002) and up to 60–80 % in sugarcane (Boddey et al. 1991). Cyanobacteria

(*Anabaena*, *Aulosira* and *Nostoc*), as free-living or in symbiosis with Azolla, a small free floating fresh water fern, were found to fix N and to release it for rice uptake in the range of 30–40 up to 70–110 kg N ha^{-1} (Wagner 1997). Arbuscular mycorrhizal fungi (AMF) may supply more than 50 % of plant N requirements (Govindarajulu et al. 2005; Leigh et al. 2009), which is particularly important under arid and semi-arid conditions, where water availability limits uptake of mobile nutrients such as inorganic N (Subramanian and Charest 1999). AM fungi can take up nitrogen both as inorganic (either ammonium or nitrate) and organic (Hawkins et al. 2000).

Arbuscular mycorrhizal fungi form the major group of microorganisms contributing to plant phosphorus (P) uptake (Smith and Read 2008) by increased exploitation of the soil (Cavagnaro et al. 2005), the solubilization of inorganic P forms (Tawaraya et al. 2006), and the hydrolization of organic P (Richardson et al. 2009). Several PGPR are very effective in solubilizing P from the highly insoluble tricalcium phosphate, hydroxyl apatite and rock phosphate (Rodríguez and Fraga 1999; Owen et al. 2015).

A wide array of bacterial genera (e.g. *Pseudomonas*, *Burkholderia*, *Acidothiobacillus*, *Bacillus* and *Paenibacillus*) are able to release potassium from minerals such as mica, illite, muscovite, biotite and orthoclases (Bennett et al. 1998, 2001; Liu et al. 2012), increasing K availability up to 15 % (Supanjani et al. 2006).

The search of new strains of microorganisms showing beneficial effects for plant nutrition has fostered studies on species that were less considered in the past. Following, we present an overview of results and potentialities which could derive from the introduction of non-mycorrhizal fungi into biofertilizers.

2.2.1 Potentialities of Non-Mycorrhizal Fungi as Inoculants for Biofertilizers

Fungi are ubiquitous in soil, and can be dominant components of the microbiota in many soil types (Gadd 2004; Burford and Gadd 2003). For example, fertile soil may contain a fungal network up to 10,000 km/m^2 (Burford et al. 2003). By adapting their metabolism to the availability of varying nutritive compounds in the soil environment, fungi produce a wide range of oxidative and hydrolytic enzymes that allow them to efficiently break down organic matter like ligno-cellulosic materials but also other natural or human-derived compounds, like in the field of xenobiotic and organic pollutant degradation (Harms et al. 2011).

The plasticity of fungi biology and the plethora of functions that can be attributed to fungal metabolism suggest that there are several potential uses and forms of exploitation of non-mycorrhizal fungi for the production of biofertilizers. The ability of some fungal groups or species in the dissolution or leaching of minerals and elements' chelation and translocation has been very little evaluated and even less exploited as a potential for the production of innovative soil amendments.

The biological activity of fungi can cause the enrichment of C, N, and S in the soil, making these as well as other nutrients available to plants. Moreover, fungi are capable of transporting substances in their hyphae that act as pipes connecting microenvironments with different concentration of nutrients and can actually transport ions against a chemical osmotic gradient (Banitz et al. 2011, 2013). Translocation across distant parts of the mycelium enables fungi to colonize places with low initial resource availability and to actively change the microenvironment and the availability of nutrients in the substrates, turning the colonizing mycelium from a resource sink into a source (Banitz et al. 2011, 2013). Jongmans et al. (1997) proposed that tunnels formed inside weatherable mineral grains were likely to have been formed by fungal hyphae and coined the term “rock-eating fungi” to describe such microscopic tunnels within feldspar and hornblende grains in the eluviated horizon of podzol soils. Within soils, a vertical distribution can be distinguished regarding fungal type in terms of their ecology (Pinzari et al. 2001). Organic layers are mostly colonized by

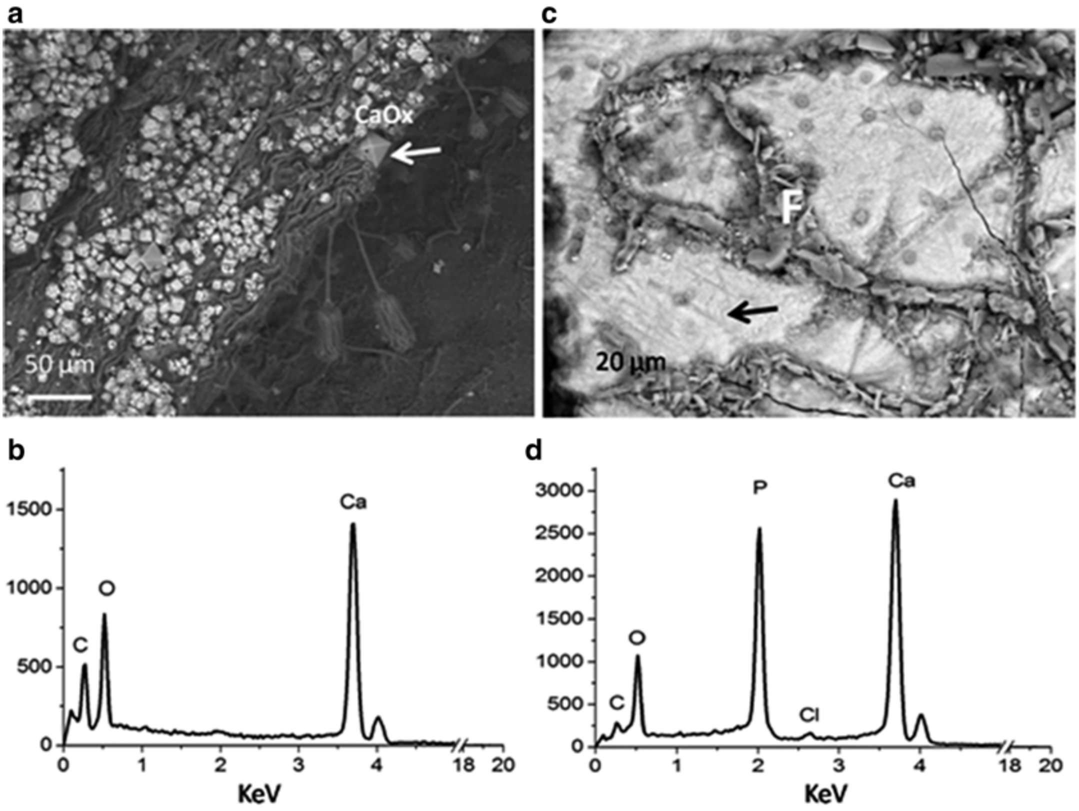

Fig. 2.1 Precipitation of calcium oxalates by filamentous fungi and solubilization of P-containing minerals observed with a Zeiss EVO 50 variable pressure scanning electron microscope (VP-SEM) operating at an accelerating voltage of 20 kV equipped with a detector for backscattered electrons (BSE) (Pinzari et al. 2012): (**a**) bipyramidal structures of calcium oxalate produced in vitro by an *Aspergillus* (*A.terreus*); (**b**) energy dispersive spectroscopy (EDS) spectra with chemical characterization of the crystals mainly containing Ca; (**c**) solubilization of apatite (P-containing minerals) by fungal hyphae (*Aspergillus niger*): tracks of dissolution of the mineral material are caused by fungal growth. In the tracks, around fungal threads other biogenic crystals are deposited. (**d**) X-ray area scan of the apatite that contains P and Ca. The y-axis on the spectra represents the EDS counts in arbitrary units

saprophytic fungi, whereas mineral layers are colonized by mycorrhizal fungi (Van Schöll et al. 2008).

Fungi can dissolve rocks and leach minerals by different mechanisms that involve the excretion of H+, or the production of primary and secondary metabolites with mineral solubilization or metal-chelating properties like siderophores, phenolic compounds, carboxylic acids, and amino acids. The potential of some fungal species in the breakdown of mineral phosphates could be very high, as shown in some recent papers (Pinzari et al. 2012) (Fig. 2.1). Fungi are more efficient than bacteria in P solubilisation, on both solid agar and in liquid cultures (Saxena et al. 2013). According to some authors, subculturing of most of the P-solubilizing bacteria results in the loss of the phosphate solubilizing activity (Halder et al. 1990) while fungi maintain their ability to leach P-containing rocks even after prolonged culturing (Kucey 1983). Such features could be important in the industrial manufacturing of biofertilizers for P nutrition.

P mobilization, particularly from Fe and Al phosphates, has been shown to be performed also by non-symbiotic fungi from different species of genera such as *Penicillium, Aspergillus*, *Trichoderma*, *Mucor*, *Candida*, *Discosia*, *Eupenicillium*, and *Gliocladium* (Ahmed and Shahab 2009; Jain et al. 2012; Saxena et al. 2013; Wakelin et al. 2007; Whitelaw 2000). The solubilizing ability of P minerals by the different organic acids produced by fungi also allows the mobilization of minerals other than phosphates (Achal et al. 2007; Ahmed and Shahab 2009; Asea et al. 1988). Esterase type enzymes released by fungi are known to be involved in liberating phosphorus from organic P compounds (Ahmed and Shahab 2009).

Fungal dissolution mechanisms can release also other cations like Si^{4+}, Fe^{3+}, Al^{3+}, and Ca^{2+} (Boberg et al. 2009). In general, fungi are strong solubilizing agents of K containing minerals such as feldspar, biotite, and phyllosilicates by organic acid release (Ahmed and Shahab 2009; Gadd 1999; Sayer et al. 1995; Singhal et al. 1994). *Piloderma* was able to extract potassium and/or magnesium from biotite, microcline, and chlorite to satisfy plant nutritional requirements (Glowa et al. 2003).

Fungal cells can also represent elective sites for biogenic mineral precipitation. This is the case of calcite or metal oxalates precipitation, which would also influence the availability of phosphates for plants that have been widely documented as coupled to fungal growth in near-surface limestones (calcretes), calcic and petrocalcic horizons in soils (Gadd 2007). Reduced forms of metals (such as Ca, Cd, Co, Cu, Va, Mn, Zn, Ag, Ni, and Pb) can be precipitated by many fungi within and around fungal cells (Gadd 2007). Mechanisms of fungal mineral weathering, translocation or bio-precipitation are still little known, but could represent useful tools especially in the perspective of using fungi in the formulation of biofertilizers aimed at improving soils' chemical and structural properties as well as plant nutrition (Table 2.1).

Table 2.1 Fungal properties that can be further explored for new biofertilizers

Fungal property	Potential applications for improving crop production	Examples or reference studies
Hyphae highly suited to growth across soil physical structure (surfaces, pores, and air gaps)	Fungi as highways or pipelines for nutrients translocation	Wick et al. (2010), Furuno et al. (2012), Banitz et al. (2011, 2013)
Ability to develop in patchy environments	Improvement of soil fertility and treatment of extreme heterogeneous soils (i.e. saline soils)	Green et al. (2008), Bashan and de-Bashan (2010)
Translocation and redistribution of biogenic elements	Improvement of soil fertility	Boberg et al. (2009)
Growth in low nutrient habitats	Widening the possibility of crop production in sites with low resource availability	Green et al. (2008)
Dissolve rocks, leach minerals, precipitation of calcium oxalate	P solubilization and availability	Sudhakara et al. (2002), Kucey (1983), Chuang et al. (2007)
	Si solubilization	Meena et al. (2014), Pradhan and Sukla (2005)
Chitin as elective sites for biogenic mineral precipitation	Ca insolubilization	Gadd (2000), Burford et al. (2003)
	Toxic metals precipitation	
Precipitation of reduced forms of metals (like Ca, Cd, Co, Cu, Va, Mn, Zn, Ag, Ni, and Pb) within and around fungal cells	The precipitation of metal oxalates may provide mechanisms that allow fungi tolerating high concentrations of toxic elements	Gadd (2007)
		Gadd (2008)
		Harms et al. (2011), Fomina et al. (2003, 2004, 2005), Daghino et al. (2010)
Degradation of organic compounds	Compost stabilization	Harms et al. (2011), Gadd (2008), Wick et al. (2010)
	Organic pollutants decomposition	

2.2.2 Fungal Inocula for Micronutrients Mobilization: The Case of Silicon

Lack of trace elements in soil is not uncommon (Bell and Dell 2008). However, the limitation of vital micronutrients can be attributed to some factors that reduce their availability for crops such as low organic matter content, high amounts of sand (soils with coarse textures), use of chemical fertilizers that change the equilibrium between soil fungi and bacteria as well as between the mineral substrates and microorganisms, or to other menaces that alter soil functions and fertility (compaction, desertification, etc.) (Brevik and Burgess 2012). Although these elements could be abundant in rocks, they are not always available to plants, as in the case of silicon (Si). Silicon is present in plants, and several studies have shown beneficial effects of silicon fertilization for agricultural crops (Belanger et al. 1995; Savant et al. 1997, 1999; Meena et al. 2014). The beneficial effects seem mainly associated with Si deposition in plant tissues, which enhances their rigidity and resistance to mechanical stress. This increased strength improves the light-receiving posture of the plant, benefiting photosynthesis, and enhances the resistance to biotic and abiotic stresses (Gascho 2001). Plants absorb silicon from the soil solution in the form of monosilicic acid, also called orthosilicic acid (H_4SiO_4) (Meena et al. 2014). Typical silicon absorbers and accumulator crops are rice, wheat, millet, and sugarcane, which require a relative large amount of silicon. However, inorganic materials such as quartz, clays, micas, and feldspars, although rich in Si, are poor sources because of their low solubility (Meena et al. 2014).

Fungi and bacteria can solubilize insoluble silicates (Wainwright et al. 1997; De Mico et al. 2004). Fungi, while degrading silica-based rocks, can release other mineral nutrients (e.g. potassium, iron and magnesium) (Daghino et al. 2010). The solubilization process occurs mainly via the production of organic and inorganic acids and complexing agents (Gadd 2008) and it is faster than that of bacteria (Castro et al. 2000; Gadd 2008; Daghino et al. 2010). The ability of *Aspergillus niger* in weathering olivine, serpentine, feldspar and other minerals, of *Penicillium simplicissimum* disgregating basalt, of *Penicillium expansum* and *Scopulariopsis brevicaulis* solubilizing alumino-silicates has been demonstrated (Daghino et al. 2010). The solubilization of silica by fungi (and bacteria) is considered as a source of supply for several crops such as cotton, maize, wheat, potato and tomatoes (Meena et al. 2014). Therefore, to fully exploit this capacity and benefit of Si nutrition by plants, further studies on application of bioinoculants for improving Si availability are needed.

From this general brief overview it appears that the availability of several beneficial strains from the different groups of microorganisms is not hindering the possibility of formulating an efficient biofertilizer.

2.3 Factors Affecting the Efficacy of Biofertilizers

The various mechanisms involved in plant promotion may be host plant-specific and strain-specific. Furthermore, once introduced into the soil, plant growth promoting microorganisms (PGPM) face competitive conditions that may severely reduce their beneficial effects (Bashan 1998). Therefore, the beneficial effects deriving from the application of a specific biofertilizer may differ greatly under different agro-environmental conditions and this has resulted in contesting the efficacy of microbial-based products (Cummings 2009; Owen et al. 2015). However, to overcome such perception and improve the propensity of farmers in using biofertilizers, it is useful to consider which factors affect the efficacy of biofertilizers on crop productivity trying to meet the point of view of the farmers, who appraise the application of a biofertilizer as for any other technical mean, on the base of its efficacy. For practical purposes, we have grouped the factors that could mainly be considered as those mostly affecting biofertilizers efficacy with relation to the plant, the soil, the farmers and the products themselves (Fig. 2.2).

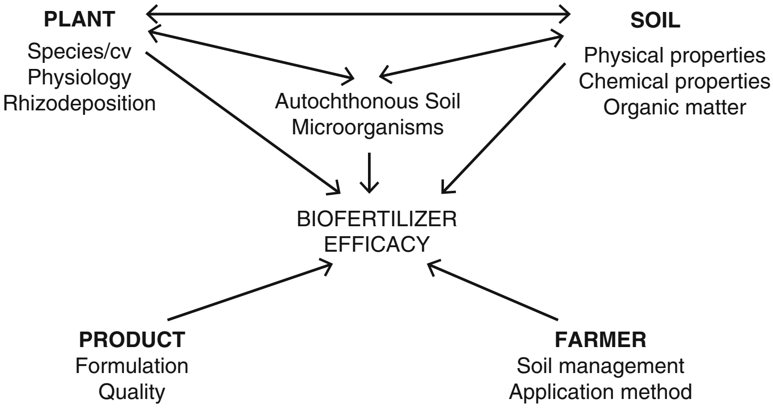

Fig. 2.2 Major factors affecting the efficacy of biofertilizers in improving crop nutrition, growth and yield

2.3.1 Factors Related to the Product

2.3.1.1 Production Process

The production process of the inoculum is key to a final high-quality product (Bashan et al. 2014), since there is a direct relationship between the population density of mother culture and the quality of the final products (Stephens and Rask 2000). Commonly, the inoculum is formed of one strain. However, the understanding of the complex relationships among the microorganisms interacting in the rhizosphere has fostered the study on inocula composed of more than one microorganism which have showed promising results both in legumes and non-legume plants. Successful examples, in case of legumes, comprised the co-inoculation of rhizobia with arbuscular mycorrhizal fungi (AMF) (Wang et al. 2011), dual inoculation of *Rhizobium* and phosphate solubilizing bacteria (Alagawadi and Gaur 1988), an inoculum formed of *Rhizobium* together with a plant growth promoting rhizobacteria (PGPR) and a phosphorous solubilizing bacteria (PSB) (Prasad and Chandra 2003). In non-legumes, nutrients uptake comparable to chemically fertilized plants have been reported with dual inoculations involving AMF and free-living N-fixing bacteria (Adesemoye et al. 2008; Barea et al. 2002; Lisette et al. 2003; Wang et al. 2011), also under dry conditions (Aseri et al. 2008). Consortia of AMF and different PGPR were beneficial for different annual and horticultural crops (Malusà et al. 2007; Wu et al. 2005), leading to a reduction of fertilizer application by up to 50 % (Singh and Adholeya 2003). Better nutrient efficacy was reported also in the case of PSB and KSB mixture inocula (Han and Lee 2005; Vassilev et al. 2006a).

When designing a consortium for a biofertilizer, it should be considered that certain bacterial groups appear to associate more frequently with AM fungi or to be inhibited by them by several mechanisms (Filion et al. 1999; Mansfeld-Giese et al. 2002; Sood 2003; Toljander et al. 2006; Vestergård et al. 2008; Wamberg et al. 2003), including the fungal release of stimulatory or inhibitory compounds (Johansson et al. 2004), which could result in a higher or limited colonization of the roots, respectively. Also the species specificity of the strains, even in case of AMF, or the differences in adaptation to environmental condition should be considered when selecting strains to formulate a biofertilizer (Antunes et al. 2011; Zoppellari et al. 2014; Malusà et al. 2012).

A PGPM consortium could be more efficient due to the different mechanisms of action of the various microorganisms present, sometimes overlapping also plant protection mechanisms (e.g. Vassilev et al. 2001, 2006b), which tend to match the requirements of both farmers, in using "multifunctional" products, and manufacturers, preferring to market a product for several purposes. A potential example of such kind of product could be that patented in the USA by Reddy and Janarthanam (2014) or already marketed in Europe under the brand name Micosat (CCS Aosta). However, not always the efficacy of consortia has proven to be consistent, and also their production and commercialization raises some technical problems (Herridge 2008; Stephens and Rask 2000). This could derive from the observation that a key aspect determining the relationship of microorganisms with plants is not their taxonomic diversity, but rather their functional diversity (Nannipieri et al. 2003; Maherali and Klironomos 2007).

A sufficiently long shelf life of the inoculant (up to at least one season), maintaining its biological traits at an adequate level, is key for assuring the efficacy of the biofertilizer, though being a major challenge for any kind of formulated product (Bashan et al. 2014). Therefore, the formulation of the inocula, i.e. a multistep process which results in mixing one or more strains of microorganisms (inoculum) with a particular carrier, with or without additives (e.g. sticking agents or other additives), plays an important role in assuring the efficacy of the biofertilizer. It allows the protection of the cells during storage and transport, possibly enhancing the persistence of the inocula in soil, in order to obtain the maximal benefits after inoculation of the host plants (Manikandan et al. 2010; Schoebitz et al. 2012).

Different carriers can be used in the formulation process, and each of them presents specific positive qualities and drawbacks, affecting thus the overall quality and efficacy of the biofertilizers (Bashan et al. 2014; Herrmann and Lesueur 2013; Herridge 2008; Malusà et al. 2012). Nevertheless, granular inoculants are showing better results under harsh soil conditions (Clayton et al. 2004; Lupwayi et al. 2006; Rice et al. 2000). Liquid inoculants, though easier to distribute, have shorter shelf life (Bashan et al. 2014; Date 2001; Stephens and Rask 2000). Encapsulation into polymers, though theoretically allowing very diverse compositions and structures (Vassilev et al. 2005), has been mainly limited in practice to formulations based on alginate, which still presents some limitations for industrial production (Bashan et al. 2014; John et al. 2011).

Besides the various additives used to improve the shelf life of the product (Bashan et al. 2014; Malusà et al. 2012; Herrmann and Lesueur 2013), specific compounds can be introduced into the formulation to enhance the efficacy of biofertilizers. Legume biofertilizers containing elicitors of nodulation are already marketed (Mabood et al. 2006; Skorupska et al. 2010; Smith and Smith 2012), but other rhizobial metabolites related to the nodulation process (Nod factors) were successful in enhancing the performance of N-fixing bacteria inoculants on soybean and maize (Marks et al. 2013). Strigolactones, also in the form of synthetic analogous, could be used to foster the establishment of the mycorrhizal symbiosis (Ruyter-Spira et al. 2011; Xie et al. 2010).

2.3.1.2 Marketing of Biofertilizers and Quality Standards

The development of a new kind of products based on microorganisms is requiring a general agreement on the definition of the terminology or name used. Frequently, in the scientific literature the term ‘biofertilizer’ has been used to describe a simple microorganism showing plant growth promotion effects (Bardi and Malusà 2012, and references therein). However, as mentioned above, to be used within agronomical practices, any beneficial microorganism (inoculum) requires to be formulated to allow the effective delivery to the soil or plant. Along with the increased understanding of the mechanisms of action of the different kinds of beneficial microorganisms, the term biofertilizer has been defined in different ways (Okon and Labandera-Gonzalez 1994; Vessey 2003; Fuentes-Ramirez and Caballero-Mellado 2005), sometimes associating also a confusing terminology that does not take into consideration the legal definitions in place for other kinds of fertilizers or amendments (Owen et al. 2015). Recently, in an effort to propose a definition that could be useful also for regulatory purposes, Malusà and Vassilev (2014) have proposed to define biofertilizers, in analogy to the mineral or organic fertilizers, as “the formulated product containing one or more microorganisms that enhance the nutrient status (the growth and yield) of the plants by either replacing soil nutrients, and/or by making nutrients more available to plants and/or by increasing plant access to nutrients”. An agreed, legally binding, definition of these products, as well as the establishment of minimum legal standards for registration and marketing of biofertilizers are also important to assure a minimum quality standard, which is another factor affecting the efficacy of biofertilizers' field performance. Indeed, it seems that the quality of biofertilizers has not been improving in the last few decades. Surveys carried out in the 1990s on products containing rhizobia showed a high level of contamination, with alien bacteria outnumbering the rhizobia in the great majority of products (Olsen et al. 1994, 1996). A similar situation emerged from a recent survey where 40 % of 65 tested commercial bacterial products (formulating also PSB and free-living N-fixing strains) did not contain the claimed strain, but only contaminants (Herrmann and Lesueur 2013). The situation does not appear more promising in case of AMF-based biofertilizers: surveys of products showed a very low quantity of viable propagules and reduced colonization potentials (Corkidi et al. 2004; Faye et al. 2013; Rowe et al. 2007; Tarbell and Koske 2007). Such frauds, together with insufficient label information, are probably the major reason for inconsistency of outcomes in field use of biofertilizers and are thus causing a lack of confidence in this kind of products which is affecting their market potential (Bhattacharyya and Jha 2012; Gemell et al. 2005; Husen et al. 2007). Marketing of biofertilizers should thus be regulated assuring a minimum quality standard of the final product (Herrmann and Lesueur 2013; Malusà and Vassilev 2014).

The distribution chain can also further affect the overall quality of biofertilizers. Indeed, several studies have demonstrated the decline of microbial populations in inoculants over time, particularly under non-optimal storage conditions, resulting in lower inoculation efficiency (Biederbeck and Geissler 1993; Maurice et al. 2001) and reduced quality (Hartley et al. 2005).

2.3.1.3 Persistence and Inoculant Traceability in Soil: Need for a Standard Method

The assessment of the persistence and traceability in soil of the strains applied with biofertilizers can be very difficult to investigate due to the complex web of microorganisms present in the soil and the rhizosphere, which can exceed hundred million units (Torsvik and Ovreas 2002), and the high variability of the microbial communities which reflects ecological, environmental and structural soil characteristics, as well as the large variety of agricultural management systems (see headings below). Therefore, no single qualitative and quantitative approach of traceability can capture the persistence of a bioinoculant in soil because of the variety of organisms marketed as biofertilizers. This raises questions about which methods should be considered suitable to monitor the persistence of the different inoculated strains. Such information is fundamental to evaluate the success of inoculation, thus helping to fine tune its application strategy. There is a perceived need for accurate and standard methods that can identify and trace the inoculants in soils.

During the past two decades, phenotypic and PCR-based methods have been developed to better characterize the structure, dynamics and diversity of soil microbial communities. The different methods address different questions, and therefore can all be suitable for the monitoring of the effects in soil due to the introduction of bioinoculants, and to give a picture of different aspects of the microbial community. For the detection of microorganisms released in the environment, molecular methods based on PCR techniques that use natural genome polymorphism have largely facilitated and allowed the discrimination at the strain level, of natural and introduced organisms, minimizing the costs and the time efforts (Öpik et al. 2010; Stockinger et al. 2010; Sýkorová et al. 2012). There are several molecular DNA fingerprinting methods that can be adopted to probe the inoculated strains, but they are mainly qualitative and not quantitative. Among the culture-independent methods available, commonly used to investigate soil microbial communities, traditional molecular fingerprinting, sequencing, or combination of different approaches can be used (Trabelsi and Mhamdi 2013; Schwieger and Tebbe 2000; Hirsch et al. 2010; Han et al. 2012).

The fingerprinting method, based on universal bacterial primers, was found not sufficient to discriminate between non-native and native microorganism when used singly (Pellegrino et al. 2012). However, combining a community level fingerprinting approach such as T-RFLP, with phylogenetic strain identification after a culture-dependent approach, proved to be a sound approach to highlight differences in community structure and at the same time to track inoculants (Pellegrino et al. 2012). To widen the understanding of the effect of the inoculant on the autochthonous microbial community, the real-time PCR with probes targeting the genes of interest, together with quantifying their copy number, can provide information on the relative abundance of the introduced strains within the microbial community; this approach could be used to follow the dynamics of the microbial community after the application of the biofertilizer (Babić et al. 2008).

The molecular marker-assisted approach, such as T-RFLP, DGGE, TGGE, can also be particularly useful for monitoring purposes. The combination of two culture-independent methods can allow assessing the persistence of microbial inoculants introduced in the soil, also evaluating at the same time, the possible changes occurring at species level for native strains. In this case, the community-level fingerprinting profile can be the preliminary method that allows to define the size of the clone library and the sequencing analysis. Nevertheless, in order to avoid inconsistent results due to the spatial heterogeneity of soil microbial populations, either horizontally or vertically, the soil sampling protocol shall follow a methodology that considers such variability. Successful examples of the application of such methodology can be found in some recent papers. Combining a community-level T-RFLP analysis, with phylogenetic strain identification by culture-dependent approach, made tracking the inoculants possible (Pellegrino et al. 2012). The tracing of an inoculated AMF isolate in the roots of target plants was carried out on the base of a nested PCR protocol (Sýkorová et al. 2012). Habteselassie et al. (2013) used, for the purpose of AMF tracing, the PCR amplification of a target gene followed by clone-assisted or direct sequences analysis. A PCR coupled with a novel combination of NS31 and Glomeromycota-specific LSUClom1 primers targeting the nuclear rDNA cistron, and classified amplicons by T-RFLP were designed to trace two inoculants of arbuscular mycorrhizal fungi discriminating them from native strains in roots up to two year post-inoculation (Pellegrino et al. 2012). Ceccarelli et al. (2010) used sequencing to better trace AMF applied strains showing that the marker-assisted fingerprinting analysis and the associated cloning and sequencing approach represents a multi-approach effective method for traceability of inoculants in soil.

2.3.2 Factors related to the plant

The plants can exert a significant effect on the strain(s) forming the biofertilizer and on their efficacy in promoting growth and yield, which are intimately related to the plant physiological status and phenological phase of growth. Indeed, depending on their nutritional status, plants can modify the release of compounds from the roots resulting in both quantitative and qualitative differences in rhizodeposits (Hartmann et al. 2009; Uren 2007), varying in time and space with respect to the position on the root (Dennis et al. 2010) and growth stage (van Overbeek and van Elsas 2008), which can lead to the selection of specific rhizosphere bacterial communities (Paterson 2003; Marschner et al. 2004; Marschner and Timonen 2005). Furthermore, root exudates contain compounds with stimulatory and inhibitory effect on rhizosphere microorganisms that affect their capacity of establishing beneficial relations with the plant (Hartmann et al. 2009; Bais et al. 2006). Under P-deficiency, plants release more chemical signals stimulating hyphal branching (Akiyama et al. 2005) and colonization (Akiyama et al. 2002) of AM fungi than under P-sufficient conditions. Plants can also influence the functions of soil microorganisms, such as nitrification (Smits et al. 2010). However, root exudates from a long-term monoculture of soybean had little effect on the nitrifier community, but reduced nitrification in the rhizosphere; in contrast, total AMF hyphal length was significantly stimulated by the increased release of genistein (Wang et al. 2012), a phenylpropanoid compound probably involved in the chemical signaling leading to AMF root colonization (Cesco et al. 2010). Phenolic acids, also exuded by roots, are responsible for the shift in soil microbial communities (Qu and Wang 2008).

However, it has been suggested that rhizosphere microbial communities respond to other rhizosphere carbon pools (e.g. microbial exudates) for the majority of their coexistence with their plant host, thus limiting in reality the role of rhizodeposits in shaping the rhizosphere microbial community (Dennis et al. 2010), therefore also of the strains inoculated with the biofertilizer. Nonetheless, root exudates are likely to be of great importance in initiating the rhizosphere effect in very young seedlings and on emerging lateral roots. In this respect, the application of biofertilizers on seeds and seedlings would increase the efficacy of the treatment.

2.3.3 Factors Related to Soil Conditions

2.3.3.1 Abiotic Interactions

Soil chemical (pH, nutrient content) and physical (texture) characteristics have been found to shape both bacterial and fungal communities (Girvan et al. 2003; Fierer and Jackson 2006; Lauber et al. 2008; Marschner et al. 2004). Soil pH has been found to be the most important predictor of bacterial community structure at the ecosystem level, with higher diversity associated with neutral soils and lower diversity in acidic soils, likely due to the relatively narrow pH growth tolerance of bacterial taxa (Fierer and Jackson 2006; Rousk et al. 2010). The field surveys of AMF communities in a wide range of soil pH suggest that it is also the major driving force for structuring these communities (Dumbrell et al. 2010; Wang et al. 1993), thus affecting the colonization potential, and efficacy, of all kinds of PGPM included in biofertilizers. Adaptations of AMF to abiotic factors such as soil temperature and nutrient availability can strongly influence the effect of the AMF symbiosis on plant growth (Treseder and Allen 2002; Antunes et al. 2011).

2.3.3.2 Interaction with Autochthonous Soil Microorganisms

When introduced into the soil, the biofertilizer strain(s) face the competition from indigenous microorganisms. However, the knowledge of the ecological interactions among soil microorganisms and about the impact of those included into biofertilizers with the soil microbial populations are still limited and do not allow to effectively predict the effect of inoculants introduced with the biofertilizers. Nevertheless, there is a great effort in evaluating these interrelationships and their impact on biofertilizers efficacy, both on the short- and long-term, using methods such as the analysis of soil microbial biomass, soil microbial activity, soil microbial community structure and diversity (Trabelsi and Mhamdi 2013). It has been demonstrated that inoculation with products containing different PGPM (e.g. fluorescent pseudomonad, symbiotic and free-living N-fixing bacteria, AM fungi, etc.) affects in different ways various taxonomical or functional groups of autochthonous soil microorganisms. The application of inocula based on N-fixing bacteria was either increasing (Trabelsi et al. 2011) or strongly reducing the local bacterial community structure and diversity (Trabelsi et al. 2012), also when the inoculation was carried out with a consortia of strains (Naiman et al. 2009; de Salamone et al. 2010). A symbiotic N-fixing strain was shown to particularly affect a specific group of Proteobacteria (Robleto et al. 1998). Many studies have confirmed a high degree of specificity of the bacteria species associated with the AMF that was reflected on the increased presence of these species after inoculation with AMF (Albertsen et al. 2006; Olsson et al. 1996; Marschner and Timonen 2006). However, inoculation with AMF also significantly affected the general development of rhizospheric bacterial and fungal biomass (Linderman 1988). Once established successfully, introduced AMF showed to decrease the species richness of indigenous AM fungal communities in host roots (Koch et al. 2011).

The selection of strains expressing features that support the colonization process, and the “fight” for the roots’ environment, is key to assure the efficacy of any biofertilizer. In this respect, quorum sensing confers an enormous competitive advantage on bacteria, improving their chances to survive (e.g. through biofilm formation) and the ability to explore more complex niches (Gera and Srivastava 2006) even by 'swarming' (i.e. moving in the soil owing to motility – Fray 2002). Such characteristics are strongly related to the need of assuring a minimum population level of the initial PGPR inoculum to promote plant growth (Persello-Cartieaux et al. 2003).

The efficacy of the biofertilizers seems to be also mediated by protozoan grazing, particularly by naked amoeba, which is the most important bacterial grazer in soil (Bonkowski 2004). An increase of the bacterial and fungal feeding nematodes population was observed after application of a biofertilizer composed on both AMF and PGPR (Malusà et al. 2012). Wheat rhizosphere colonization by two *Pseudomonas* species and *Bacillus subtilis* was substantially reduced by three species of nematodes (*Caenorhabditis elegans*, *Acrobeloides thornei* and *Cruznema* sp.) (Knox et al. 2003).

However, it must be underlined that the observed relationships between indigenous and introduced microorganisms would depend largely on the techniques used to address the dynamics of soil microbial communities (Trabelsi and Mhamdi 2013). Indeed, although the number of microbial taxa could be clearly identified through novel metagenomic approaches combined with culture-dependent method, it is still very difficult to identify which functions are attributable to a specific microorganism or group, what are the metabolic potential of soil microbial communities in response to inoculation, and what is the link between the effects on soil microbial communities structure and the functional capabilities of soil microbial population. The study of genes coding for important enzymatic activities or key genes in the interaction process between the inoculant and native microbial population may contribute to gain such knowledge, which could unveil possible functions for the application of biofertilizers specifically designed for particular soil/crops.

2.3.4 Factors Related to Farmers' Practices

2.3.4.1 Fertilization

Fertilization is surely the agronomical practice that affects the efficacy of biofertilizers the most. The application of large quantities of mineral fertilizers has profound effects on soil microorganisms (Gosling et al. 2006; Johansson et al. 2004) and is thus expected to strongly affect the inoculated ones. Long-term application of mineral nitrogen has been shown to reduce soil microbial activity, with both quantitative and qualitative effects on soil bacterial and AMF communities which negatively impacted natural mycorrhizal colonization of roots (Mäder et al. 2002; Johnson et al. 2005; Hartmann and Widmer 2006; Oehl et al. 2004; Toljander et al. 2008). P-accumulation in the soils due to 10-year (Jensen and Jakobsen 1980) or 90-year application of P fertilizers (Cheng et al. 2013) or irrigation with wastewater (Ortega-Larrocea et al. 2001) decreased the spore density, colonization and communities of AM fungi. However, a lower level of differences was observed in sporulating AMF diversity despite 70 years of different soil fertilization regimes (Antunes et al. 2012). Duan et al. (2010) found low AMF colonization levels in maize, soybean, and wheat grown on fertilized soils. The kind of nitrogen fertilizer used can also impact on the AMF community: the occurrence of *Glomus intraradices*, a nitrophilic taxon (Jumpponen et al. 2005), among the most frequent taxa in arable soils (Hijri et al. 2006), was drastically reduced by ammonium nitrate while it was favored by calcium nitrate inputs (Toljander et al. 2008). However, in case of AMF, it has been suggested that the fertilizer rate might have a larger impact than fertilizer nature, mineral or organic, under some conditions (Beauregard et al. 2013).

Nevertheless, in terms of expected efficacy of AMF-based biofertilizers, it is important to consider that the overall fertility of the soil is supposed to regulate the kind of relation between the AMF and the plant. According to the trade balance model (Johnson 2010), parasitic, commensalism or mutualistic outcomes in the AMF symbiosis might be determined according to the relative abundance or availability of N and P and their interaction with carbon supply and demand among plants and fungi. When N and P are available in sufficient amounts, then AM fungi are more likely to cause growth depression; on the other hand with sufficient N availability, but limited P, the plant benefits from the mutualistic symbiosis (Johnson 2010).

Organic fertilizers generally affect rhizosphere microorganisms positively, though this is not necessarily a favorable condition for inocula introduced with biofertilizers. Root colonization by AMF and development of AM fungal mycelia in soil can be stimulated by amendment of different organic substrates (Gryndler et al. 2005, 2006). Manure application can induce a general increase of bacteria and AMF richness (Esperschutz et al. 2007; Toljander et al. 2008), but can differently impact on specific groups of rhizosphere microorganisms such as denitrifying, aerobic N-fixing or sulfate reducing bacteria (Enwall et al. 2005). Compost treatments increased the frequency of Gram-positive bacteria to more than 80 % of total isolates and to a major frequency of rhizobacteria populations exhibiting PGPR characters (Viti et al. 2010). Application of two liquid organic fertilizers, derived from alternative sources of organic matter (a stillage and a vermicompost extract), with strikingly different composition and nature, differentially affected the size and biodiversity of rhizospheric Archaea and Eubacteria populations even after a short period of the plant growth, in contrast with common mineral fertilizers (Canfora et al. 2015). However, not all organic fertilizers can exert positive effects on AMF bioinoculants. Sewage sludge applications, for example, proved to reduce AMF richness and strongly altered the local bacterial community (Esperschutz et al. 2007; Toljander et al. 2008).

Considering that higher efficacy of colonization and activity of PGPM is expressed under low nutritional conditions, it is thus advised to reduce, but not to eliminate, the quantity of chemical fertilizers applied to favor the establishment of inoculated strain(s). A reduction by 20–50 % of chemical fertilizers has been proved feasible with several crops (Adesemoye et al. 2009; Jeffries et al. 2003). A medium level of N fertilization resulted in a higher N uptake from mycorrhizal plants with respect to high or low N fertilization rates (Azcón et al. 2008). In case of PGPR, when two strains of *Pseudomonas fluorescens* were tested on wheat in combination with varying levels of N, P, and K (at 0, 25, 50, 75, and 100 % of recommended doses), the efficacy was reduced with the increasing rates of NPK added to the soil and the maximum nutrient use efficiency was recorded with the 25 % of recommended NPK fertilizers dose (Shaharoona et al. 2008).

The use of biofertilizers can also allow utilizing different inorganic fertilizers, with lower nutrient availability, thus cheaper for farmers in comparison to synthetic fertilizers. For example, co-inoculation of PSB and KSB together with direct application of phosphate and potassium rocks, characterized by low solubility, increased yield and N, P and K uptake with different vegetable plants grown on soils deficient in P and K (Han and Lee 2005; Supanjani et al. 2006; Vassilev et al. 2006a).

2.3.4.2 Other Soil Management Practices

The structure of the soil microbiome is generally influenced by agricultural management practices (Bernard et al. 2012; Lumini et al. 2011; Reeve et al. 2010; Watt et al. 2006), with contrasting effects when comparing intensive and more environmental-friendly systems: the higher the management intensity (i.e. high inorganic fertilization, no rotation, deep tillage) the lower the microbial diversity (Franke-Snyder et al. 2001; Jansa et al. 2002, 2003; Oehl et al. 2003, 2004). Twenty years of organic management altered soil bacterial and fungal community structure compared to continuous conventional management with the bacterial differences caused primarily by a large increase in diversity (Berthrong et al. 2013). Practices, such as tillage, pest management, combined mineral and organic fertilization, and water regime can modify the efficacy of AMF inoculation (Lumini et al. 2011; Van Der Gast et al. 2011; Malusà et al. 2013; Alguacil et al. 2014). Regular disturbance by plowing in the arable soils strongly reduce AMF survival

(Helgason et al. 1998). Furthermore, some AMF taxa like *Acaulospora*, *Gigaspora*, *Paraglomus*, and *Scutellospora* appear to be more sensitive to some soil management practices (e.g. tillage) (Hijri et al. 2006; Maherali and Klironomos 2007) probably due to fewer intramycelial anastomoses (hyphal fusions) with respect to *Glomus* species (De La Providencia et al. 2005), a feature that could lead to using different species for biofertilizers adapted to specific crops. Several investigations on the diversity of AMF communities in conventional versus low input agricultural sites concluded that the status of nutrients and soil disturbance play a more influential role in homogenizing fungi diversity than any differences due to the employed farming systems (Franke-Snyder et al. 2001; Viti et al. 2010).

Finally, when considering the practice of substrate preparation for potted crops (e.g. in nursery), it was found that the characteristics of the peat used could differently affect root colonization by AMF (Linderman and Davis 2003; Ma et al. 2007).

2.3.4.3 Application Methods

Farmers need to better understand how microorganisms are acting in soil in order to learn the appropriate methods to perform a successful crop inoculation (Date 2001). The method of application can indeed affect the performance of the biofertilizer (Deaker et al. 2004). However, very little work has been done to assess and optimize the application of biofertilizers, in order to meet the farmers' requirement of using technologies already available in the farm or to verify how much the application method utilized can affect the viability of the distributed inocula (Bashan et al. 2014; Malusà et al. 2012). Among the few efforts in this regard can be mentioned by the development of machines to apply biofertilizers having different physical form (Malusà and Sas Paszt 2009).

The already available machines can be normally used to distribute biofertilizers, particularly granulated formulations. However, some machines have been developed for their distribution, by small adaptation of existing machines to be used in horticultural crops (Wawrzyńczak et al. 2011), or for specific purposes, e.g. to inject a slurry containing AMF to inoculate big trees (Symbiom© Inject System), which have shown to support a better performance of the biofertilizer (Hołownicki 2014). Application of inoculants by seed treatment or in furrows by mixing the inocula with soil or vermicompost provided comparable efficacy with regard to grain and straw yields in *Cicer* (Bhattacharjya and Chandra 2013). The application of liquid formulations with a normal sprayer based on hydraulic atomization system only slightly affected bacteria viability, but a prolonged working time reduced the amount of living cells up to 50 % (Świechowski et al. 2012). Effect of water volume and adjuvants were also affecting the amount of spores delivered and their efficacy in case of a fungus (Bailey et al. 2007). Foliar application can also be considered for PGPM application, particularly for endophytic species. Examples of growth and yield promotion using of such application method were demonstrated with several fruit species (Esitken et al. 2003; Pirlak et al. 2007; Sudhakar et al. 2000).

Since the recovery of the inoculated strains in the soil or on root rhizosphere was found to be limited to 30–40 days after inoculation in case of PGPR (Bashan et al. 1995), it would be more efficient to foresee repeated applications (2–4) during the growing season, with an interval of 3–4 weeks. This is not considered an additional drawback for biofertilizers in comparison to the inorganic ones, since normally, even for cereal crops, at least two fertilization treatments are performed, also to fulfill legal requirements or quality standards (e.g. Directive 676/91/CE concerning the protection of waters against pollution by nitrates).

2.4 Conclusion

The global market for biofertilizers was estimated to be worth about five billion USD in 2011 and is forecasted to double by 2017 (Marketsandmarkets 2013), actively in Latin America, India and China (Fuentes-Ramirez and Caballero-Mellado 2005; Bashan and de-Bashan

2010; Bashan et al. 2014). Improvement of quality standards of production and a clear legal framework that guarantees both manufacturers and farmers are needed to sustain such potential economic development.

Considering that, in general, 60–90 % of the total applied fertilizer is lost and only 30–50 % of applied N fertilizers and 10–45 % of P fertilizers are taken up by crops (Adesemoye et al. 2008, 2009), the application of biofertilizers can play a key role to develop an integrated nutrient management system, sustaining agricultural productivity with low environmental impact (Adesemoye et al. 2009; Adesemoye and Kloepper 2009; Malusà and Sas Paszt 2009). However, even though in some cases the application of biofertilizers resulted in an increased yield over respective un-inoculated controls in the presence of 100 % of recommended fertilizer doses, we believe that a valid target for this practice would be reaching the same crop productivity obtained without biofertilizers, but with a significant reduction of mineral fertilizers use. Biofertilizers have the potential to help reducing the buildup, leaching, or runoff of nutrients from fields when used in the framework of an integrated nutrient management system, participating in nutrient cycling and benefiting crop productivity (Singh et al. 2011). It has been demonstrated that such approach, combining in different ways, depending on the crops, the use of organic fertilizers and no or limited tillage, is promising and can support an economically and environmentally sustainable management of the crops (Adesemoye et al. 2009; Grzyb et al. 2012; 2013).

More impetus for a wider and effective use of biofertilizers can derive from recent knowledge on microorganisms and technological development. Use of strains cooperating with autochthonous microorganisms, such as endophytic bacteria (Reinhold-Hurek and Hurek 2011; Ryan et al. 2008), or exploiting the synergies with microbial communities (Bernard et al. 2012), as well as the inclusion of protozoa in the formulation of biofertilizers (Bonkowski 2004; Ronn et al. 2002) could also be key for the development of new kinds of biofertilizers. The observation that dimethyl sulfide, a volatile organic compound, is released by legumes to attract nematodes that transport rhizobia toward the roots is also supporting a wider use of the different microorganisms forming the soil web (Horiuchi et al. 2005).

New kinds of biofertilizers can benefit from the inclusion in the inoculum of yeasts, since isolates from genera such as *Williopsis*, *Saccharomyces*, *Candida*, *Meyerozyma* and *Pichia* have been shown to promote plant growth and nutrition with different crops (Amprayn et al. 2012; Agamy et al. 2013; El-Tarabily and Sivasithamparam 2006; Xiao et al. 2013) also with an integrated nutrient management (Nakayan et al. 2013).

The use of non-obligate endosymbiont mycorrhizal fungi, of the order Sebacinales, could ease the production process of this kind of biofertilizers, which have shown beneficial effect also in association with PGPR and with non-mycorrhizal species (Kumar et al. 2012).

New kind of additives could derive from biological substances that are involved in the colonization of roots such as the strigolactones synthetic analogs for the AMF–plant symbiosis (Ruyter-Spira et al. 2011), or that can support the root colonization by inoculated microorganisms such as vitamins (Palacios et al. 2014).

Biofertilizers could also be developed for in-vitro grown plant material leading to enhanced growth of seedlings, being more resistant to biotic and abiotic stresses (Sekar and Kandavel 2010), as well as for their quantitative and/or qualitative enhancement of plant secondary metabolites content in medicinal plants (Zubek et al. 2012).

From the data presented, it emerges that the several biotic, abiotic and anthropogenic factors pose challenges in successful application of commercial biofertilizer and are responsible for the efficacy of the biofertilizers as a field practice. Mathematical simulations showed that the most significant factors affecting PGPR survival, and thus the ability of providing beneficial effect to plants, were the competition with autochthonous bacteria, the compatibility with the exuded compounds by the plant host (rhizodeposition) and their ability to utilize them (Strigul and

Kravchenko 2006). On the other hand, there are several tools and actions which can be already utilized and implemented to improve the field efficacy of biofertilizers. The assurance of efficacy for a biofertilizer in a particular soil with a specific variety of crop is thus a complex task, which shall be considered by researchers, manufacturers, agricultural advisors and farmers when designing and applying a specific biofertilizer: a challenge to transform the fertilization with these products into a common practice for twenty-first century agriculture.

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References

Achal V, Savant VV, Reddy MS (2007) Phosphate solubilization by a wild type strain and UV induced mutants of *Aspergillus tubingensis*. Soil Biol Biochem 39:695–699

Adesemoye AO, Kloepper JW (2009) Plant-microbes interactions in enhanced fertilizer-use efficiency. Appl Microbiol Biotechnol 85:1–12

Adesemoye AO, Torbert HA, Kloepper JW (2008) Enhanced plant nutrient use efficiency with PGPR and AMF in an integrated nutrient management system. Can J Microbiol 54:876–886

Adesemoye AO, Torbert HA, Kloepper JW (2009) Plant growth-promoting rhizobacteria allow reduced application rates of chemical fertilizers. Microb Ecol 58:921–929

Agamy R, Hashem M, Alamri S (2013) Effect of soil amendment with yeasts as bio-fertilizers on the growth and productivity of sugar beet. Afr J Agric Res 8:46–56

Ahmed N, Shahab S (2009) Phosphate solubilization: their mechanism genetics and application. Internet J Microb 9(1). https://ispub.com/IJMB/9/1/12025

Akiyama K, Matsuoka H, Hayashi H (2002) Isolation and identification of a phosphate deficiency-induced C-glycosylflavonoid that stimulates arbuscular mycorrhiza formation in melon roots. Mol Plant Microbe Interact 15:334–340

Akiyama K, Matsuzaki K, Hayashi H (2005) Plant sesquiterpenes induce hyphal branching in arbuscular mycorrhizal fungi. Nature 435:824–827

Alagawadi AR, Gaur AC (1988) Associative effect of *Rhizobium* and phosphate solubilizing bacteria on the yield and nutrient uptake of chickpea. Plant Soil 105:241–246

Albertsen A, Ravnskov S, Green H, Jensen DF, Larsen J (2006) Interactions between the externalmyceliumof themycorrhizal fungus Glomus intraradices and other soil microorganisms as affected by organic matter. Soil Biol Biochem 38(5):1008–1014

Alguacil MM, Torrecillas E, Lozano Z, Torres MP, Roldan A (2014) *Prunus persica* crop management differentially promotes arbuscular mycorrhizal fungi diversity in a tropical agro-ecosystem. PLoS ONE 9(2), e88454. doi:10.1371/journal.pone.0088454

Amprayn K, Rose MT, Kecskés M, Pereg L, Nguyen HT, Kennedy IR (2012) Plant growth promoting characteristics of soil yeast (*Candida tropicalis* HY) and its effectiveness for promoting rice growth. Appl Soil Ecol 61:295–299

Antunes PM, Koch AM, Morton JB, Rillig MC, Klironomos JN (2011) Evidence for functional divergence in arbuscular mycorrhizal fungi from contrasting climatic origins. New Phytol 189:507–514

Antunes PM, Lehmann A, Hart MM, Baumecker M, Rillig MC (2012) Long-term effects of soil nutrient deficiency on arbuscular mycorrhizal communities. Funct Ecol 26:532–540

Asea PEA, Kucey RMN, Stewart JWB (1988) Inorganic phosphate solubilization by two Penicilium species in solution culture and soil. Soil Biol Biochem 20:459–464

Aseri GK, Jain N, Panwar J, Rao AV, Meghwal PR (2008) Biofertilizers improve plant growth, fruit yield, nutrition, metabolism and rhizosphere enzyme activities of pomegranate (*Punica granatum* L.) in Indian Thar Desert. Sci Hortic 117:130–135

Azcón R, Rodríguez R, Amora-Lazcano E, Ambrosano E (2008) Uptake and metabolism of nitrate in mycorrhizal plants as affected by water availability and N concentration in soil. Eur J Soil Sci 59:131–138

Babić KH, Schauss K, Hai B et al (2008) Influence of different *Sinorhizobium meliloti* inocula on abundance of genes involved in nitrogen transformations in the rhizosphere of alfalfa (*Medicago sativa L.*). Environ Microbiol 10(11):2922–2930

Bailey KL, Carisse O, Leggett M, Holloway G, Leggett F, Wolf TM, Shivpuri A, Derby JA, Caldwell B, Geissler HJ (2007) Effect of spraying adjuvants with the biocontrol fungus *Microsphaeropsis ochracea* at different water volumes on the colonization of apple leaves. Biocontrol Sci Technol 17:1021–1036

Bais HP, Weir LP, Perry LG, Gilroy S, Vivanco JM (2006) The role of root exudates in rhizosphere interactions with plants and other organisms. Annu Rev Plant Biol 57:233–266

Baldani VLD, Baldani JI, Dobereiner J (2000) Inoculation of rice plants with the endophytic diazotrophs *Herbaspirillums seropidicae*. Biol Fertil Soils 30:485–491

Banitz T, Wick LY, Fetzer I, Frank K, Harms H, Johst K (2011) Dispersal networks for enhancing bacterial degradation in heterogeneous environments. Environ Pollut 159(10):2781–2788. doi:10.1016/j.envpol.2011.05.008

Banitz T, Johst K, Wick LY, Schamfuß S, Harms H, Frank K (2013) Highways versus pipelines: contributions of two fungal transport mechanisms to efficient bioremediation. Environ Microbiol Rep 5(2):211–218. doi:10.1111/1758-2229.12002

Bardi L, Malusà E (2012) Drought and nutritional stresses in plant: alleviating role of rhizospheric microorganisms. In: Haryana N, Punj S (eds) Abiotic stress: new research. Nova Science Publishers Inc, Hauppauge, pp 1–57

Barea JM, Azcon R, Azcon-Aguilar C (2002) Mycorrhizosphere interactions to improve plant fitness and soil quality. Antonie Van Leeuwenhoek 81:343–351

Bashan Y (1998) Inoculants of plant growth-promoting bacteria for use in agriculture. Biotechnol Adv 16:729–770

Bashan Y, de-Bashan LE (2010) Microbial populations of arid lands and their potential for restoration of deserts. In: Dion P (ed) Soil biology and agriculture in the tropics, Soil biology series. Springer, Berlin, pp 109–137

Bashan Y, Puente ME, Rodriguez-Mendoza MN, Toledo G, Holguin G, Ferrera-Cerrato R, Pedrin S (1995) Survival of *Azospirillum brasilense* in the bulk soil and rhizosphere of 23 soil types. Appl Environ Microbiol 61:1938–1945

Bashan Y, de-Bashan LE, Prabhu SR, Hernandez JP (2014) Advances in plant growth-promoting bacterial inoculant technology: formulations and practical perspectives (1998–2013). Plant Soil 378:1–33

Beauregard MS, Gauthier MP, Hamel C, Zhang T, Welacky T, Tan CS, St-Arnaud M (2013) Various forms of organic and inorganic P fertilizers did not negatively affect soil- and root-inhabiting AM fungi in a maize–soybean rotation system. Mycorrhiza 23:143–154

Belanger RB, Bowen PA, Ehret DL, Menzies JG (1995) Soluble silicon: its role in crop and disease management of greenhouse crops. Plant Dis 79:329–336

Bell RW, Dell B (2008) Micronutrients for sustainable food, feed, fibre and bioenergy production. IFA, Paris

Bennett PC, Choi WJ, Rogera JR (1998) Microbial destruction of feldspars. Mineral Manage 8:149–150

Bennett PC, Rogers JR, Choi WJ (2001) Silicates, silicate weathering, and microbial ecology. Geomicrobiol J 18:3–19

Bernard E, Larkin RP, Tavantzis S, Erich MS, Alyokhin A, Sewell G, Lannan A, Gross SD (2012) Compost, rapeseed rotation, and biocontrol agents significantly impact soil microbial communities in organic and conventional potato production systems. Appl Soil Ecol 52:29–41

Berthrong ST, Buckley DH, Drinkwater LE (2013) Agricultural management and labile carbon additions affect soil microbial community structure and interact with carbon and nitrogen cycling. Microb Ecol 66:158–170

Bhattacharjya S, Chandra R (2013) Effect of inoculation methods of *Mesorhizobium ciceri* and PGPR in chickpea (*Cicer aretinum* L.) on symbiotic traits, yields, nutrient uptake and soil properties. Legume Res 36:331–337

Bhattacharyya PN, Jha DK (2012) Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. World J Microbiol Biotechnol 28:1327–1350

Biederbeck VO, Geissler HJ (1993) Effect of storage temperatures on *Rhizobium meliloti* survival in peat- and clay-based inoculants. Can J Plant Sci 73:101–110

Boberg JB, Finlay RD, Stenlid J, Lindahl BD (2009) Fungal C translocation restricts N-mineralization in heterogeneous environments. Funct Ecol 24:454–459

Boddey RM, Urquiaga S, Reis V, Döbereiner J (1991) Biological nitrogen fixation associated with sugar cane. Plant Soil 137:111–117

Bonkowski M (2004) Protozoa and plant growth: the microbial loop in soil revisited. New Phytol 162:617–631

Brevik EC, Burgess LC (2012) Soils and human health. CRC Press, Boca Raton, 408 p

Burford EP, Gadd GM (2003) Geomycology: fungal growth in mineral substrata. Mycologist 17:98–107

Burford EP, Fomina M, Gadd GM (2003) Fungal involvement in bioweathering and biotransformation of rocks and minerals. Mineral Mag 67:1127–1155

Canfora L, Malusà E, Salvati L, Renzi G, Petrarulo M, Benedetti A (2015) Short-term impact of two liquid organic fertilizers on *Solanum lycopersicum* L. rhizosphere Eubacteria and Archaea diversity. Appl Soil Ecol 88:50–59

Castro IM, Fietto JLR, Vieira RX, Tropia MJM, Campos LMM, Paniago EB, Brandao RL (2000) Bioleaching of zinc and nickel from silicates using *Aspergillus niger* cultures. Hydrometal 57:39–49

Cavagnaro TR, Smith FA, Smith SE, Jakobsen I (2005) Functional diversity in arbuscular mycorrhizas: exploitation of soil patches with different phosphate enrichment differs among fungal species. Plant Cell Environ 28:642–650

Ceccarelli N, Curadi M, Martelloni L, Sbrana C, Picciarelli P, Giovannetti M (2010) Mycorrhizal colonization impacts on phenolic content and antioxidant properties of artichoke leaves and flower heads two years after field transplant. Plant Soil 335:311–323

Cesco S, Neumann G, Tomasi N, Pinton R, Weisskopf L (2010) Release of plant-borne flavonoids into the rhizosphere and their role in plant nutrition. Plant Soil 329:1–25

Cheng Y, Ishimoto K, Kuriyama Y, Osaki M, Ezawa T (2013) Ninety-year, but not single, application of phosphorus fertilizer has a major impact on arbuscular mycorrhizal fungal communities. Plant Soil 365:397–407

Chuang C, Kuo YL, Chao CC, Chao WL (2007) Solubilization of inorganic phosphates and plant growth promotion by *Aspergillus niger*. Biol Fertil Soils 43:575–584

Clayton GW, Rice WA, Lupwayi NZ, Johnston AM, Lafond GP, Grant CA, Walley F (2004) Inoculant formulation and fertilizer nitrogen effects on field pea: crop yield and seed quality. Can J Plant Sci 84:89–96

Corkidi L, Allen EB, Merhaut D, Allen MF, Downer J, Bohn J, Evans M (2004) Assessing the infectivity of commercial mycorrhizal inoculants in plant nursery conditions. J Environ Hortic 22:149–154

Cummings SP (2009) The application of plant growth promoting rhizobacteria (PGPR) in low input and organic cultivation of graminaceous crops; potential and problems. Environ Biotechnol 5:43–50

Daghino S, Martino E, Perotto S (2010) Fungal weathering and implications in the solubilization of metals from soil and from asbestos fibres. In: Mendez-Vilas A (ed) Current research, technology and education topics in applied microbiology and microbial biotechnology, vol 1, Microbiology book series, 2. Formatex Research Center, Badajoz, pp 329–338. ISBN: 9788461461943

Date RA (2001) Advances in inoculant technology: a brief review. Anim Prod Sci 41:321–325

De La Providencia IE, De Souza FA, Fernández F, Delmas NS, Declerck S (2005) Arbuscular mycorrhizal fungi reveal distinct patterns of anastomosis formation and hyphal healing mechanisms between different phylogenic groups. New Phytol 165:261–271

De Mico A, Pasquariello G, Pinzari F (2004) Study of surface morphologies in biologically degraded paper with variable pressure SEM couplet with Electronic Dispersion Spectroscopy (EDS). In: Abstracts of the 7th international symposium transitional metals in Paper University of Rome La Sapienza,- EU project EVK4 2002 ÷ 2010

de Salamone IEG, Di Salvo LP, Ortega JSE, Sorte PMFB, Urquiaga S, Teixeira KRS (2010) Field response of rice paddy crop to *Azospirillum* inoculation: physiology of rhizosphere bacterial communities and the genetic diversity of endophytic bacteria in different parts of the plants. Plant Soil 336(1):351–362

Deaker R, Roughley RJ, Kennedy IR (2004) Legume seed inoculation technology-a review. Soil Biol Biochem 36:1275–1288

Dennis PG, Miller AJ, Hirsch PR (2010) Are root exudatesmore important than other sources of rhizodeposits in structuring rhizosphere bacterial communities? FEMS Microbiol Ecol 72:313–327

Duan T, Shen Y, Facelli E, Smith SE, Nan Z (2010) New agricultural practices in the Loess Plateau of China do not reduce colonisation by arbuscular mycorrhizal or root invading fungi and do not carry a yield penalty. Plant Soil 331:265–275

Dumbrell AJ, Nelson M, Helgason T, Dytham C, Fitter AH (2010) Relative roles of niche and neutral processes in structuring a soil microbial community. ISME J 4:337–345

El-Tarabily KA, Sivasithamparam K (2006) Potential of yeasts as biocontrol agents of soil-borne fungal plant pathogens and as plant growth promoters. Mycoscience 47:25–35

Enwall K, Philippot L, Hallin S (2005) Activity and composition of the denitrifying bacterial community respond differently to long-term fertilization. Appl Environ Microbiol 71(12):8335–8343

Esitken A, Karlidag H, Ercisli S, Turan M, Sahin F (2003) The effect of spraying a growth promoting bacterium on the yield, growth and nutrient element composition of leaves of apricot (*Prunus armeniaca* L. cv. Hacihaliloglu). Aust J Agric Res 54:377–380

Esperschutz J, Gattinger A, Mader P, Schloter M, Fliessbach A (2007) Response of soil microbial biomass and community structures to conventional and organic farming systems under identical crop rotations. FEMS Microbiol Ecol 61:26–37

Faye A, Dalpé Y, Ndung'u-Magiroi K, Jefwa J, Ndoye ID, Lesueur D (2013) Evaluation of commercial arbuscular mycorrhizal inoculants on maize in Kenya. Can J Plant Sci 93:1201–1208

Fierer N, Jackson RB (2006) The diversity and biogeography of soil bacterial communities. Proc Natl Acad Sci U S A 103:626–631

Filion M, St-Arnaud M, Fortin JA (1999) Direct interaction between the arbuscular mycorrhizal fungus *Glomus intraradices* and different microorganisms. New Phytol 141:525–533

Fomina M, Ritz K, Gadd GM (2003) Nutritional influence on the ability of fungal mycelia to penetrate toxic metal-containing domains. Mycol Res 107:861–871

Fomina M, Alexander IJ, Hillier S, Gadd GM (2004) Zinc phosphate and pyromorphite solubilization by soil plant-symbiotic fungi. Geomicrob J 21:351–366

Fomina MA, Alexander IJ, Colpaert JV, Gadd GM (2005) Solubilization of toxic metal minerals and metal tolerance of mycorrhizal fungi. Soil Biol Biochem 37:851–866

Franche C, Lindström K, Elmerich C (2009) Nitrogen-fixing bacteria associated with leguminous and non-leguminous plants. Plant Soil 321:35–59

Franke-Snyder M, Douds DD, Galvez L, Phillips JG, Wagoner P, Drinkwater L, Morton JB (2001) Diversity of communities of arbuscular mycorrhizal (AM) fungi present in conventional versus low-input agricultural sites in eastern Pennsylvania, USA. Appl Soil Ecol 16:35–48

Fray RG (2002) Altering plant–microbe interaction through artificially manipulating bacterial quorum sensing. Ann Bot 89:245–253

Fuentes-Ramirez LE, Caballero-Mellado J (2005) Bacterial biofertilizers. In: Siddiqui ZA (ed) PGPR: biocontrol and biofertilization. Springer, Dordrecht, pp 143–72

Furuno S, Remer R, Chatzinotas A, Harms H, Wick LY (2012) Fungal mycelia as paths for the isolation of contaminant degrading soil bacteria. Microb Biotechnol 5:142–148

Gadd GM (1999) Fungal production of citric and oxalic acid: importance in metal speciation, physiology and biogeochemical processes. Adv Microb Physiol 41:47–92

Gadd GM (2000) Bioremedial potential of microbial mechanisms of metal mobilization and immobilization. Curr Opin Biotechnol 11:271–279

Gadd GM (2004) Mycotransformation of organic and inorganic substrates. Mycologist, vol 18, Part 2 May.

Cambridge University Press, Cambridge, Printed in the United Kingdom. doi: 10.1017/S0269915XO4002022

Gadd GM (2007) Geomycology: biogeochemical transformations of rocks, minerals, metals and radionuclides by fungi, biowatering and bioremediation. Mycol Res 111:3–49

Gadd GM (ed) (2008) Fungi in bioremediation. Cambridge University Press, Cambridge, 481 pp. British Mycological Society Symposia N 23. ISBN: 9780521065313. Book doi: http://dx.doi.org/10.1017/CBO9780511541780

Gascho GJ (2001) Silicon sources for agriculture. In: Datnoff LE, Snyder GH, Korndorfer GH (eds) Silicon in agriculture. Elsevier Science, Amsterdam

Gemell LG, Hartley EJ, Herridge DF (2005) Point-of-sale evaluation of preinoculated and custom-inoculated pasture legume seed. Anim Prod Sci 45:161–169

Gera C, Srivastava S (2006) Quorum-sensing, the phenomenon of microbial communication. Curr Sci 90:566–677

Girvan MS, Bullimore J, Pretty JN, Osborn AM, Ball AS (2003) Soil type is the primary determinant of the composition of the total and active bacterial communities in arable soils. Appl Environ Microbiol 69:1800–1809

Glowa KR, Arocena JM, Massicotte HB (2003) Extraction of potassium and/or magnesium from selected soil minerals by *Piloderma*. Geomicrobiol J 20:99–111

Gosling P, Hodge A, Goodlass G, Bending GD (2006) Arbuscular mycorrhizal fungi and organic farming. Agric Ecosyst Environ 113:17–35

Govindarajulu M, Pfeffer PE, Jin H, Abubaker J, Douds DD, Allen JW, Bücking H, Lammers PJ, Shachar-Hill Y (2005) Nitrogen transfer in the arbuscular mycorrhizal symbiosis. Nature 435:819–823

Green LE, Porras-Alfaro A, Sinsabaugh RL (2008) Translocation of nitrogen and carbon integrates biotic crust and grass production in desert grassland. J Ecol 96:1076–1085

Gryndler M, Hršelová H, Sudová R, Gryndlerová H, Řezáčová V, Merhautová V (2005) Hyphal growth and mycorrhiza formation by the arbuscular mycorrhizal fungus *Glomus claroideum* BEG 23 is stimulated by humic substances. Mycorrhiza 15:483–488

Gryndler M, Larsen J, Hršelová H, Řezáčová V, Gryndlerova H, Kubat J (2006) Organic and mineral fertilization, respectively, increase and decrease the development of external mycelium of arbuscular mycorrhizal fungi in a long-term field experiment. Mycorrhiza 16:159–166

Grzyb ZS, Piotrowski W, Bielicki P, Sas Paszt L, Malusà E (2012) Effect of different fertilizers and amendments on the growth of apple and sour cherry rootstocks in an organic nursery. J Fruit Ornam Plant Res 20(1):43–53

Grzyb ZS, Piotrowski W, Bielicki P, Sas-Paszt L, Malusà E (2013) Effect of organic fertilizers and soil conditioners on the quality of maiden apple trees. Acta Horticult 1001:311–322

Habteselassie MY, Xu L, Norton JM (2013) Ammonia-oxidizer communities in an agricultural soil treated with contrasting nitrogen sources. Front Microbiol 4(326):1–10. doi: 10.3389/fmicb.2013.00326

Halder AK, Mishra AK, Chakrabarty PK (1990) Solubilization of phosphate by Aspergillus niger. Sci Cult 56:455–457

Han HS, Lee KD (2005) Phosphate and potassium solubilizing bacteria effect on mineral uptake, soil availability and growth of eggplant. Res J Agric Biol Sci 1:176–180

Han I, Lee TK, Han J, Doan TV, Kim SB, Park J (2012) Improved detection of microbial risk of releasing genetically modified bacteria in soil by using massive sequencing and antibiotic resistance selection. J Hazard Mat 227–228:172–178

Harms H, Schlosser D, Wick LY (2011) Untapped potential: Exploiting fungi in bioremediation, waste air and water treatment. Nat Rev Microbiol 9:177–192

Hartley EJ, Gemell LG, Slattery JF, Howieson JG, Herridge DF (2005) Age of peat-based lupin and chickpea inoculants in relation to quality and efficacy. Anim Prod Sci 45:183–188

Hartmann M, Widmer F (2006) Community structure analyses are more sensitive to differences in soil bacterial communities than anonymous diversity indices. Appl Environ Microbiol 72:7804–7812

Hartmann A, Schmid M, van Tuinen D, Berg G (2009) Plant-driven selection of microbes. Plant Soil 321:235–257

Hawkins HJ, Johansen A, George E (2000) Uptake and transport of organic and inorganic nitrogen by arbuscular mycorrhizal fungi. Plant Soil 226:275–285

Hayat R, Ali S, Amara U, Khalid R, Ahmed I (2010) Soil beneficial bacteria and their role in plant growth promotion: a review. Ann Microbiol 60:579–598

Helgason T, Daniell TJ, Husband R, Fitter AH, Young JPW (1998) Ploughing up the wood-wide web? Nature 394, 431 (30 July 1998). doi :10.1038/28764

Herridge DF (2008) Inoculation technology for legumes. In: Dilworth MJ, James EK, Sprent JI, Newton WE (eds) Nitrogen-fixing leguminous symbioses. Springer, Dordrecht, pp 77–115

Herrmann L, Lesueur D (2013) Challenges of formulation and quality of biofertilizers for successful inoculation. Appl Microbiol Biotechnol 97:8859–8873

Hijri I, Sykorova Z, Oehl F, Ineichen K, Mader P, Wiemken A, Redecker D (2006) Communities of arbuscular mycorrhizal fungi in arable soils are not necessarily low in diversity. Mol Ecol 15:2277–2289

Hirsch PR, Mauchline TH, Clark IM (2010) Culture independent molecular techniques for soil microbial ecology. Soil Biol Biochem 42(6):878–887

Hołownicki R (2014) Application methods for bioproducts in organic fruit production. In: International conference "Innovative technologies in organic horticultural production", Skierniewice, 23–24 October 2014, pp 59–60

Horiuchi J, Prithiviraj B, Bais HP, Kimball BA, Vivanco JM (2005) Soil nematodes mediate positive interactions between legume plants and rhizobium bacteria. Planta 222:848–857

Husen E, Simanungkalit RDM, Saraswati R (2007) Characterization and quality assessment of Indonesian commercial biofertilizers. Indones J Agric Sci 8:31–38

Jain R, Saxena J, Sharma V (2012) Solubilization of inorganic phosphates by *Aspergillus awamori* S19 isolated from agricultural soil of semi-arid region. Ann Microbiol 62:725–735

Jansa J, Mozafar A, Anken T, Ruh R, Sanders IR, Frossard E (2002) Diversity and structure of AMF communities as affected by tillage in a temperate soil. Mycorrhiza 12:225–234

Jansa J, Mozafar A, Kuhn G, Anken T, Ruh R, Sanders IR, Frossard E (2003) Soil tillage affects the community structure of mycorrhizal fungi in maize roots. Ecol Appl 13:1164–1176

Jeffries P, Gianinazzi S, Perotto S, Turnau K, Barea JM (2003) The contribution of arbuscular mycorrhizal fungi in sustainable maintenance of plant health and soil fertility. Biol Fertil Soils 37:1–16

Jensen A, Jakobsen I (1980) The occurrence of vesicular arbuscular mycorrhiza in barley and wheat grown in some Danish soils with different fertilizer treatments. Plant Soil 55:403–414

Johansson JF, Paul LR, Finlay RD (2004) Microbial interactions in the mycorrhizosphere and their significance for sustainable agriculture. FEMS Microbiol Ecol 48:1–13

John RP, Tyagi RD, Brar SK, Surampalli RY, Prevost D (2011) Bioencapsulation of microbial cells for targeted agricultural delivery. Crit Rev Biotechnol 31:211–226

Johnson NC (2010) Resource stoichiometry elucidates the structure and function of arbuscular mycorrhizas across scales. New Phytol 185:631–647

Johnson D, Leake JR, Read DJ (2005) Liming and nitrogen fertilization affects phosphatase activities, microbial biomass and mycorrhizal colonisation in upland grassland. Plant Soil 271:157–164

Jongmans AG, Van Breemen N, Lundström US, Van Hees PAW, Finlay RD, Srinivasan M, Unestam T, Giesler R, Melkerud P-A, Olsson M (1997) Rock-eating fungi. Nature 389:682–683

Jumpponen A, Trowbridge J, Mandyam K, Johnson L (2005) Nitrogen enrichment causes minimal changes in arbuscular mycorrhizal colonization but shifts community composition evidence from rDNA data. Biol Fertil Soils 41:217–224

Kilian M, Steiner U, Krebs B, Junge H, Schmiedeknecht G, Hain R (2000) FZB24 *Bacillus subtilis* -mode of action of a microbial agent enhancing plant vitality. Pflanzenschutz-Nachrichten Bayer 1:72–93

Knox OGG, Killham K, Mullins CE, Wilson MJ (2003) Nematode-enhanced colonization of the wheat rhizosphere. FEMS Microbiol Lett 225:227–233

Koch A, Antunes P, Barto E, Cipollini D, Mummey D, Klironomos J (2011) The effects of arbuscular mycorrhizal (AM) fungal and garlic mustard introductions on native AM fungal diversity. Biol Invasions 13:1627–1639

Kucey RMN (1983) Effect of *Penicillium bilaji* on the solubility and uptake of phosphorus and micronutrients from soil by wheat. Can J Soil Sci 68:261–270

Kumar V, Sarma MVRK, Saharan K, Srivastava R, Kumar L, Sahai V, Bisaria VS, Sharma AK (2012) Effect of formulated root endophytic fungus *Piriformospora indica* and plant growth promoting rhizobacteria fluorescent pseudomonads R62 and R81 on *Vigna mungo*. World J Microbiol Biotechnol 28:595–603

Lauber CL, Strickland MS, Bradford MA, Fierer N (2008) The influence of soil properties on the structure of bacterial and fungal communities across land-use types. Soil Biol Biochem 40:2407–2415

Leigh J, Hodge A, Fitter AH (2009) Arbuscular mycorrhizal fungi can transfer substantial amounts of nitrogen to their host plant from organic material. New Phytol 181:199–207

Linderman RG (1988) Mycorrhizal interactions with the rhizosphere microflora: the mycorrhizosphere effect. Phytopathology 78:366–371

Linderman RG, Davis EA (2003) Soil amendment with different peat mosses affects mycorrhizae of onion. Hortic Technol 13:285–289

Lisette J, Xavier C, Germida JJ (2003) Selective interactions between arbuscular mycorrhizal fungi and *Rhizobium leguminosarum* bv. *viceae* enhance pea yield and nutrition. Biol Fertil Soils 37:261–267

Liu D, Lian B, Dong H (2012) Isolation of *Paenibacillus* sp. and assessment of its potential for enhancing mineral weathering. Geomicrobiol J 29:413–421

Lucy M, Reed E, Glick BR (2004) Application of free living plant growth-promoting rhizobacteria. Antonie Van Leeuwenhoek 86:1–25

Lumini E, Vallino M, Alguacil MM, Romani M, Bianciotto V (2011) Different farming and water regimes in Italian rice fields affect arbuscular mycorrhizal fungal soil communities. Ecol Appl 21:1696–1707

Lupwayi NZ, Clayton GW, Rice WA (2006) Rhizobial inoculants for legume crops. J Crop Improv 15:289–321

Ma N, Yokoyama K, Marumoto T (2007) Effect of peat on mycorrhizal colonization and effectiveness of the arbuscular mycorrhizal fungus *Gigaspora margarita*. Soil Sci Plant Nutr 53:744–752

Mabood F, Zhou X, Smith D (2006) Preincubated with methyl jasmonates increases soybean nodulation and nitrogen fixation. Agron J 98:289–294

Mäder P, Fliessbach A, Dubois D, Gunst L, Fried P, Niggli U (2002) Soil fertility and biodiversity in organic farming. Science 296:1694–1697

Maherali H, Klironomos JN (2007) Influence of phylogeny on fungal community assembly and ecosystem functioning. Science 316:1746–1748

Malik KA, Mirza MS, Hassan U, Mehnaz S, Rasul G, Haurat J et al (2002) The role of plant associated beneficial bacteria in rice-wheat cropping system. In:

Kennedy IR, Chaudhry ATMA (ed) Biofertilisers in action. Rural industries research and development. Corporation, Canberra, pp 73–83

Malusà E, Sas Paszt L (2009) The development of innovative technologies and products for organic fruit production. An integrated project. In: Proceedings of international plant nutrition Coll. XVI. Sacramento (USA). Paper 1359. http://repositories.cdlib.org/ipnc/xvi/1359, pp 1–4

Malusà E, Vassilev N (2014) A contribution to set a legal framework for biofertilizers. Appl Microbiol Biotechnol 98:6599–6607

Malusà E, Sas-Paszt L, Zurawicz E, Popinska W (2007) The effect of a mycorrhiza-bacteria substrate and foliar fertilization on growth response and rhizosphere pH of three strawberry cultivars. Int J Fruit Sci 6:25–41

Malusà E, Sas-Paszt L, Trzcinski P, Górska A (2012) Influences of different organic fertilizers and amendments on nematode trophic groups and soil microbial communities during strawberry growth. Acta Hortic (ISHS) 933:253–260

Malusà E, Sala G, Chitarra W, Bardi L (2013) Improvement of response to low water availability in maize plants inoculated with selected rhizospheric microbial consortia under different irrigation regimes. EQA – Environ Quality 12:13–21

Manikandan R, Saravanakumar D, Rajendran L, Raguchander T, Samiyappan R (2010) Standardization of liquid formulation of *Pseudomonas fluorescens* Pf1 for its efficacy against Fusarium wilt of tomato. Biol Control 54:83–89

Mansfeld-Giese K, Larsen J, Bodker L (2002) Bacterial populations associated with mycelium of the arbuscular mycorrhizal fungus *Glomus intraradices*. FEMS Microbiol Ecol 41:133–140

Marketsandmarkets (2013) Global biofertilizers market by types, applications and geography – trends and Forecasts to 2017. Marketsandmarkets, Dallas

Marks BB, Megías M, Nogueira MA, Hungria M (2013) Biotechnological potential of rhizobial metabolites to enhance the performance of *Bradyrhizobium* spp. and *Azospirillum brasilense* inoculants with soybean and maize. AMB Exp 3:1–10

Marschner P, Timonen S (2005) Interactions between plant species and mycorrhizal colonization on the bacterial community composition in the rhizosphere. Appl Soil Ecol 28:23–36

Marschner P, Timonen S (2006) Bacterial community composition and activity in rhizosphere of roots colonized by arbuscular mycorrhizal fungi. In: Mukerji KG, Manoharachary C, Singh J (eds) Microbial activity in the rhizosphere. Springer, Berlin, pp 139–154

Marschner P, Crowley D, Yang CH (2004) Development of specific rhizosphere bacterial communities in relation to plant species, nutrition and soil type. Plant Soil 261:199–208

Maurice S, Beauclair P, Giraud JJ, Sommer G, Hartmann A, Catroux G (2001) Survival and change in physiological state of Bradyrhizobium japonicum in soybean (*Glycine max* L. Merril) liquid inoculants after long-term storage. World J Microbiol Biotechnol 17:635–643

Meena VD, Dotaniya ML, Vassanda C, Rajendiran S, Ajay S, Kundu A, Rao S (2014) A case for silicon fertilization to improve crop yields in tropical soils. Proc Natl Acad Sci, Sect B Biol Sci 84(3):505–518

Morrison BA, Cozatl-Manzano R (2003) Initial evidence for use of periphyton as an agricultural fertilizer by the ancient Maya associated with El Eden wetland, Northern Quintana Roo, Mexico. In: Fedick S, Allen M, Jimenez-Osornio J, Gomez-Pompa A (eds) The Lowland Maya area: three millennia at the human-wildland interface. CRC Press, New York, pp 401–413

Naiman AD, Latronico DA, de Salamone IEG (2009) Inoculation of wheat with *Azospirillum brasilense* and *Pseudomonas fluorescens*: impact on the production and culturable rhizosphere microflora. Eur J Soil Biol 45(1):44–51

Nakayan P, Hameed A, Singh S, Young L-S, Hung M-H, Young C-C (2013) Phosphate-solubilizing soil yeast *Meyerozyma guilliermondii* CC1 improves maize (*Zeamays* L) productivity and minimizes requisite chemical fertilization. Plant Soil 373:301–315

Nannipieri P, Ascher J, Ceccherini MT, Landi L, Pietramellara G, Renella G (2003) Microbial diversity and soil functions. Eur J Soil Sci 54:655–670

Oehl F, Sieverding E, Ineichen K et al (2003) Impact of land use intensity on the species diversity of arbuscular mycorrhizal fungi in agroecosystems of Central Europe. Appl Environ Microbiol 69:2816–2824

Oehl F, Sieverding E, Mäder P et al (2004) Impact of long-term conventional and organic farming on the diversity of arbuscular mycorrhizal fungi. Oecologia 138:574–583

Okon Y, Labandera-Gonzalez CA (1994) Agronomic applications of *Azospirillum*: an evaluation of 20 years worldwide field inoculation. Soil Biol Biochem 26:1591–1601

Olsen PE, Rice WA, Collins MM (1994) Biological contaminants in North American legume inoculants. Soil Biol Biochem 27:699–701

Olsen PE, Rice WA, Bordeleau LM, Demidoff AH, Collins MM (1996) Levels and identities of nonrhizobial microorganisms found in commercial legume inoculant made with nonsterile peat carrier. Can J Microbiol 42:72–75

Olsson PA, Baath E, Jakobsen I, Söderström B (1996) Soil bacteria respond to presence of roots but not to mycelium of arbuscular mycorrhizal fungi. Soil Biol Biochem 28(4–5):463–470

Öpik M, Vanatoa A, Vanatoa E, Moora M, Davison J, Kalwij JM, Reier Ü, Zobel M (2010) The online database MaarjAM reveals global and ecosystemic distribution patterns in arbuscular mycorrhizal fungi (Glomeromycota). New Phytol 188:223–241

Ortega-Larrocea MP, Siebe C, Bécard G, Mendez I, Webster R (2001) Impact of a century of wastewater irrigation on the abundance of arbuscular mycorrhizal spores in the soil of the Mezquital Valley of Mexico. Appl Soil Ecol 16:149–157

Owen D, Williams AP, Griffith GW, Withers PJA (2015) Use of commercial bio-inoculants to increase agricultural production through improved phosphorus acquisition. Appl Soil Ecol 86:41–54

Palacios OA, Bashan Y, de-Bashan LE (2014) Proven and potential involvement of vitamins in interactions of plants with plant growth-promoting bacteria – an overview. Biol Fertil Soils 50:415–432

Paterson E (2003) Importance of rhizodeposition in the coupling of plant and microbial productivity. Eur J Soil Sci 54:741–750

Pellegrino E, Turrini A, Gamper HA, Cafà G, Bonari E, Young PW, Giovannetti M (2012) Establishment, persistence and effectiveness of arbuscular mycorrhizal fungal inoculants in the field revealed using molecular genetic tracing and measurement of yield components. New Phytol 194:810–822

Persello-Cartieaux F, Nussaume L, Robaglia C (2003) Tales from the underground, molecular plant-rhizobacteria interactions. Plant Cell Environ 26:189–199

Pinzari F, Dell'Abate MT, Benedetti A, Dazzi C (2001) Effects of *Cedrus atlantica* and *Pinus halepensis* on the chemistry and fertility of a Mediterranean soil after 40 years. Can J Soil Sci 81:553–560

Pinzari F, Tate J, Bicchieri M, Rhee YJ, Gadd GM (2012) Biodegradation of ivory (natural apatite): possible involvement of fungal activity in biodeterioration of the Lewis Chessmen. Environ Microbiol 15(4):1050–1062

Pirlak L, Turan M, Sahin F, Esitken A (2007) Floral and foliar application of plant growth promoting rhizobacteria (PGPR) to apples increases yield, growth, and nutrient element contents of leaves. J Sustain Agric 30(4):145–155

Pradhan N, Sukla LB (2005) Solubilization of inorganic phosphate by fungi isolated from agricultural soil. Afr J Biotechnol 5:850–854

Prasad H, Chandra R (2003) Growth pattern of urdbean *Rhizobium* sp. with PSB and PGPR in consortia. J Indian Soc Soil Sci 51:76–78

Qu XH, Wang JG (2008) Effect of amendments with different phenolic acids on soil microbial biomass, activity, and community diversity. Appl Soil Ecol 39:172–179

Reddy CA, Janarthanam L (2014) Polymicrobial formulations for enhancing plant productivity. US Patent n. US8822190B2

Reeve JR, Schadt CW, Carpenter-Boggs L, Kang S, Zhou J, Reganold JP (2010) Effects of soil type and farm management on soil ecological functional genes and microbial activities. ISME J 4:1099–1107

Reinhold-Hurek B, Hurek T (2011) Living inside plants: bacterial endophytes. Curr Opin Plant Biol 14:435–443

Rice WA, Clayton GW, Olsen PE, Lupwayi NZ (2000) Rhizobial inoculant formulations and soil pH influence field pea nodulation and nitrogen fixation. Can J Soil Sci 80:395–400

Richardson AE, Barea JM, McNeill AM, Prigent-Combaret C (2009) Acquisition of phosphorus and nitrogen in the rhizosphere and plant growth promotion by microorganisms. Plant Soil 321:305–339

Robleto EA, Borneman J, Triplett EW (1998) Effects of bacterial antibiotic production on rhizosphere microbial communities from a culture-independent perspective. Appl Environ Microbiol 64(12):5020–5022

Rodríguez H, Fraga R (1999) Phosphate solubilizing bacteria and their role in plant growth promotion. Biotechnol Adv 17:319–339

Ronn R, McGraig AE, Griffiths BS, Prosser JI (2002) Impact of protozoan grazing on the bacterial community structure in soil microcosms. Appl Environ Microbiol 68:6094–6105

Rousk J, Baath E, Brookes PC, Lauber CL, Lozupone C, Caporaso JG, Knight R, Fierer N (2010) Soil bacterial and fungal communities across a pH gradient in an arable soil. ISME J 4:1340–1351

Rowe HI, Brown CS, Claassen VP (2007) Comparisons of mycorrhizal responsiveness with field soil and commercial inoculum for six native montane species and *Bromus tectorum*. Restor Ecol 15:44–52

Ruyter-Spira C, Kohlen W, Charnikhova T, van Zeijl A, van Bezouwen L, de Ruijter N, Cardoso C, Lopez-Raez JA, Matusova R, Bours R (2011) Physiological effects of the synthetic strigolactone analog GR24 on root system architecture in *Arabidopsis*: another belowground role for strigolactones? Plant Physiol 155:721–734

Ryan RP, Germaine K, Franks A, Ryan DJ, Dowling DN (2008) Bacterial endophytes: recent developments and applications. FEMS Microbiol Lett 278:1–9

Savant NK, Datnoff LE, Snyder GH (1997) Depletion of plant available silicon in soils: a possible cause of declining rice yields. Commun Soil Sci Plant Anal 28(13&14):1245–1252

Savant NK, Korndorfer GH, Datnoff LE, Snyder GH (1999) Silicon nutrition and sugarcane production: A review. J Plant Nutri 22(12):1853–1903

Saxena J, Basu P, Jaligam V, Chandra S (2013) Phosphate solubilization by a few fungal strains belonging to the genera *Aspergillus* and *Penicillium*. Afr J Microbiol Res 7(41):4862–4869

Sayer JA, Raggett SC, Gadd GM (1995) Solubilization of insoluble metal compounds by soil fungi: development of a screening method for solubilizing activity and metal tolerance. Mycol Res 99:987–993

Schoebitz M, Simonin H, Poncelet D (2012) Starch filler and osmoprotectants improve the survival of rhizobacteria in dried alginate beads. J Microencapsul 29:532–538

Schwieger F, Tebbe CC (2000) Effect of field inoculation with *Sinorhizobium meliloti* L33 on the composition of bacterial communities in rhizospheres of a target plant (Medicago sativa) and a non-target plant (*Chenopodium album*)—linking of 16S rRNA gene-based single-strand conformation polymorphism community profiles to the diversity of cultivated bacteria. Appl Environ Microbiol 66(8):3556–3565

Sekar S, Kandavel D (2010) Interaction of plant growth promoting rhizobacteria (PGPR) and endophytes with medicinal plants– new avenues for phytochemicals. J Phytol 2:91–100

Shaharoona B, Naveed M, Arshad M, Zahir ZA (2008) Fertilizer-dependent efficiency of Pseudomonads for improving growth, yield, and nutrient use efficiency of wheat (*Triticum aestivum* L.). Appl Microbiol Biotechnol 79:147–155

Singh R, Adholeya A (2003) Interactions between arbuscular mycorrhizal fungi and plant-growth promoting rhizobacteria. Mycorrhiza News 15:16–17

Singh JS, Pandey VC, Singh DP (2011) Efficient soil microorganisms: a new dimension for sustainable agriculture and environmental development. Agric Ecosyst Environ 140:339–353

Singhal R, Gupta R, Saxena RK (1994) Rock phosphate solubilization under alkaline conditions by *Aspergillus foetidus* and *A. japonicus*. Folia Microbiol 39:33–36

Skorupska A, Wielbo J, Kidaj D, Marek-Kozaczuk M (2010) Enhancing *Rhizobium*–legume symbiosis using signaling factors. In: Khan MS (ed) Microbes for legume improvement. Springer, Wien, pp 27–54

Smith SE, Read DJ (2008) Mycorrhizal symbiosis, 3rd edn. Elsevier/Academic, New York/London/Burlington/San Diego, p 605

Smith SE, Smith FA (2012) Fresh perspectives on the roles of arbuscular mycorrhizal fungi in plant nutrition and growth. Mycology 104:1–13

Smits NAC, Bobbink R, Laanbroek HJ, Paalman AJ, Hefting MM (2010) Repression of potential nitrification activities by matgrass sward species. Plant Soil 337:435–445

Sood SG (2003) Chemotactic response of plant-growth-promoting bacteria towards roots of vesicular-arbuscular mycorrhizal tomato plants. FEMS Microbiol Ecol 45:219–227

Stephens JHG, Rask HM (2000) Inoculant production and formulation. Field Crops Res 65:249–258

Stockinger H, Krüger M, Schüßler A (2010) DNA barcoding of arbuscular mycorrhizal fungi. New Phytol 187:461–474

Strigul NS, Kravchenko LV (2006) Mathematical modelling of PGPR inoculation into the rhizosphere. Environ Model Softw 21:1158–1171

Subramanian K, Charest C (1999) Acquisition of N by external hyphae of an arbuscular mycorrhizal fungus and its impact on physiological responses in maize under drought-stressed and well-watered conditions. Mycorrhiza 9:69–75

Sudhakar P, Chattopadhyay GN, Gangwar SK, Ghosh JK (2000) Effect of foliar application of *Azotobacter*, *Azospirillum* and *Beijerinckia* on leaf yield and quality of mulberry (*Morus alba*). J Agric Sci 134:227–234

Sudhakara RM, Kumar S, Babita K, Reddy MS (2002) Biosolubilization of poorly soluble rock phosphates by *Aspergillus tubingensis* and *Aspergillus niger*. Bioresour Technol 84:187–189

Supanjani Han HS, Jung SJ, Lee KD (2006) Rock phosphate potassium and rock solubilizing bacteria as alternative sustainable fertilizers. Agro Sustain Dev 26:233–240

Świechowski W, Doruchowski G, Trzciński P (2012) Effect of spray application parameters on viability of bacterium *Pseudomonas fluorescens* used as biopesticide in organic fruit production. In: Granatstein D, Andrews P (ed) Proceedings of II International congress on organic fruit research symposium, 18–21 June 2012. ISHS, Leavenworth, p 9

Sýkorová Z, Börstler B, Zvolenská S, Fehrer J, Gryndler M, Vosátka M, Redecker D (2012) Long-term tracing of *Rhizophagus irregularis* isolate BEG140 inoculated on Phalaris *arundinacea* in a coal mine spoil bank, using mitochondrial large subunit rDNA markers. Mycorrhiza 22:69–80

Tarbell TJ, Koske RE (2007) Evaluation of commercial arbuscular mycorrhizal inocula in a sand/peat medium. Mycorrhiza 18:51–56

Tawaraya K, Naito M, Wagatsuma T (2006) Solubilization of insoluble inorganic phosphate by hyphal exudates of arbuscular mycorrhizal fungi. J Plant Nutr 29:657–665

Toljander JF, Artursson V, Paul LR, Jansson JK, Finlay RD (2006) Attachment of different soil bacteria to arbuscular mycorrhizal fungal extraradical hyphae is determined by hyphal vitality and fungal species. FEMS Microbiol Lett 254:34–40

Toljander JF, Santos-Gonzalez JC, Tehler A, Finlay RD (2008) Community analysis of arbuscular mycorrhizal fungi and bacteria in the maize mycorrhizosphere in a long-term fertilization trial. FEMS Microbiol Ecol 65:323–338

Torsvik V, Ovreas L (2002) Microbial diversity and function in soil: from genes to ecosystems. Curr Opin Microbiol 5:240–245

Trabelsi D, Mhamdi R (2013) Microbial inoculants and their impact on soil microbial communities: a review. Biomed Res Int 863240. doi: 10.1155/2013/863240

Trabelsi D, Mengoni A, Ben Ammar H, Mhamdi R (2011) Effect of on-field inoculation of Phaseolus vulgaris with rhizobia on soil bacterial communities. FEMS Microbiol Ecol 77(1):211–222

Trabelsi D, Ben Ammar H, Mengoni A, Mhamdi R (2012) Appraisal of the crop-rotation effect of rhizobial inoculation on potato cropping systems in relation to soil bacterial communities. Soil Biol Biochem 54:16

Treseder KK, Allen MF (2002) Direct nitrogen and phosphorus limitation of arbuscular mycorrhizal fungi: a model and field test. New Phytol 155:507–515

Uren NC (2007) Types, amounts and possible functions of compounds released into the rhizosphere by soil-grown plants. In: Pinto RZ, Varanini PN (eds) The rhizosphere: biochemistry and organic substances at the soil-plant interface. CRC Press, Boca Raton, pp 1–21

Van der Gast CJ, Gosling P, Tiwari B, Bending GD (2011) Spatial scaling of arbuscular mycorrhizal fungal diversity is affected by farming practice. Environ Microbiol 13:241–249 van Overbeek L, van Elsas JD (2008) Effects of plant genotype and growth stage on the structure of bacterial communities associated with potato (*Solanum tuberosum* L.). FEMS Microbiol Ecol 64:283–296

Van Schöll L, Kuyper TW, Smits MM, Landeweert R, Hoffland E, Van Breemen N (2008) Rock-eating mycorrhizas: their role in plant nutrition and biogeochemical cycles. Plant Soil 303(1–2):35–47

Vassilev N, Vassileva M, Fenice M, Federici F (2001) Immobilized cell technology applied in solubilization of insoluble inorganic (rock) phosphates and P plant acquisition. Biores Technol 79:263–271

Vassilev N, Nikolaeva I, Vassileva M (2005) Polymer-based preparation of soil inoculants: applications to arbuscular mycorrhizal fungi. Rev Environ Sci Biotechnol 4:235–243

Vassilev N, Medina A, Azcon R, Vassilev M (2006a) Microbial solubilization of rock phosphate as media containing agro industrial wastes and effect of the resulting products on plant growth and phosphorus uptake. Plant Soil 287:77–84

Vassilev N, Vassileva M, Nikolaeva I (2006b) Simultaneous P-solubilizing and biocontrol activity of microorganisms: potentials and future trends. Appl Microbiol Biotechnol 71:137–144

Vessey JK (2003) Plant growth promoting rhizobacteria as biofertilizers. Plant Soil 255:571–586

Vestergård M, Henry F, Rangel-Castro JI, Michelsen A, Prosser JI, Christensen S (2008) Rhizosphere bacterial community composition responds to arbuscular mycorrhiza, but not to reductions in microbial activity induced by foliar cutting. FEMS Microbiol Ecol 64:78–89

Viti C, Tatti E, Decorosi F, Lista E, Rea E, Tullio M, Sparvoli E, Giovannetti L (2010) Compost effect on plant growth-promoting rhizobacteria and mycorrhizal fungi population in Maize cultivations. Comp Sci Utiliz 18(4):273–281

Wagner GM (1997) Azolla. A review of its biology and utilisation. Bot Rev 63:1–26

Wainwright M, Al-Wajeeh K, Grayston J (1997) Effect of silicic acid and other silicon compounds on fungal growth in oligotrophic and nutrient-rich media. Mycol Res 101(8):933–938

Wakelin SA, Gupta VVSR, Harvey PR, Ryder MH (2007) The effect of *Penicillium* fungi on plant growth and phosphorus mobilization in neutral to alkaline soils from southern Australia. Can J Microbiol 53:106–115

Wamberg C, Christensen S, Jakobsen I, Müller AK, Sørensen SJ (2003) The mycorrhizal fungus (*Glomus intraradices*) affects microbial activity in the rhizosphere of pea plants (*Pisum sativum*). Soil Biol Biochem 35:1349–1357

Wang GM, Stribley DP, Tinker PB, Walker C (1993) Effects of pH on arbuscular mycorrhiza. 1. Field observations on the long-term liming experiments at Rothamsted and Woburn. New Phytol 124:465–472

Wang X, Pan Q, Chen F, Yan X, Liao H (2011) Effects of co-inoculation with arbuscular mycorrhizal fungi and rhizobia on soybean growth as related to root architecture and availability of N and P. Mycorrhiza 21:173–181

Wang J, Li X, Zhang J, Yao T, Wei D, Wang Y, Wang J (2012) Effect of root exudates on beneficial microorganisms – evidence from a continuous soybean monoculture. Plant Ecol 213:1883–1892

Watt M, Kirkegaard JA, Passioura JB (2006) Rhizosphere biology and crop productivity – a review. Aust J Soil Res 44:299–317

Wawrzyńczak P, Białkowski P, Rabcewicz J, Plaskota M, Gotowicki B (2011) Application of biofertilizers and biostimulants in organic orchards. In: Sas-Paszt L, Malusá E (eds) Proceedings of Ogólnopolską Naukową Konferencję Ekologiczną „Osiągnięcia i możliwości rozwoju badań i wdrożeń w ekologicznej produkcji ogrodniczej". Skierniewice 6–7/10/2011 Skierniewice, Poland: Institute Horticultural Research, pp 85–86

Whitelaw MA (2000) Growth promotion of plants inoculated with phosphate-solubilizing fungi. Adv Agron 69:99–151

Wick LY, Furuno S, Harms H (2010) Fungi as transport vectors for contaminants and contaminant-degrading bacteria. In: Timmis K, Mc Genity T, van der Meer JR, de Lorenzo V (eds) Handbook of hydrocarbon and lipid microbiology, Part 8 (51), vol 2. Springer, Berlin/Heidelberg/New York, pp 1555–1561

Wu SC, Cao ZH, Li ZG, Cheung KC, Wong MH (2005) Effects of biofertilizer containing N-fixer, P and K solubilizers and AM fungi on maize growth: a greenhouse trial. Geoderma 125:155–166

Xiao C, Chi R, Pan X, Liu F, He J (2013) Rock phosphate solubilization by four yeast strains. Ann Microbiol 63:173–178

Xie X, Yoneyama K, Yoneyama K (2010) The strigolacone story. Annu Rev Phytopathol 48:93–117

Yanni YG, Rizk RY, Abd El-Fattah FK, Squartini A, Corich V, Giacomini A, de Bruijn F, Rademaker J, Maya-Flores J, Ostrom P, Vega-Hernandez M, Hollingsworth RI, Martinez-Molina E, Mateos P, Velazquez E, Wopereis E, Triplett E, Umali-Garcia M, Anarna JA, Rolfe BG, Ladha JK, Hill J, Mujoo R, Ng PK, Dazzo FB (2001) The beneficial plant growth-promoting association of *Rhizobium leguminosarum* bv. *trifolii* with rice roots. Aust J Plant Physiol 28:845–870

Zoppellari F, Malusà E, Chitarra W, Lovisolo C, Spanna F, Bardi L (2014) Improvement of drought tolerance in maize (*Zea mais* L.) by selected rhizospheric microorganisms. Ital J Agrometeorol 18(1):5–18

Zubek S, Mielcarek S, Turnau K (2012) Hypericin and pseudohypericin concentrations of a valuable medicinal plant *Hypericum perforatum* L are enhanced by arbuscular mycorrhizal fungi. Mycorrhiza 22:149–156

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