The role of microbial inoculants in the improvement of livestock food

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I hereby declare that the work submitted is mine and that where I have made use of another’s work, I have attributed the source(s) according to the Regulations set in the Student’s Handbook.

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Abstract

This dissertation was written as part of the MSc in Sustainable Agriculture and Business at the International Hellenic University.

The continuously increasing demand for human food, consequently creates the need for increase of edible plant and livestock production. The demand for the replacement of chemical fertilizers and the introduction of alternatives in order to enhance crop productivity led to the research and use of microorganisms that affect positively the soil, the rhizosphere and finally the plants promoting its development. Such microorganisms are called microbial inoculants and they are mainly a) plant growth promoting rhizobacteria, b) arbuscular mycorrhizal fungi and c) endophytes. The inoculation of these inoculants of plants with main concern for livestock as maize (*Zea mays*), wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), oats (*Avena sativa*), soybean (*Glycine max*), sorghum (*Sorghum spp.*), alfalfa (*Medicago sativa*) and trefoil (*Trifolium spp.*) revealed their beneficial effect on most cases improvement of the quantity and quality of plant food, although in some cases they had a negative or neutral impact.

It is shown that these microorganisms can promote plant growth in terms of root and aerial parts parameters, yield production as well as nutrient uptake from the soil and so to enhance the quality of the feed. Moreover, they managed to alleviate stressful environmental conditions as drought, salinity and toxicity of soils polluted by heavy metals. Especially, our study showed that bacteria of the genera Bacillus and Pseudomonas revealed their beneficial effects on maize, wheat, barley and soybean in nutrient deficiency, environmental stressed and non-stressed conditions. Additionally, fungal genera Glomus promoted plant growth and yield production of maize, wheat and soybean under every investigated soil condition. Furthermore, bacteria of genera Arthrobacter, Rhodococcus, Burkholderia and Aeromonas reduced the nutrient deficiency, especially for N, P and K. Environmental stresses caused by drought were reduced or neutralized by inoculants of genera Pseudomonas, Glomus, Azospirillum, Enterobacter, Burkholderia and Acaulospora and those caused by salinity by Hartmanibacter, Glomus, Bacillus and Halobacillus respectively. Bacteria as *Bradyrhizobium diazoefficiens* and *Enterobacter ludwigi* and fungi as *Claroideoglomus etunicatum* alleviated the pollution of soil by heavy metals and improved plant development. In addition, it was revealed that most microorganisms do not have a plant specificity as they inoculated and affected more than one of the plants concerning us. Specifically, *Pseudomonas fluorescens*, bacteria of genera Burkholderia, Arthrobacter and Rhodococcus promoted maize’s and wheat’s development and productivity. *Glomus spp.*, *Azospirillum spp.* and *Enterobacter spp.* improved maize’s, wheat’s and soybean’s performance. Finally, *Paenibacillus spp.* and *Pantoea spp.* affected positively the growth and performance of maize, wheat and barley and especially *Paenibacillus polymixa* revealed its ability to induce systemic resistance against pathogenic microorganisms in wheat. In summary, the application of these microbial inoculants in maize, wheat, barley and soybean is a promising strategy for the enhancement of productivity of these plants and the livestock fed with them.
I would like to thank my supervisor Associate Professor Mrs. Efimia Papatheodorou and also Dr. Nikolaos Monokroussos for their patience, persistence and guidance through all the stages of the completion of this dissertation. Their uninterrupted presence and stable consistency encouraged me and presented me a more methodical and accurate way of working.

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Contents

Abstract ......................................................................................................................... II
Acknowledgements ....................................................................................................... III
Introduction .................................................................................................................. 1
Role of Microbial Inoculants ......................................................................................... 5
Methods ....................................................................................................................... 7
PGPR .............................................................................................................................. 10
AMF .............................................................................................................................. 18
Endophytes .................................................................................................................. 22
Combinations of Microbial Inoculants ........................................................................ 26
Discussion .................................................................................................................... 30
Conclusion .................................................................................................................... 40
References .................................................................................................................... 40
Electronic References .................................................................................................. 50
Introduction

As FAO has already demonstrated, the global population will reach 9.1 billion by 2050, 34% higher than today, and the majority of this increase will be in developing countries (1). So, as shown in the graphs below, food production and especially meat production has to be greater by 70% in order to feed the new world’s population (Figure 1 and 2) (1,2). Additionally, cereal production has to reach the limit of 3 billion tones and the meat quantity to be increased to more than 200 million tones for each year (1,2). Undoubtedly, an increase in crop productivity will result in more food for animals, in order to increase meat production and finally in greater supplies of human food (1,2).

Figure 1. Global human need for meat and eggs.

Figure 2. Allocation of global surface area for food production.
Higher yield, better quality, biotic and abiotic stress resistance, expression of various desirable agronomic traits, better and wider adaptability of crops especially in climatic changes are signs of improvement of crop yield. The main categories concerning this study are higher yield (quantity) and better quality. Quantity can be defined as the measurement of grains or seeds that are generated from a unit of land expressed as Kg/ha and actually represents the agricultural output. Referring to qualitative food, we have to take into consideration the concentrations of water, dry matter (organic and inorganic) and basic nutrients such as carbohydrates, fat, protein, minerals and vitamins of the feed (Voutsinos et al. 1999, 3).

In order to fill their life cycle needs, animals need to intake various chemical compounds (Egan, 2017). These compounds are mainly carbohydrates, protein, fats, minerals and vitamins (Egan, 2017). Especially, fats and carbohydrates provide the required for the maintenance of their life and basic functions such as health, growth and production (Egan, 2017). Besides, the composition of the ration and the intake of required elements affect the immune system of the animals (Dänicke et al., 2018). So, it is essential that the ration insures both the quantity and the quality of the feed in order to protect the stability of animal health and production. (Dänicke et al., 2018).

Apart from proteins, some lipids and some minerals contribute to the formation of main structures of the body tissues acting towards the renewal of the body units, the formation of muscles (meat), eggs and milk and the protection of the basic life circle of the animal. Moreover, some minerals and vitamins which cannot be synthesized inside the animal body promote the function and completion of basic metabolic pathways that are involved in the provision of energy or the construction of main body tissues. It essential to be referred that these requirements vary among the animals due to differences in species, age, live weight, utilization of nutrients and the demand of production (Adrian 2017, Voutsinos et al. 1999). Water is another basic component of life and health of animals as it is the 55%-80% of their total live weight. It affects the main chemical reactions of the body and is the main component of blood, lymph and animal products such as milk, urine and feces (Voutsinos et al. 1999).

Specifically, ruminants’ basic functions require 5 key nutrients which are protein, energy (fiber), fat (lipids), vitamins and minerals (Mcgrath et al., 2018). The main source of energy for them in intensive systems are cereals, mainly maize and sorghum.
Mcgrath et al., 2018). These plants provide the required for the animal starch. Defined as crops that are cultivated for the nutrition of animals, fodder crops can be classified as temporary or permanent. Temporary fodder crops are cultivated and then harvested as usual whereas permanent crops are used for five years or more for forage crops either for cultivation or for wild plant species growth. These crops include cereals, legumes and grasses that are fed to animals as green plants, hays or either as silage after the proper procedure. Fodder crops, include also natural grasslands, pastures and parts of forests if they are cultivated or used for grazing.

As we can observe from the statistics presented in figures 3 and 4 in USA, the most cultivated crops worldwide are corn, wheat, rice and barley and oats. All these crops are used as livestock food, except from rice which is fed to animals in lower scale. In USA, the main cereals used for the animal nutrition in 2016 are corn (50%), soybean, bakery meals and sorghum. Moreover, alfalfa constitutes the fourth most cultivated crop in U.S.A. and high quality Trifolium spp. is major feed for animals worldwide (Tekeli, Ates and Varol, 2005). So, the main crops used for the nutrition of livestock animals are maize (Zea mays), wheat (Triticum aestivum), barley (Hordeum vulgare), oats (Avena sativa), soybean (Glycine max), sorghum (Sorghum spp.), alfalfa (Medicago sativa) and trefoil (Trifolium spp).

![Total diet composition for top livestock and poultry in 2016](image)

**Figure 3.** Total diet composition of livestock and poultry in 2016 in USA.
Each species of plants has its own nutritional value. It is found that grasses have crude fibers, protein and minerals whereas legumes contain big amounts of protein and minerals (4). Maize is on the base of the feeding pyramid (8,9). Almost every product of maize that can be further processed for the production of flour, starch and alcohol or biofuel industries can be used as animal feed (8,9). It is fed to animals as germs, silage or green forage (8,9). Maize is the main source of energy supplement for the animals as it provides the 30% of protein, 60% of energy and 90% of starch required by animals (8,9). Furthermore, it contains sufficient quantities of vitamin of complex B, especially thiamin (vitamin B1), niacin and essential amino acids as lysine and tryptophan (8,9). Also, contains great amounts of water, dietary fibers and essential minerals as Mg, P, K, Mn and Zn (8,9). Wheat is the third most produced cereal after maize and rice worldwide (10,11,12). It is used as food source, with many forms, either grain, bran, middlings, germs, forage or straw, for human and animals (10,11,12). Especially the wheat grains contain great amounts of carbohydrate and starch so it is a primary source of energy as maize is (10,11,12). Moreover, they equip the animals with fibers, vitamins, minerals and protein (10,11,12). Mainly, they contain vitamins A, B6, E, K, niacin, elements as Mn, P, Mg, Cu, Fe, Se, Zn and essential amino acids like tryptophan, valine and lysine (10,11,12). The fourth most cultivated cereal globally is barley (13,14). It is of main importance for animal husbandry, as 85% of barley production is used for animal feeding (13,14). Barley contains significant amounts of dietary fibers, vitamins, especially B6 and choline and minerals like K, Ca, Mg, Fe, P, Mn, Zn and Se (13,14). It is fed mainly
as pasture, hay or silage\(^{(13,14)}\). Like barley, oats’ primary usage is in livestock nutrition (70\%)\(^{(15,16)}\). Oats contain great concentrations of protein and dietary fibers, vitamins like thiamin and pantothenic acid, minerals, mainly Mn, P, Mg, Fe, ZN and essential amino acids as tryptophan, isoleucine, leucine, valine and threonine\(^{(15,16)}\).

Soybean provides a really high percentage of excellent quality protein to animals, the highest among all legumes [[Masciarelli et al. 2014, 17,18,19,20]. Fats and dietary fibers are presented in great amounts [[Masciarelli et al. 2014, 17,18,19,20]. Moreover, gives to livestock vitamins, especially folates, riboflavin and thiamin and essential elements in great concentrations as Fe, Cu, Mn, P, Zn, Mg [[Masciarelli et al. 2014], 17,18,19,20]. The soybean products that are used are soybean oil, soybean meal or whole soybeans. [[Masciarelli, Llanes and Luna, 2014], 17,18,19,20]. Sorghum is considered a nutritionally valuable feed measuring protein, carbohydrates and micronutrients \(^{(4,21,22,23)}\). In livestock nutrition it is used for grazing, it can be cut fresh, or to be fed as hay or ensiled \(^{(4,21,22,23)}\). Vitamin B6, thiamin, Mn, P, Mg, leucine, phenylalanine, tryptophan and threonine have been found to be mostly presented in sorghum \(^{(4,21,22,23)}\). Alfalfa and Trifolium spp. are crops with high nutritional value that provide significant proportions of dietary fibers and protein \(^{(24,25,26,27,28,29,30,31)}\). Especially, alfalfa is another major protein source for livestock \(^{(24,25,26,27,28,29,30,31)}\). They both can be fed as pasture, hay, silage, dehydrated pellets or can be used for grazing by the animals \(^{(24,25,26,27,28,29,30,31)}\). Nutritionally, the provide vitamin K and B6 and essential elements as Mn, Mg, P, Cu, P, Fe and Se \(^{(24,25,26,27,28,29,30,31)}\).

**Role of microbial inoculants**

In the last decades the biological agents seem to be preferred by farmers than the chemical fertilization as they are considered friendlier to the environment and more economically sufficient in order to improve the agricultural conditions (Prasanna et al., 2016). The definition given to plant biostimulants by the European Biostimulants Industry in 2012 is the following: “Plant biostimulants contain substance(s) and/or microorganisms whose function when applied to plants or the rhizosphere is to stimulate natural processes to enhance/ benefit nutrient uptake, nutrient efficiency, tolerance to abiotic stress, and crop quality. Biostimulants have no direct action
against pests, and therefore do not fall within the regulatory framework of pesticides” (Calvo et al. 2014).

Microbial inoculants, microorganisms that can be classified either as biocontrol agents or biofertilizers, consist a category of biostimulants (Calvo et al. 2014). Their main action is the plant growth promotion by increasing the available to the plant nutrients, the root biomass and area and the uptake of nutrients by the plant after their application on the seed, the surface of the plant or even on the soil (Calvo et al. 2014; Gómez and Luiz, 2018). There are three main categories of microbial inoculants which have been deeply studied, a) the free-living bacteria that contain the plant growth promoting rhizobacteria (PGPR) and bacteria (PGPB), b) the fungi and c) the endophytes (Calvo et al. 2014; Gómez and Luiz, 2018). It has been demonstrated that the promotion of plant growth and the increase in yield by microbial inoculants has been a result of the elevated nutrient uptake and the better nutrient status of the inoculated plant (Calvo et al. 2014; Di Salvo et al., 2018). This is supported by the fact that the application of inoculants could utilize, mineralize and mobilize soil nutrients such as P, K, the Fe reserves, enhance the organic matter or even convert N of atmosphere to usable from the plant forms (Rashid et al., 2016).

Some inoculants are capable of solubilizing nutrients making them available to the plant more efficiently (Prasanna et al., 2016). PGPR affect the growth of the plants in a direct way by the production of phytohormones on indirectly by acting as biological control agents or by being involved in the availability and uptake of nutritional parts from the roots (Ibañez et al., 2014; Prasanna et al., 2016). Many bacterial genera have been identified as P-solubilizers (Pseudomonas, Bacillus, Burkholderia etc.) via the production of organic acids and phosphatases (Krey et al., 2013; Calvo et al. 2014; Rouphael et al., 2015). Moreover, free – living and symbiotic bacteria provide N through the fixation of atmospheric N and the production of hormones such as auxins, cytokinins, gibberellins and ethylene (Calvo et al. 2014; Rashid et al., 2016). Usually, the combination of these hormones gives better results than their individual action (Calvo et al. 2014). Furtherly, PGPR have the ability to induce systemic resistance against various bacteria, fungi and viruses (Samain et al., 2017). Especially, arbuscular mycorrhizal fungi (AMF) promote the uptake of nutrients such as P, especially in P-deficient soils, K by dissolving rock K or chelating silicon ions (Calvo et al. 2014), NH4,
Cu, Zn and other soil-derived cations (K⁺, Ca²⁺, Mg²⁺, Fe³⁺) (Rouphael et al., 2015). Inoculants also assist indirectly the uptake of nutrients by enhancing the root biomass, surface area and hairs (Calvo et al. 2014).

The aims of this review are to investigate i) which microorganisms, families or specific strains are used as microbial inoculants, ii) if these microbial inoculants are applicable only in one or more plants as maize, wheat, barley and soybean and iii) if these microbial inoculants are being used only for the enhancement of yield production or for the improvement of plant growth and yield production of maize, wheat, barley and soybean in areas with environmental stress and nutrient deficiency.

**Methods**

Taking into consideration all the previous information about animal nutrition, a review of literature published from 2013 until today for maize and from 2010 until today for the rest of the plants concerning our work was organized. This differentiation in dates of search was due to the sufficient number of review papers referring to maize till 2013 that formed the need for more recent information about maize. The search of academic literature was based on the use of Science Direct, Web of Science and Scopus databases. The search terms used were: (maize* or Zea mays* or wheat * or Triticum aestivum* or barley* or Hordeum vulgare* or sorghum* or Sorghum spp* or oat* or Avena sativa * or soybean* or Glycine max* or alfalfa* or Medicago sativa* or trefoil* or Trifolium spp*) and (PGPR* or PGPF* or AMF* or endophytes*), (name of plant) and (drought stress* or salinity* or yield improvement * or crop production* or quality improvement*). We only retained articles where the action of microbial inoculants on plants in different environmental conditions (stress, pollution, nutrient deficiency or unstressed cultivation conditions) was measured.

Totally, 72 articles were identified using the search criteria. 60 of these articles were referring to only 4 plants, specifically maize, wheat, barley and soybean, while the rest 12 referred to the rest 4 plants: sorghum, oats, alfalfa, trefoil. Although at the beginning of our study we present information regarding all eight plants, later the presented results are based on the analysis of data found only regarding the first 4
plants (maize, wheat, barley and soybean) therefore we used 60 papers. We categorized the papers in three aspects. Firstly, by the kind of microbial inoculant, individually or combination of two or more inoculants e.g. PGPR and AMF or AMF and endophytes or PGPR and endophytes. Secondly, by the reference on stress environmental conditions (stress, pollution, nutrient deficiency) or in increase of plant productivity under unstressed environmental conditions. Furthermore, we categorized the articles by the country where the studies were conducted in order to understand the locations of the main interest on these agriculture techniques.

Clearly, the plant growth promoting rhizobacteria are of main interest in the last years since 2010 as they are represented in almost half (27/72) of the papers selected, as shown in Chart 1. The AMF have been extensively analyzed in the years before 2010 and many review papers have been written (Hildebrandt et al. 2007; Rouphael et al. 2015; Lenoir et al. 2016) and that is the reason why they cover only 22% (13/60) of the papers found from our search; almost the same percentage with AMF covers the endophyte activity (12/60). The application of combined inocula of microbes is studied in even less papers, mostly referring to the combination of PGPR and AMF whereas the combination of endophytes with AMF does not constitute a main interest for researchers until now.

In Chart 2 the environmental conditions have been charted. We categorized articles referring to application of the inoculant in soils with environmental stress as drought stress, salinity or even temperature stress. As pollution we defined the cases with toxicity or surplus of heavy metals or other elements. Moreover, we categorized as nutrient deficiency or fertilization the articles showing inoculation of plants in soils with limited or very low concentrations of one or more elements or microorganisms. In most cases the results of the application of microbial inoculation have been studied under abiotic stress, or nutrient deficient or toxicity soil conditions. So, the main focus is in the alleviation of these uncertain conditions and the improvement of agroecosystems. Non-stressed environmental soil conditions are studied in 40% of papers. Afterwards, the most studied categories are these of environmental stresses and nutrient deficiency on one or more nutrients. Moreover, many studies have been completed on polluted with heavy metal or surpluses of other elements. At last, few
cases on soils with environmental stresses and even fewer that resulted in biological control of diseases after the inoculation have been demonstrated. Furthermore, as we polled in Chart 3 the countries showing the most interest on these studies, we found out that countries with overpopulation, great population or with stressful environmental conditions (close to the equator) have conducted the most researches.

**Chart 1.** Categorization by the type of microbial inoculant used in each paper.

**Chart 2.** Categorization by the environmental conditions existing in each paper.
In recent years, farmers tend to replace the application of chemical fertilizers and pesticides with the inoculation of plants with PGPR due to the need for environmental protection and decrease of economic losses (Kaur and Reddy, 2015; Shaikh and Saraf, 2017). The effects of the application of PGPR on plants have been studied mainly in unstressed environmental conditions, in nutrient deficiency conditions and less in environmental stress situations such as drought stress or salinity and in a few cases in metal polluted soils. The main interest of these studies was focused on the effectiveness of the inoculants on growth promotion, yield enhancement and nutritional quality improvement as it is observed in Table 1.

Table 1. PGPR referring studies.

<table>
<thead>
<tr>
<th>STUDY</th>
<th>INOCULANT</th>
<th>CONDITIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mumtaz et al. 2017</td>
<td><em>Bacillus spp.</em></td>
<td>fertilization</td>
</tr>
<tr>
<td>Krey et al. 2013</td>
<td><em>Pseudomonas fluorescens, Enterobacter radicincitans</em></td>
<td>fertilization</td>
</tr>
<tr>
<td>Pereira and Castro 2014</td>
<td><em>Rhodococcus spp.</em>, <em>Pseudomonas spp.</em>, <em>Arthrobacter spp.</em>, and <em>Burkholderia spp.</em></td>
<td>fertilization</td>
</tr>
<tr>
<td>Authors</td>
<td>Species Descriptions</td>
<td>Conditions</td>
</tr>
<tr>
<td>--------------------</td>
<td>------------------------------------------------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Kaur and Reddy 2015</td>
<td>Pantoea cypripedii and Pseudomonas plecoglossicida</td>
<td>fertilization</td>
</tr>
<tr>
<td>Batool and Iqbal 2018</td>
<td>Rhodococcus spp., Pseudomonas spp. and Arthrobacter nicotinovorans</td>
<td>fertilization</td>
</tr>
<tr>
<td>Ramesh et al. 2014</td>
<td>Bacillus aryabhattai</td>
<td>fertilization</td>
</tr>
<tr>
<td>Shaikh and Saraf 2017</td>
<td>Trabusiella spp., Aeromonas spp., Arthrobacter spp. and Exiguobacterium aurantiacum</td>
<td>fertilization</td>
</tr>
<tr>
<td>Kumar et al. 2018</td>
<td>Aneurinibacillus aneurinilyticus, Aeromonas spp. and Pseudomonas spp.</td>
<td>fertilization</td>
</tr>
<tr>
<td>Iqbal et al. 2018</td>
<td>Pseudomonas striata</td>
<td>drought stress</td>
</tr>
<tr>
<td>Vurukonda et al. 2016</td>
<td>Pseudomonas putida strain FBKV2</td>
<td>drought stress</td>
</tr>
<tr>
<td>Garcia et al. 2017</td>
<td>Azospirillum spp.</td>
<td>drought stress</td>
</tr>
<tr>
<td>Orhan 2016</td>
<td>Bacillus spp., Halobacillus spp., Bacillus gibsonii, Staphylococcus succinus, Zhihengliuella spp., Zhihengliuella halotolerans, Oceanobacillus spp., Oceanobacillus oncorhynchi, Exiguobacterium aurantiacum, Bacillus atrophaeus, Halomonas spp., Virgibacillus picturae and Thalassobacillus spp.</td>
<td>salinity</td>
</tr>
<tr>
<td>Suarez et al. 2015</td>
<td>Hartmannibacter diazotrophicus</td>
<td>salinity</td>
</tr>
<tr>
<td>Cardinale et al. 2015</td>
<td>Pseudomonas spp., Bacillus simplex, Curtobacterium flaccumfaciens, Ensifer garamanticus, Microbacterium natoriense, ‘Streptomyces spp, Hartmannibacter diazotrophicus, Sphingopyxis taejonensis, Rheinhejmera hassiensis, Cellvibrio diazotrophicus</td>
<td>salinity</td>
</tr>
<tr>
<td>Zimmer et al. 2016</td>
<td>Bradyrhizobium spp.</td>
<td>temperature stress</td>
</tr>
<tr>
<td>Singh et al. 2018</td>
<td>Enterobacter ludwigii</td>
<td>pollution</td>
</tr>
</tbody>
</table>
The development and yield production of a plant are correlated with the absorption of N, P and Zn. In soils with limited concentrations of these elements, plant growth, productivity and seed germination were inhibited (Pereira and Castro, 2014; Ramesh et al., 2014; Kaur and Reddy, 2015; Prasanna et al., 2016). Phosphorous is a main macronutrient for the completion of biological functions of plants but P amounts in soils are mainly immobilized and so unavailable for the plants (Kaur and Reddy, 2015; Batool and Iqbal, 2018). Moreover, deficiency of Zn, another essential element, limits not only the crop production but also the nutritional quality of the plants (Ramesh et al., 2014). The action of PGPR in nutrient deficient soils has been studied in many laboratory or field experiments. The application of phosphate solubilizing bacteria (PSB) resulted in increases in growth parameters and uptake of phosphorus in plants as maize, wheat and wheat.
Especially PGPR of the genera Rhodococcus, Pseudomonas and Arthrobacter, enhanced the maize dry biomass and increased the P content of roots and shoot (Pereira and Castro, 2014). Same results were also revealed by application of other bacteria such as Achromobacter spp., Agroacterium spp., Bordetella spp., Cupravidus spp., Ochrobactrum spp., Chryseobacterium spp. and Flavobacterium spp. (Youseif, 2018). Pantoea cyripedii and Pseudomonas plecoglossicida inoculation in maize and wheat increased P concentrations in grain, root and shoot, enhanced the shoot length, the grain yield and the dry biomass of the plants and also contributed to the soil fertility by improving the availability of P, the enzymatic action and the population of phosphate solubilizing bacteria (Krey et al., 2013; Kaur and Reddy, 2015). The above results were also confirmed after the inoculation of wheat with phosphate solubilizing bacterial strains that were isolated from various soils in order to investigate their effect on wheat growth and nutrition (Batool and Iqbal, 2018). On the other hand, Enterobacter radicincitans proved to rather have a drawback on P availability and yield production (Krey et al., 2013).

Furthermore, PGPR as Acinetobacter spp., Bacillus spp., Gluconacetobacter spp., Pseudomonas spp., Trabusiella spp., Aeromonas spp., Arthrobacter spp., and Exiquobacterium spp. are considered zinc solubilizing bacteria (Ramesh et al., 2014; Shaikh and Saraf, 2017). Zn is essential for plants as it is a part of over 300 proteins, having a main role in enzymatic activity and the production of auxins in plats, although it appears to be toxic for plants and animals in great amounts (Bassey, Mitsumoto and Sakamoto, 2017). The solubilization of Zn is promoted by the production and secretion of many acids, hormones and vitamins (Ramesh et al., 2014; Mumtaz et al., 2017). These strains are capable of enhancing growth and yield and improving quality of the crops (Ramesh et al., 2014; Mumtaz et al., 2017). Specifically, the application of Bacillus aryabhattai on soybean and wheat increased the Zn content in the broths of the experiment, enhanced the solubilization of Zn and this resulted in improved seed yield, root and shoot dry weight and increased Zn concentrations in the plants (Ramesh et al., 2014). Moreover, as for the production of IAA and siderophores, some strains of Bacillus spp. revealed a positive reaction, but in case of IAA production the simultaneous presence of L-tryptophan gave greater results (Mumtaz et al., 2017). Bacillus spp., promoted also plant growth as the measurements for shoot and root
length, shoot, root and total fresh and dry biomass showed significant improvement (Mumtaz et al., 2017).

Except from gains in quantity Zn solubilizing bacteria offer also qualitative profit to the plants as they enhance the amounts of micronutrients such as Zn, Fe, N, P and K (Shaikh and Saraf, 2017). Additionally, Kumar et al in 2018 proved the importance of Fe for the plant growth, as the enhanced siderophore production by bacterial strains of *Aneurinibacillus aneurinilyticus, Aeromonas spp. and Pseudomonas spp.* resulted in increased seed germination, plant height, and total dry weight of wheat plants (Kumar et al., 2018). Some of these strains revealed also an action against *Fusarium solani*, a pathogenic agent of wheat (Kumar et al., 2018).

The inoculation of plants with PGPR, promotes the overleap of environmental stresses such as drought stress, salinity and temperature stress that inhibit the development of agricultural crops (Vurukonda et al., 2016; García et al., 2017). Experiments took place in Iraq and in Pakistan in order to investigate the effect of application of plant residues and P-solubilizing bacteria, mainly *Pseudomonas striata*, along with the proper management of P on maize yield and its components (Iqbal et al., 2018). The researchers found out that the individual application of bacteria or plant residue or phosphorus sources had significantly positive effects on yield and its components such as total number of plants, ear length, number of grains per row or per ear, grain yield as Kg/ha, harvest index and selling percentage that specifically were increased (Iqbal et al., 2018). However, the interactions of the applicants had no serious effect on yield and its components (Iqbal et al., 2018).

Earlier, in 2016 in India, Vurukonda et. al., investigated the effects of the application of *Pseudomonas putida strain FBKV2* in maize (Vurukonda et al., 2016). It was revealed that this strain promoted production of IAA, HCN, siderophore and the solubilization of P under both control and drought conditions (Vurukonda et al., 2016). Moreover, under drought stress conditions, inoculation with the strain FBKV2 increased the sugars, starch, proline, chlorophyll and the amino acids contained in maize seedlings (Vurukonda et al., 2016). Additionally, the seedling was promoted as found by the increases in root and shoot length, the dry biomass, the metabolites presence and action and the stomatal activity (Vurukonda et al., 2016). Moreover, the inoculation of maize with *Azospirillum spp.* in vitro, revealed that these bacteria and especially the
strains Az39 and Az19 can offer osmotic, salt and drought tolerance to the plants by increasing the production of IAA and proline as well as promoting the enhancement of the plant height, the dry weight of shoot and roots and maintaining the relative water content at a certain level (García et al., 2017).

Additionally, the alleviation of salinity, an abiotic stress condition that might affect half of global agricultural soils by 2050 (Cardinale et al., 2015), by PGPR has been studied. The PGPR inoculation not only improved salinity tolerance but also enhanced the plant development (Orhan, 2016). The major mechanism of defense against salinity is the production of ACC-deaminase by bacterial strains (Cardinale et al., 2015). ACC – deaminase producing bacteria manage to decrease the ethylene aggregation in plants under salt stress and promote plant development and elongation of roots (Suarez et al., 2015). Bacterial strains that alleviate salinity increased the length, the fresh and dry weight of aerial and root parts, the root-to-shoot ratio and also the relative water content significantly as proven by experiments in wheat and barley (Cardinale et al., 2015; Suarez et al., 2015; Orhan, 2016). Especially, Hartmannibacter diazotrophicus also decreased the uptake of Na by the roots which led to the restoration of nutrient balance (Suarez et al., 2015). Moreover, soybean yield production has been increased after inoculation with Bradyrhizobium spp. strains and commercially available inoculants under cool conditions (Zimmer et al., 2016). The rhizobium strains achieved to promote the highest grain yield and protein content and yield in measurements of Zimmer et al. on soybean varieties (Zimmer et al., 2016).

ACC-deaminase is a major cofactor for the alleviation for toxicity in heavy metal polluted soils also (Singh et al., 2018). The application of Enterobacter ludwigii CDP-14 on wheat, a Zn-resistant bacterium, increased the production of ACC-deaminase, IAA, and the solubilization of phosphates, aspects that promote plant growth (Singh et al., 2018). Zn is an element, that mobilizes plant enzymes and proteins but its surplus can cause oxidative cellular damages (Singh et al., 2018). Consequently, the inoculation resulted in enhancement of root and shoot length, fresh and dry weight and the uptake of Zn by the plant (Singh et al., 2018).

The beneficial activity of PGPR application has also been studied under non-stressed environmental conditions. The availability of N in soil is essential for the enhancement of growth and productivity of plants (Prasanna et al., 2016). Moreover, sodium also
affects the mobility and the uptake of P and Zn and the N availability enhances the translocation of nutrients between shoot and root (Rana et al., 2012). In experiments with cyanobacteria strains in maize, Prasanna et. al., found out that these bacteria promote the crop production as they helped the plants gain more height and they enhanced the cob yields (Prasanna et al., 2016). Furthermore, they improved the soil functional activities and the soil aggregation due to the increase of glomalin related soil proteins (Prasanna et al., 2016).

Cyanobacteria based biofilms, that were inoculated with bacteria *Azotobacter chroococcum, Mesorhizobium cicero, Serratia marcescens* and *Pseudomonas striata* managed to increase the N-fixing potential by increasing the acetylene reducing activity in pot experiments in wheat, promoting so the plant growth and production (Swarnalakshmi et al., 2013). The application of consortium of *Providencia spp.* with cyanobacteria of genera *Anabaena spp.* and *Calothrix spp.* and a commercial fertilizer N<sub>60</sub>P<sub>60</sub>K<sub>60</sub> managed to enhance at highest level the wheat grain yield (Rana et al., 2012). Qualitatively, concerning the concentration of protein content and essential micronutrients as Fe, Cu, Zn and Mn, the best improvement was achieved by the application of *Providencia spp.* and the fertilizer above (Rana et al., 2012). Especially, the individual application of *Providencia spp.* showed the ability of this PGPR in production of NH<sub>3</sub>, siderophores, HCN, indolic compounds and the solubilization of P and Zn (Rana et al., 2012).

The application of *Pseudomonas fluorescens* has also been studied in experiments in maize and wheat along with nitrogen fertilization and the application of *Azospirillum brasilense*. Although the results showed no interactions between the fertilizers and the PGPR, the application of each of them individually or in combinations resulted in enhancement of grain yield and root biomass but decreased the aerial biomass of the plants. However, it was estimated that the aerial biomass decreased due to P-deficient soils as *P. fluorescens*’ main action is the solubilization of P (Di Salvo et al., 2018). Maize’s total fresh and dry weight, as well as the shoot length have also been increased after the positive synergistic effect of the inoculation with *Pseudomonas spp.*, *Enterobacter spp.* and *Klebsiella spp.* (Ibañez et al., 2014). This studies also revealed that after years of continuous bacterial application on the same field the promotion of maize growth will present efficient enhancement (Ibañez et al., 2014).
Azospirillum brasilense, which is a non-symbiotic PGPR, was also studied on maize after its application, either at sowing on seed or by leaf spray at the V3 stage of plant growth, in combination with metabolites of Rhizobium tropici (Marks et al., 2015). Both application ways resulted in increased grain yield, N uptake and shoot dry weight (Marks et al., 2015). However, it was found out that the shoot dry weight was increased only by the individual application of A. brasilense on seed, whereas when applied by spray on leaves the enrichment with metabolites of R. tropici was needed for this increase (Marks et al., 2015). The results of application's manner of PGPR revealed also that either soil application or foliar spraying of PGPR N-fixing bacteria improved wheat’s root parameters as length, ties and surface area (Cortivo et al., 2017). Specifically, the application of Azospirillum spp., Azoarcus spp., and Azorhizobium spp. along with a commercial bio-fertilizer improved root growth, the resistance in stress conditions and also reduced N-losses offering enhancement of grain yield (Cortivo et al., 2017).

The promotion of growth, yield and nutrient uptake in wheat has also been proved after the inoculation in pot and field experiments with Bacillus megaterium, Arthrobacter chlorophenolicus and Enterobacter spp., bacteria that promote N-fixation, P solubilization and HCN and siderophore production (Kumar et al. 2014). The application of this triple consortium enhanced the plant height, grain and straw yield and also maximized the Zn, Fe, Cu and Mn concentrations in wheat plants in both pot and field conditions (Kumar et al. 2014). Also, all individual applications of these bacteria resulted in increased grain yield which shows that this improvement is a result of higher nutrient concentration in soil and plant (Kumar et al. 2014).

PGPR also promote K+ uptake by plants which is another essential element for plant’s life cycle (Rankl et al., 2016). Especially, the effect of N-acyl-homoserine lactones (AHLs) on growth promotion, root development and K+ uptake was studied in barley (Rankl et al., 2016). They promoted root elongation and increased the number of tips per root system, changing so the root architecture which resulted in increased uptake of K cations by the plant (Rankl et al., 2016). This consequently enhanced the plant biomass (Rankl et al., 2016).

In soybean the application of Bacillus amyloliquefaciens subsp. plantarum with Bradyrhizobium japonicum, a soybean microsymbiont resulted in growth promotion
due to the production of great levels of auxin, gibberellins and salicylic acid by the Bacillus and the nitrogen fixation by the microsymbiont (Masciarelli et al. 2014).

**AMF**

The activity and the contribution of AMF to the plant growth and nutrient accumulation has been studied during the previous years (Liu et al., 2018). AMF are the most widespread symbionts forming symbiosis with host – plant roots and so they constitute an immediate linkage between the soil and the below-ground part of the plant (Bi et al. 2018; Cozzolino et al. 2013). So, they enhance the mineral nutrition and water acquisition of plants, reduce their fertilizing needs, limit the leakage of nutrients to the environment and also have the ability to alleviate the consequences of biotic and abiotic stresses (Chang et al. 2018; Cozzolino et al. 2013; Liu et al. 2018). Moreover, AMF promote the reaction of the antioxidant defense system, improves systemic tolerance and also reduces the reactive oxygen species and the oxidative damage caused to plants due to promotion of synthesis of phytohormones (Hashem et al., 2016). The papers examining the AMF activity are presented in Table 2.

**Table 2.** AMF referring studies.

<table>
<thead>
<tr>
<th>STUDY</th>
<th>INOCULANT</th>
<th>CONDITIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sarabia et al. 2017</td>
<td><em>Cryptococcus flavus</em> and <em>Candida railenensis</em></td>
<td>fertilization</td>
</tr>
<tr>
<td>Cozzolino et al. 2013</td>
<td><em>Glomus intraradices</em> (commercial inoculant AEGIS)</td>
<td>fertilization</td>
</tr>
<tr>
<td>Bulgarelli et al. 2017</td>
<td><em>Glomus macrocarpum.</em></td>
<td>fertilization</td>
</tr>
<tr>
<td>Liu et al. 2018</td>
<td><em>Glomus intraradices</em></td>
<td>pollution</td>
</tr>
<tr>
<td>Chang et al. 2018</td>
<td><em>Claroideoglomus etunicatum</em></td>
<td>pollution</td>
</tr>
<tr>
<td>Zhang et al. 2016</td>
<td><em>Funneliformis mosseae</em></td>
<td>salinity</td>
</tr>
</tbody>
</table>
The role of AMF in P nutrition is well known as it is an essential nutrient for the plant growth or suppression (Sarabia et al., 2017). Field experiments under P-deficiency conditions in maize inoculated at sowing with AEGIS, a commercial inoculant, mainly based on *Glomus intraradices* and the application of NPK fertilizers in various concentrations, revealed that the activity of AMF, promoted the plant growth, increased the stalk and leaf dry weight and enhanced the productivity at any concentration of the NPK fertilizers (Cozzolino et al. 2013). However, the application of fertilizers usually, decreases marginally the root colonization by AMF (Cozzolino et al. 2013; Sarabia et al. 2017). Additionally, total P concentration in plants and field was increased by all treatments (Cozzolino et al. 2013).

The limited info about the combination of AMF with yeasts and the application of P-fertilizers impelled Sarabia et al. to experiment on mycorrhizal and non mycorrhizal maize (Sarabia et al., 2017). It was revealed that P-fertilization harmonizes the interactions between AMF and rhizosphere yeasts on maize (Sarabia et al., 2017). Specifically, while the application of P-fertilizer and the inoculation of *Candida raileenensis* on P-fertilized maize increased the shoot and root biomass and the root colonization, in unfertilized with P plants, inoculation with *Cryptococcus flavus* had the opposite effects (Sarabia et al., 2017). Moreover, AMF highly enhanced the plant biomass and nodulation in both flowering and grain stages under P –deficiency conditions (Bulgarelli et al., 2017; Sarabia et al., 2017).

Except from quantitative results, AMF application in these conditions, affects the nutrient uptake of plants. Measurements on nutrient uptake on soybean plants after
their inoculation with *Glomus macrocarpum* revealed differences among the accumulation of essential elements (Bulgarelli et al., 2017). AMF increased the concentrations of Cu and Zn in shoots, while there were no differences in K, Ca, Mg, S, Fe, Mn and B concentrations in shoots (Bulgarelli et al., 2017). Generally, both at flowering and grain filling stage AMF inoculation increased the presence of N, P, S and B in shoots and decreased the presence of K, Ca, Fe, Mn, Mg in shoots (Bulgarelli et al., 2017). In roots accumulation of N, P, Mg, Cu, Zn was increased while uptake of K, Ca, S, Mn, B was decreased (Bulgarelli et al., 2017). Especially, worthy is that the highest values of N and P content were revealed in non-inoculated but only P-fertilized plants (Bulgarelli et al., 2017). This is a prove that AM symbiosis has a negative impact on biomass production or that the P uptake via this symbiosis cannot satisfy fully the nutritional plant needs (Bulgarelli et al., 2017).

Additionally, AMF have been proven as a great alternative for the rehabilitation of contaminated with heavy metals, rare earth elements or mine-tailing substrates soils (Chang et al., 2018). The increasing contamination of soils or substrates with these toxic elements decrease the plant growth consistently (Liu et al., 2018). *Glomus intraradicenses* on wheat and *Claroideoglomus etunicatum* on maize revealed the positive effect of AMF on fertility, productivity and protection of Cadmium (Cd)- and Lanthanum (La)- contaminated soils (Chang et al., 2018; Liu et al., 2018). Maize is a C4 plant easily colonized by AMF due to its dependency on these fungi. Pot experiments with *Glomus intraradicenses* and biochar, a charcoal used as soil amendment that improves fertility and productivity, showed that AMF alone or in combination with biochar can enhance plant growth and reduce Cd accumulation and translocation of Cd in plant tissues (Liu et al., 2018). The combined inoculation offered the largest increase in plant growth and root colonization and the greatest decrease in Cd concentrations than the single inoculations (Liu et al., 2018).

Rare earth elements as La consist a threat for humanity, animals and agroecosystems but also enhance the plant resistance to heavy metal contamination (Chang et al., 2018). In greenhouse experiments with contaminated by Cd and La soil on inoculated with *Claroideoglomus etunicatum* wheat, the combination of AMF, Cd and La increased the shoot, root and total biomass (Chang et al., 2018). Only toxic elements’ application decreased the above parameters, whereas only AMF application had the opposite
result (Chang et al., 2018). So, it is revealed that AM symbiosis lessened the phytotoxicity of single or combined metal presence as Cd and La uptake and translocation were decreased by AMF colonization (Chang et al., 2018). Also, that the excess presence of heavy metals is always linked with deficiency of available elements as P and K (Chang et al., 2018).

In addition, AMF activity have tremendous impact on the alleviation of environmental stresses as drought and salinity (Zhang et al., 2016; Bi et al., 2018). Greenhouse experiments on maize and soybean confirmed the mitigation of these crops from salinity by AMF (Hashem et al., 2016; Zhang et al., 2016). Under excess salt, AMF enhance nutrient and water uptake by plants, ability of photosynthesis and the enzymatic activity of plants (Zhang et al., 2016). Funneliformis mosseae in single or in combined with earthworm inoculations in maize plants under excess salt increased the root and shoot biomass, the concentration of N and P in all parts of maize as well as the bacterial (Methylobacterium spp. and Pontibacter spp.) and fungal (Trichoderma spp. and Stachybotrys spp.) diversity. Only single AMF application didn’t affect the K+ uptake by roots (Zhang et al., 2016). Funneliformis mosseae, Glomus intraradices and Claroideoglomus etunicatum managed to overcome the impact of NaCl concentrations, improved symbiotic performance on soybean plants and increased the nitrogenase activity and the number and fresh and dry weight of the nodules (Hashem et al., 2016).

On the contrary, under salinity, AMF inoculation decreased IAA and IBA production whereas under normal condition they were increased by AMF (Hashem et al., 2016). The promotion of metabolic and enzymatic (auxins) synthesis resulted in increased mineral uptake by plants (Hashem et al., 2016). Funneliformis mosseae proved efficient growth promoter of maize in semiarid regions too (Bi et al., 2018). In single applications or combined with plastic film mulching (PFM) increased water soil content, plant height and biomass and yield production (Bi et al., 2018). AMF inoculation extended the root colonization and the external hyphal length (Bi et al., 2018). On drought stressed wheat, AMF and PFM inoculation increased also productivity and above ground biomass in every growth stage of plants and the water use efficiency, resulting so to economic crop benefit (Zhu et al., 2017).

Further field and pot experiments revealed these actions of AMF (Ortas, 2015; Debeljak et al., 2018). Inoculation of maize, cultivated in 3 Turkey soil samples, with
Glomeromycota AMF, especially Funneliformis mosseae, Glomus spp., Rhizophagus spp. and Acaulospora spp., increased shoot and root biomass, P and Zn concentration and enhanced the colonization and root length in all 3 soil samples (Ortas, 2015). The co-inoculation of Glomus spp. and the commercial AM inoculum Symbivit in maize in experiments with Hg- contaminated and non-contaminated soils resulted in increased plant biomass in non-contaminated soils and in increased Hg uptake in roots and its translocation in aerial parts (Debeljak et al., 2018). In both cases chlorophyll and carotenoid contents were decreased (Debeljak et al., 2018). In barley, inoculation with Rhizophagus irregularis resulted in enhanced productivity and Zn concentration in straw, especially in soils with low Zn content (Watts-Williams and Cavagnaro, 2018). As the Zn concentration in substrates was increasing, Zn and P content in straw and grain were increasing too (Watts-Williams and Cavagnaro, 2018).

On the contrary, the impact of excluding AMF from soil was investigated on barley cultivations (Williams et al. 2014). It is known that agricultural disturbance pressures and decrease AMF abundance and the colonization resulting in gains in yield (Williams et al. 2014). These experiments of Williams et al. revealed that in non-AMF barley pots, the total barley biomass, especially shoot biomass was at highest levels than all pots, uptake of P and allocation of P and C in shoots, grain N and P content all reached their greatest values (Williams et al. 2014). Moreover, in absence of AMF bacterial biomass was greater but AMF biomass decreased (Williams et al. 2014).

**Endophytes**

Endophytes are microbial organisms that live inside the plant parts for a part of their life cycle without acting harmfully or gaining benefit from that plant (Naveed et al. 2014; Patel and Archana 2017; Puri et al. 2015). Some of the most abundant endophytes belong to the genera Pseudomonas, Bacillus, Burkholderia, Stenotrophus, Micrococcus, Pantoea and Microbacterium (Ban et al. 2017). Some of them act beneficially for their hosts by increasing metabolic activity for the reduction of stress, promoting the root development, the availability of nutrients and the tolerance to toxic compounds (Ban et al. 2017). Moreover, they promote plant growth by the production of phytohormones as auxins, cytokinins and gibberelins (Mohanty et al.
The main experiments on endophytic activity on the plants of our interest are presented in Table 3.

### Table 3. Endophyte referring studies.

<table>
<thead>
<tr>
<th>STUDY</th>
<th>INOCULANT</th>
<th>CONDITIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naveed et al. 2014</td>
<td><em>Burkholderia phytofirmans</em> strain PsJN, <em>Enterobacter</em> spp. strain FD17</td>
<td>drought stress</td>
</tr>
<tr>
<td>Ban et al. 2017</td>
<td><em>Gaeumannomyces cylindrosporus</em></td>
<td>heavy metal stress</td>
</tr>
<tr>
<td>Diaz Herrera et al. 2016</td>
<td><em>Paenibacillus</em> spp., <em>Enterobacteraceae of Pantoea and Fictibacillus/Bacillus</em> spp.</td>
<td>biological control</td>
</tr>
<tr>
<td>Samain et al. 2017</td>
<td><em>Paenibacillus</em> spp. and <em>Curtobacterium plantarum</em></td>
<td>biological control</td>
</tr>
<tr>
<td>Puri et al. 2015</td>
<td><em>Paenibacillus polymyxa</em></td>
<td>non-stress</td>
</tr>
<tr>
<td>Patel et al. 2018</td>
<td><em>Streptomyces</em> spp.</td>
<td>non-stress</td>
</tr>
<tr>
<td>Patel and Archana 2017</td>
<td>31 nitrogen fixing endophytic bacteria affiliated to <em>Actinobacteria</em>, <em>Proteobacteria</em> and <em>Firmicutes</em> representing 14 genera, mainly <em>Arthrobacter</em> spp., <em>Rhizobium</em> spp., and <em>Bacillus</em> spp.</td>
<td>non-stress</td>
</tr>
<tr>
<td>Parada et al. 2016</td>
<td><em>Azospirillum brasilense</em>, <em>Achromobacter insolitus</em>, <em>Zoogloearamigera</em></td>
<td>non-stress</td>
</tr>
<tr>
<td>Rahman et al. 2018</td>
<td><em>Paenibacillus</em> spp., <em>Pantoea</em> spp. and <em>Pseudomonas</em> spp.</td>
<td>non-stress</td>
</tr>
<tr>
<td>Zhao et al. 2017</td>
<td><em>Enterobacter cloacae</em>, <em>Acinetobacter calcoaceticus</em>, <em>Pseudomonas putida</em>, <em>Ochrobactrum haematophilum</em>, <em>Bacillus amyloliquifaciens</em> and <em>Bacillus cereus</em></td>
<td>non-stress</td>
</tr>
<tr>
<td>Russo et al. 2018</td>
<td><em>Beauveria bassiana</em>, <em>Metarhizium anisopliae</em> and <em>Metarhizium robertsii</em></td>
<td>non-stress</td>
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</table>
In experiments on maize, the positive effect of endophytes on N-fixation has been displayed (Mohanty et al. 2016; Puri et al. 2015). *Paenibacillus polymixa* strain P2b-2R increased N-fixation, colonized the rhizosphere and the inner of roots, assisted in the use of N from the atmospheric N pool, and finally promoted plant development by increasing the shoot and the seedling length and maize’s biomass (Puri et al. 2015). *Penibacillus* *spp.* unveiled its effect on N-fixation and its antipathogenic action on maize, in experiments where endophytic bacteria isolated from the rhizosphere of *Jatropha curcas* (Mohanty et al. 2016). *Bacillus* *spp.*, *Paenibacillus* *spp.*, *Brevibacillus* *spp.*, *Sphingomonas* *spp.*, *Rhizobium* *spp.*, *Teribacillus* *spp.* and *Staphylococcus* *spp.* promoted maize’s growth mainly by the production of IAA, ACC deaminase, N-fixation, the activity of phosphatase and the further solubilization of P and K (Mohanty et al. 2016). Also, the importance of siderophores in mineral uptake and that of P solubilization on K accumulation were confirmed (Mohanty et al. 2016).

Inoculation of endophytes in wheat, resulted in increased colonization, element solubilization, development of plants and in some cases in protective activity against diseases (Díaz Herrera et al. 2016; Patel and Archana 2017; Patel et al. 2018; Samain et al. 2017). Foliar inoculation of *Streptomyces* *spp.* colonized extensively wheat plants, increased the underground parts of them and the wet weight of the shoot and also impeded the infection and activity of *Rhizoctonia solani* and *Magnaporthe oryzae* (Patel and Archana 2017; Patel et al. 2018). Moreover, in greenhouse experiments, inoculation of *Azospirillum brasilense*, *Achromobacter insolitus* and *Zooglea ramigera* increased the chlorophyll content of plants, the root and shoot biomass and also promoted the production of IAA and N-fixation. Especially, they increased glutamine synthetase which is a major enzyme in the assimilation of NH₄⁺, contributed mostly in grain growth and N-content of shoots (Parada et al., 2016). Endophytic bacteria of phylum Actinobacteria, Proteobacteria and Firmicutes strengthened the above indication of endophytic activity as their inoculation promoted plant growth and the production of IAA and siderophores (Patel and Archana, 2017). Bacteria of Acinetobacter phylum were indicated as P-solubilizers enhancing so the uptake of this essential for plant growth element (Patel and Archana, 2017).

The defensive activity of endophytes, especially of *Paenibacillus* *spp.*, was reported in experiments in 2016 and 2017 (Díaz Herrera et al., 2016; Samain et al., 2017). The
inoculation of wheat plants with Paenibacillus spp., Pantoea spp., and Fictibacillus spp., resulted in the promotion of plant development and in the increased production of antifungal substances that acted towards the suppression of Fusarium graminarum (Díaz Herrera et al., 2016). Paenibacillus spp. has the ability to produce lipopeptides with antibiotic action called paenymixins. Paenibacillus spp. strain B2 and Curtobacterium plantarum EDS were applicable on wheat plants and the production of paenymixins resulted to the induction of resistance against the pathogenic Mycosphaerella graminicola which causes the septoria leaf blotch disease (Samain et al., 2017). Moreover, the inoculation of B2 strain promoted the further root colonization by EDS which contributed to the increase of the total fresh weight and the grain yield (Samain et al., 2017).

In barley, the inoculation of Paenibacillus spp, Pseudomonas spp., and Pantoea spp. had positive effects on plant development, mineral nutrition and defense mechanisms (Rahman et al., 2018). Especially, under harsh conditions, these microorganisms managed to increase plant height, chlorophyll content, water content and the concentration of essential elements as K and Mg, while inducing resistance against Blumeria graminis (Rahman et al., 2018).

The effects of application of endophytic inoculants were also researched in soybean plants (Russo et al. 2018; Zhao et al. 2017). Enterobacter cloaceae, Acinetobacter calcoaceticus, Pseudomonas putida, Bacillus spp., Beauveria bassiana, and Metarhizium spp., had the ability to promote N-fixation and the production of IAA and siderophores (Russo et al. 2018; Zhao et al. 2017). Especially, results showed a positive interaction between siderophores and restriction of pathogenic Phytophthora sojae (Zhao et al. 2017). Bacillus spp., Acinetobacter spp. and Enterobacter spp., increased shoot and root length, the chlorophyll content and the plant’s fresh weight (Zhao et al. 2017). Beauveria Bassiana and Metarhizium spp. were applied either by foliar spray or immersion on seeds or roots. B. bassiana was inoculated by all techniques while Metarhizium spp. was not inoculated by seed immersion (Russo et al., 2018). B. bassiana increased the growth parameters and managed to decrease the impact of insect pests or antagonistic pathogens on soybean plants (Russo et al., 2018).

Endophytes alleviate also abiotic stress conditions or toxicity (Ban et al. 2017; Naveed et al. 2014). Burkholderia phytofirmans and Enterobacter sp. FC17 minimized the
impact of drought stress on maize and managed to increase plant’s biomass, photosynthesis and development (Naveed et al., 2014). The main ways they managed it were the boost of photosynthetic rate, conductance of stomata and transpiration, and the improvement of leaf water content (Naveed et al., 2014). The inoculation of maize plants with Gaemannomyces cylindrosporus at Pb and Zn–mine tailings, under greenhouse conditions revealed the ability of this endophyte to promote plant development and the accumulation of this heavy metals (Ban et al. 2017). G. cylindrosporus alleviated the toxicity caused by heavy metals and promoted the increase of growth parameters (Ban et al. 2017). Moreover, the inoculation promoted the Pb accumulation and its translocation to shoots, which mainly decreased the toxic effect of Pb (Ban et al. 2017).

**Combinations of microbial inoculants**

Except from the results of the inoculation of a single category of microbes, the synergistic or antagonistic effects of combined application of microbial inoculation have been studied. In table 4 are presented the papers investigating these combination, with main interest on simultaneous application of PGPR and AMF and only one paper for the application of AMF and endophytes.

**Table 4.** Combined inoculation referring studies.

<table>
<thead>
<tr>
<th>STUDY</th>
<th>INOCULANT</th>
<th>CONDITIONS</th>
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<tbody>
<tr>
<td>Dhawi et al. 2015</td>
<td><em>The endomycorrhizal mix MycoApply Endo with spores of Glomus intraradices, Glomus mosseae, Glomus aggregatum and Glomus etunicatum and the PGPB Pseudomonas spp.</em></td>
<td>heavy metal stress</td>
</tr>
<tr>
<td>Bassey and Sakamoto 2018</td>
<td><em>Claroideoglomus etunicatum and Bradyrhizobium diazoefficiens</em></td>
<td>heavy metal stress</td>
</tr>
<tr>
<td>Bassey et al. 2017</td>
<td><em>Gigaspora rosea and Bradyrhizobium diazoefficiens</em></td>
<td>heavy metal stress</td>
</tr>
<tr>
<td>Shahabivand et al. 2012</td>
<td><em>Piriformospora indica and Glomus mosseae</em></td>
<td>heavy metal stress</td>
</tr>
</tbody>
</table>
Ghorchiani et al. 2018 | Glomus mosseae and Pseudomonas fluorescens | drought stress
---|---|---
Larsen et al. 2017 | Rhizopagus irregularis, Trichoderma harzianum and Azospirillum brasilense | fertilization
Saxena et al. 2013 | Pseudomonas fluorescens, Burkholderia cepacia and AM fungus Glomus etunicatum | fertilization
Juge et al. 2012 | Bradyrhizobium japonicum., Azospirillum canadense. and AMF Glomus irregulare. | non-stress

The combined application of PGPR and AMF showed both synergistic and antagonistic activity in all cases studied. Firstly, experiments tried to identify their effect on polluted with heavy metals soils (Bassey et al. 2017; Bassey and Sakamoto 2018; Dhawi et al. 2015). On marginal, due to mining, land, which is described by high soil acidity, low N and P content, excess of heavy metals, low water holding capacity and tendency to erosion, the synergistic effect of *Pseudomonas spp.* and *Glomus spp.* was obvious on root colonization, the biomass of the plant and the growth of the bacterial population (Dhawi et al. 2015). This is of main importance as the ability of the plants to uptake essential macro and micronutrients depends on the roots’ architecture, their exudates and the microflora of the rhizosphere (Dhawi et al. 2015). So, they managed to enhance the uptake of Zn, Al, Cu and K significantly by the roots and the concentration of P, S, K and Al in aerial parts (Dhawi et al. 2015). On soils with excess Zn accumulation, soybean growth and nutrient uptake has been investigated (Bassey et al. 2017; Bassey and Sakamoto 2018). *Bradyrhizobium diazoefficiens*, a promoter of N2-fixation and *Gigaspora rosea*, an improver of N supplement to the plant, were applied on soybean under various concentrations of Zn (Bassey et al. 2017). As the concentration of Zn was increasing, the mycorrhization was also elevated as well as the plants’ Zn content in root and shoot (Bassey et al. 2017). Combined inoculation increased growth parameters as root and shoot length and number of nodules per plant at the presence of a low Zn concentration and also enhanced the presence of Zn, Fe, Mn in shoots and P in shoots and roots. So, the synergistic effect of these inoculants was more obvious in greater Zn concentrations (Bassey et al. 2017). The combination of *Bradyrhizobium diazoefficiens* with *Claroideoglomus etunicatum* was
studied a year later by Bassey and Sakamoto on soybean plants under excess Zn again and revealed that dual inoculation improved soybean production more than single or no inoculation (Bassey and Sakamoto, 2018). The combined application improved the total biomass at maximum level, including the increases in stem and leaf biomass, enhanced the root mycorrhizal colonization and the abundance of arbuscules as well as the Zn, Mn under Zn deficiency, and Fe uptake by the plants (Bassey and Sakamoto, 2018).

Under drought stress conditions the mixed inoculation of *Pseudomonas fluorescens* and *Funneliformis mosseae* among with the application of trisodium phosphate fertilizer (TSP) increased leaf dry weight, leaf area and the tassel and P content of maize plants (Ghorchiani et al. 2018). Also, yield production, chlorophyll concentration, N and P concentrations in aerial parts and root colonization was improved (Ghorchiani et al. 2018). The chlorophyll increased due to improved uptake and better plant metabolism (Ghorchiani et al. 2018). The same results were presented when rock phosphate (RP) fertilizer was used. It is hypothesized that *P. fluorescens* might solubilize primitive P and TSP fertilizer better than RP as in absence of RP the plants couldn’t accumulate any P from soluble P sources (Ghorchiani et al. 2018).

Under fertilization and non-fertilization with NPK fertilizers conditions, *Rhizophagus irregularis*, *Trichoderma harzianum* and *Azospirillum brasilense* were applied (Larsen et al., 2017). Single application of *T. Harzianum*, with mineral fertilization improved plant growth (Larsen et al., 2017). However, without fertilization improved maximum the shoot dry weight (Larsen et al., 2017). The common application of *T. Harzianum* and *Azospirillum brasilense* generally reduced growth parameters and root colonization (Larsen et al., 2017). *Rhizophagus irregularis* and *A. Brasilense* managed to increase the bacterial population density under fertilization (Larsen et al., 2017). In conclusion the fertilizers had greater beneficial effects on plant growth than the microbial inoculants, as only *T. Harzianum* enhanced plant growth (Larsen et al., 2017). The inoculations of *Pseudomonas fluorescens* and *Burkholderia cepacia* with *Glomus etunicatum*, and the application or not of tricalcium phosphate (TCP) fertilizer were studied on wheat in nutrient deficient soils (Saxena et al. 2013). Every single or combined inoculation of PGPR and AMF microbe under TCP fertilization, increased the growth parameters as shoot and root dry weight, crop yield, root colonization and P
content (Saxena et al. 2013). The highest levels were achieved after the co-inoculation of all three microbes and TCP (Saxena et al. 2013).

The effect of double combinations of Bradyrhizobium japonicum, Azospirillum canadense and Glomus irregulare or even the triple combination of these three microbes was investigated in soybean plants under non-stressed soil conditions (Juge et al., 2012). Every combination increased root biomass but the highest root and total biomass was achieved by the inoculation of Br. japonicum and Az. canadense (Juge et al., 2012). However, this combination reduces the number of nodules, that gained their greatest size by the triple combination (Juge et al., 2012). The triple combination reduced the shoot growth and the number of small nodules but increased the number of large nodules and the production of stress-induced amino acid proline, which is an important stress factor for soybean (Juge et al., 2012). Also, the triple combination increased at highest level the soluble sugars and the carbohydrates in roots and leaves (Juge et al., 2012). Moreover, these combinations increased the presence of amino acids as glutamate, GABA and proline in nodules and even more (10 times) in leaves (Juge et al., 2012).

Additionally, the combined inoculation with AMF and endophytes was studied in Cd-contaminated soil (Shahabivand et al., 2012). Cd toxicity declines chlorophyll content due to its biosynthesis’ inhibition (Shahabivand et al., 2012). The co-inoculation of Piriformosa indica and Glomus mosseae resulted in increase of growth, chlorophyll content and performance index (Shahabivand et al., 2012). AMF symbiosis change the uptake of heavy metals whereas the endophytes protect the plant by inducing oxidative stress tolerance (Shahabivand et al., 2012). The root colonization was at highest level only by Pi. indica inoculation, whereas the co-inoculation reduced it (Shahabivand et al., 2012). Plant growth was inhibited as Cd concentrations were increasing but each inoculation resulted in the opposite effect, increasing at least the shoot length and dry weight (Shahabivand et al., 2012). As for the Cd – concentrations they were increased in root but decreased in shoot for each inoculation (Shahabivand et al., 2012).

Generally, we can conclude that the co-inoculation of different microorganisms either two bacterial strains, bacteria with AMF or endophytic fungus with AMF present differentiated results (Bassey et al. 2017; Ghorchiani et al. 2018; Juge et al. 2012;
Saxena et al. 2013). The co-inoculation of two bacterial strains, *Bradyrhizobium japonicum* and *Azospirillum canadense* resulted in high increase in soybean’s biomass, whereas the co-inoculation of *B. japonicum* and *Glomus irregulare* enhanced only the root biomass and the N-metabolism in nodules, which mainly sustain the promotion of N-fixation (Juge et al. 2012). Moreover, the triple combination of the two bacterial strains and the AMF revealed the competition between PGPR and AMF as it resulted in lower soybean biomass and reduced mycorrhization (Juge et al. 2012). Furthermore, the co-inoculation of P-solubilizing bacteria *Pseudomonas fluorescens* and *Burkholderia cepacia* with *Glomus etunicatum* confirmed the hypothesis of synergistic effect on P uptake and plant development and productivity (Saxena, Chandra and Nain, 2013). The co-inoculation of PGPR and AMF resulted in higher root biomass than bacterial inoculation alone and in higher shoot biomass than mycorrhizal inoculation alone, but both microorganisms alleviated the metal stress (Dhawi et al. 2015). Also, the synergistic effect of PGPR and AMF co-application enhanced nutrient provision to plants and showed that P-solubilization by AMF and their accumulation by plants is impossible without the bacterial help (Ghorchiani et al. 2018; Saxena et al. 2013). Additionally, the co-inoculation of *Bradyrhizobium diazoefficiens* and *Gigaspora rosea* showed the metal binding ability of mycorrhizal hyphae, as they increased Zn- binding and Mn uptake resulting in higher shoot biomass (Bassey et al. 2017). *Piriformosa indica*, an endophytic fungi and *Glomus mosseae* enhanced plant development and also the resistance to Cd, particularly higher than *G. mosseae* single inoculation (Shahabivand et al., 2012). On the other hand, Larsen et al. in 2017, showed that the co-inoculation of *Rhizophagus irregularis*, *Trichoderma harzianum* and *Azospirillum brasilense* had negative effect on maize plants and especially the application of *A. brasilense* inhibited the previous positive effect of *T. harzianum* (Larsen et al., 2017).

**Discussion**

A large variety of microbial inoculants has been used in the plants that concern us, under different soil and environmental conditions. Various microorganisms have been used as microbial inoculants, aiming to the improvement of plant development and productivity of nutrient deficient soils (Chart 4). The most frequently used inoculants
were bacteria of the genera Bacillus (Ramesh et al., 2014; Mumtaz et al., 2017), Pseudomonas, especially *P. fluorescens* and *P. plecoglossicida*, (Batool and Iqbal, 2018; Krey et al. 2013; Kumar et al. 2018; Saxena et al. 2013), Burkholderia (Pereira and Castro, 2014; Saxena et al., 2013), Arthrobacter (Pereira and Castro, 2014; Batool and Iqbal, 2018), Aeromonas (Kumar et al. 2018; Shaikh and Saraf, 2017), Enterobacter (Krey et al., 2013), Rhodococcus (Pereira and Castro 2014; Batool and Iqbal 2018), Azospirillum (Larsen et al., 2017), Pantoea (Kaur and Reddy, 2015), Trabusiella, Exiquobacterium (Shaikh and Saraf, 2017) and Aneurinibacillus (Kumar et al., 2018).

Also, fungal strains of genera Glomus (Bulgarelli et al. 2017; Cozzolino et al. 2013; Saxena et al. 2013), Rhizophagus, Trichoderma (Larsen et al., 2017), Cryptococcus and *Candida railenensis* (Sarabia et al., 2017) were used in experiments in nutrient deficient conditions.

**Chart 4.** Frequency of microbial inoculants used in experiments under nutrient deficiency conditions.

Under environmental stresses, especially under drought, salt or even cool stress, a variety of microorganisms has been inoculated in plants as shown in Charts 5 and 6. Specifically, under drought stress conditions the main beneficial inoculants were the bacterial strains of the genera Pseudomonas, especially *P. fluorescens* (Ghorchiani et al. 2018), *P. striata* (Iqbal et al., 2018) and *P. putida* (Vurukonda et al., 2016), *Azospirillum* spp. (García et al., 2017), *Burkholderia phytofirmans* and *Enterobacter*
spp. (Naveed et al., 2014) and fungal strains of the genera Glomus, mainly G. mosseae (Bi et al. 2018; Ghorchiani et al. 2018; Zhu et al. 2017), G. monosporum and G. intraradices (Zhu et al., 2017) and Acaulospora laevis (Zhu et al., 2017).

Chart 5. Frequency of microbial inoculants used in experiments under drought stress conditions.

In experiments with salt stress conditions a larger variety of inoculants, especially bacterial genera, were used. Mostly researched for the alleviation of salinity were bacteria of the genera Bacillus (Cardinale et al., 2015; Orhan, 2016), and fungi Hartmanibacter diazotrophicus (Cardinale et al., 2015; Suarez et al., 2015), and Glomus spp., especially G. mosseae (Hashem et al., 2016; Zhang et al., 2016), G. etunicatum and G. intraradices (Hashem et al., 2016). Moreover, but only in a single research, Halobacillus spp., Staphylococcus succinus, Zhihenglinella halotolerans, Oceanobacillus oncorhunchi, Exiguobacterium aurantiacum, Halomonas spp., Virgibacillus spp., Thalassobacillus spp. (Orhan, 2016), Pseudomonas spp., Curtobacterium flaccumfaciens, Ensifer garamanticus, Microbacterium natoriense, Streptomyces spp., Sphingopyxis taejonensis, Rheinheimeria hassiensis and Cellvibrio diazotrophicus (Cardinale et al., 2015) were applicable with mostly beneficial results in plants.

In addition, it essential to mention that Bradyrhizobium spp., was inoculated under cool stress condition in soybean, resulting in improvement of plant development and environmental condition (Zimmer et al., 2016).
In heavy metal stress, mainly contaminated with heavy metals soils, the activity of fungal genera Glomus and specifically *G. intraradices* (Dhawi et al. 2015; Liu et al. 2018), *G. mosseae*, *G. aggregatum*, *G. etunicatum* (Dhawi et al. 2015), *Claroideoglomus etunicatum* (Bassey and Sakamoto, 2018; Chang *et al.*, 2018) and bacterium *Bradyrhizobium diazoefficiens* (Bassey et al.; Bassey and Sakamoto 2018) was mostly researched. Moreover, experiments with bacteria *Enterobacter ludwigii* (Singh *et al.*, 2018), *Gaeumannomyces cylindrosphorus* (Ban et al. 2017), *Pseudomonas spp.* (Dhawi et al. 2015), *Piriformosa indica* (Shahabivand *et al.*, 2012) and fungi *Gigaspora rosea* (Bassey et al. 2017), as shown in Chart 7.

**Chart 6.** Frequency of microbial inoculants used in experiments under salt stress conditions.

**Chart 7.** Frequency of microbial inoculants used in experiments under heavy metal stress.
Regarding the ability of some inoculants to induce resistance against some pathogenic strains that cause severe diseases in plants resulting in reduced productivity, the activity of single inoculation of *Paenibacillus* spp. (Díaz Herrera *et al.*, 2016; Samain *et al.*, 2017) or in combinations with *Curtobacterium* spp. (Samain *et al.*, 2017) or *Pantoea* spp. and *Bacillus* spp. (Díaz Herrera *et al.*, 2016) was researched revealing the beneficial effects of these inoculants against *Mycosphaerella graminicola* (Samain *et al.*, 2017) and *Fusarium graminearum* (Díaz Herrera *et al.*, 2016).

Except from the ability of microbial inoculants to alleviate biotic or abiotic stresses in order to promote plant growth and productivity, their inoculation in plants under non-stressed environmental conditions aimed to the research of their activities on quantitative and qualitative improvement of plants. A large variety of microorganisms has been used for this purpose. As shown in Charts 8a and 8b, the most experimentally inoculated microbes were bacteria of genera *Bacillus* (Kumar *et al.*, 2014; Masciarelli *et al.*, 2014; Mohanty *et al.*, 2016; Patel and Archana 2017; Zhao *et al.*, 2017), *Pseudomonas* (Ibañez *et al.*, 2014; Rahman *et al.*, 2018; Di Salvo *et al.*, 2018; Swarnalakshmi *et al.*, 2013; Zhao *et al.*, 2017), *Azospirillum* (Juge *et al.*, 2012; Marks *et al.*, 2015; Cortivo *et al.*, 2017; Di Salvo *et al.*, 2018), *Enterobacter* (Ibañez *et al.*, 2014; Kumar *et al.*, 2014; Zhao *et al.*, 2017), *Paenibacillus* (Mohanty *et al.*, 2016; Puri *et al.*, 2015; Rahman *et al.*, 2018) and fungal genera *Glomus* (Juge *et al.*, 2012; Ortas, 2015; Debeljak *et al.*, 2018).

**Chart 8a.** Number of papers referring to each microbial inoculant under non-stressed environmental conditions.
In less papers, the effect on plant development and productivity of *Providencia* *spp.* (Rana *et al.*, 2012; Prasanna *et al.*, 2016), *Azotobacter chroococcum* (Swarnalakshmi *et al.*, 2013; Prasanna *et al.*, 2016), *Arthrobacter* *spp.* (Kaur and Reddy, 2015; Patel and Archana, 2017), *Bradyrhizobium japonicum* (Juge *et al.*, 2012; Masciarelli, Llanes and Luna, 2014), *Achromobacter* *spp.* (Parada *et al.*, 2016; Youseif, 2018), *Ochrobactrum* *spp.* (Zhao, Xu and Lai, 2017; Youseif, 2018), *Rhizobium* *spp.* (Mohanty, Dubey and Kollah, 2016; Patel and Archana, 2017) and *Rhizophagus* *spp.* (Ortas, 2015; Watts-Williams and Cavagnaro, 2018) was studied.

![Chart 8b. Number of papers referring to each microbial inoculant under non-stressed environmental conditions.](image)

Furthermore, *Klebsiella* *spp.* (Ibañez *et al.*, 2014), *Anabaena* *spp.* and *Nostoc* *spp.* (Prasanna *et al.*, 2016), *Mesorhizobium* *spp.* and *Serratia marcescens* (Swarnalakshmi *et al.*, 2013), *Azoarcus* *spp.* and *Azorhizobium* *spp.* (Cortivo *et al.*, 2017), *Calothrix* *spp.* (Rana *et al.*, 2012), *Achromobacter* *spp.*, *Agrobacterium* *spp.*, *Bordetella* *spp.*, *Cupriavidus* *spp.*, *Pseudoxanthomonas* *spp.*, *Stenotrophomonas* *spp.*, *Chryseobacterium* *spp.*, *Flavobacterium* *spp.* (Youseif, 2018), *Braevibacillus* *spp.*, *Sphingomonas* *spp.*, *Staphylococcus* *spp.*, *Teribacillus* *spp.* (Mohanty *et al.* 2016), *Streptomyces* *spp.* (Patel *et al.* 2018), *Zooglea ramigera* (Parada *et al.*, 2016), *Pantoea* *spp.* (Rahman *et al.*, 2018), *Acinetobacter calcoaceticus* (Zhao *et al.* 2017), *Beauveria bassiana* and *Metarhizium* *spp.* (Russo *et al.*, 2018) and *Acaulospora* *spp.* (Ortas, 2015) were each investigated only in one case.
So, we can easily assume from all above that many microorganisms not only promote plant growth and yield production but also offer their ability to confront stressful abilities to the plants. Particularly, *Bacillus spp.*, *Pseudomonas spp.* and *Glomus spp.* managed to prevent abiotic stressed and to promote productivity in every case, either nutrient deficiency, toxicity, drought, salinity or normal conditions. Moreover, *Bradyrhizobium spp.* alleviated cold stress and pollution of soil and *Azospirillum spp.* and *Enterobacter spp.* enhanced plant growth under normal conditions, nutrient deficiency or drought stress. Also, *Paenibacillus spp.* promoted plant development under normal conditions and enhanced tolerance against pathogenic microorganisms.

The activity of the rest inoculants was mainly investigated under a stressful condition or only under non-stressed environmental conditions.

Many of these microbial inoculants have been used in more than one plant species with beneficial activity for the plant, while others have revealed actually host specialty enhancing only a plant species’ growth and productivity. In maize, as shown in Chart 9., the most inoculated bacterial microorganisms belonged to the genera *Pseudomonas* (Dhawi et al. 2015; Ibañez et al. 2014) especially, subspecies *P. fluorescens* (Ghorchiani et al. 2018; Krey et al. 2013; Pereira and Castro 2014; Di Salvo et al. 2018), *P. plecoglossida* (Kaur and Reddy, 2015), *P. striata* (Iqbal et al., 2018), *P. putida* (Vurukonda et al., 2016), *Azospirillum*, mainly *Azospirillum brasilense* (Marks et al., 2015; Garcia et al., 2017; Larsen et al., 2017; Di Salvo et al., 2018), *Paenibacillus* (Mohanty et al. 2016; Puri et al. 2015), *Burkholderia* (Naveed et al., 2014; Pereira and Castro, 2014), *Enterobacter* (Krey et al., 2013; Ibañez et al., 2014; Naveed et al., 2014) and *Bacillus* (Mohanty et al. 2016; Mumtaz et al. 2017) and also the fungal genera *Glomus* (Debeljak et al. 2018; Dhawi et al. 2015; Ortas 2015), mainly *G. mosseae* (Bi et al. 2018; Ghorchiani et al. 2018; Zhang et al. 2016), *G. intraradicens* (Cozzoizino et al. 2013; Hashem et al. 2016; Liu et al. 2018) and *G. etunicatum* (Hashem et al., 2016).

Chryseobacterium, and Flavobacterium (Youseif, 2018) and the fungal genera Cryptococcus, Candida (Sarabia et al., 2017), Rhizosphagus (Ortas, 2015; Larsen et al., 2017), Acaulospora (Ortas, 2015), Trichoderma (Larsen et al., 2017), Claroideoglomus (Chang et al., 2018), Gaeumannomyces (Ban et al. 2017) were used in some experiments.

In wheat, as shown in Chart 10, the most repeatedly used bacterial genera were Pseudomonas (Batool and Iqbal 2018; Kaur and Reddy 2015; Kumar et al. 2018), especially P. fluorescens (Saxena et al. 2013) and P. striata (Swarnalakshmi et al., 2013), Arthrobacter (Batool and Iqbal 2018; Kumar et al. 2014; Patel and Archana 2017; Shaikh and Saraf 2017), Bacillus (Díaz Herrera et al. 2016; Kumar et al. 2014; Orhan 2016; Patel and Archana 2017), Enterobacter (Kumar et al. 2014; Singh et al. 2018), Pantoea (Kaur and Reddy, 2015; Díaz Herrera et al., 2016), Aeromonas (Kumar

Chart 9. Microbial inoculants’ presence in papers referring to experiments in maize.
et al. 2018; Shaikh and Saraf 2017), Exiquobacterium (Orhan, 2016; Shaikh and Saraf, 2017) and the fungal genera Glomus especially, *G. mosseae* (Shahabivand et al., 2012; Zhu et al., 2017), *G. intraradices* (Zhu et al., 2017) and *G. etunicatum* (Saxena et al. 2013).

In addition, bacterial strains of the genera Rhodococcus (Batool and Iqbal, 2018), Trabusiella (Shaikh and Saraf, 2017), Paenibacillus (Díaz Herrera et al., 2016; Samain et al., 2017), Curtobacterium (Samain et al., 2017), Halobacillus, Staphylococcus, Zhihenglinella, Oceanobacillus, Halomonas, Virgibacillus, Thalassobacillus (Orhan, 2016), Piriformosa (Shahabivand et al., 2012), Azotobacter, Mesorhizobium, Serratia (Swarnalakshmi et al., 2013), Azospirillum, Azoarcus, Azorhizobium (Cortivo et al., 2017), Providencia, Calothrix (Rana et al., 2012), Streptomyces (Patel et al. 2018), Rhizobium (Patel and Archana, 2017), Achromobacter, Zooglea (Parada et al., 2016), inoculants *Aneurinibacillus aeurinilyticus* (Kumar et al. 2018), *Burkholderia cepacia* (Saxena et al. 2013) and fungal strains of the genera Acaulospora (Zhu et al., 2017) were also used in experiments in wheat.

In barley, as shown in Chart 11, the inoculants that were experimentally investigated were *Hartmanibacter diazotrophicus* (Cardinale et al., 2015; Suarez et al., 2015) and

![Chart 10. Microbial inoculants’ presence in papers referring to experiments in wheat.](chart.png)
inoculants of the genera Pseudomonas (Cardinale et al., 2015; Rahman et al., 2018), Bacillus, Curtobacterium, Ensifer, Microbacterium, Streptomyces, Sphingopyxis, Rheinheimeria, Cellvibrio (Cardinale et al., 2015), Rhizophagus (Watts-Williams and Cavagnaro, 2018), Paenibacillus and Pantoea (Rahman et al., 2018).

**Chart 11.** Microbial inoculants’ presence in papers referring to experiments in barley.

The experiments with inoculants in soybean plants, as shown in Chart 12, were performed with microorganisms of the genera Bacillus (Masciarelli et al. 2014; Ramesh et al. 2014; Zhao et al. 2017), Glomus (Bulgarelli et al. 2017; Hashem et al. 2016; Juge et al. 2012; Masciarelli et al. 2014; Zhao et al. 2017), Bradyrhizobium (Bassey et al. 2017; Bassey and Sakamoto 2018; Juge et al. 2012; Masciarelli et al. 2014; Zimmer et al. 2016), Claroideoglomus (Bassey and Sakamoto, 2018), Gigaspora (Bassey et al. 2017), Enterobacter, Acinetobacter, Pseudomonas, Ochrobactrum (Zhao et al. 2017) Beauveria, Metarhizium (Russo et al., 2018) and Azospirillum (Juge et al., 2012).

Many of the previously referred microorganisms have been applied to more than one plant either individually or in combinations. Pseudomonas and Bacillus were the only genera inoculated in maize, wheat, barley and soybean. Especially, *P. fluorescens*, revealed its positive effect in both maize and wheat growth. *Glomus spp.*, *Enterobacter spp.* and *Azospirillum spp.* were inoculated in maize, wheat and soybean. *Paenibacillus spp.* and *Pantoea spp.* were used in maize, wheat and barley’s experiments, while *Burkholderia spp.*, *Arthrobacter spp.* and *Rhodococcus spp.* were applicable in maize and
wheat. The rest microorganisms referred above showed their host-dependent action as they were tested only in one plant species.

**Chart 12.** Microbial inoculants’ presence in papers referring to experiments in soybean.

**Conclusion**

To sum it up, the target of improving plant growth, yield production and alleviating stressful environmental conditions is achievable by the application of microbial inoculants on plants comprising livestock food as shown by the studies. Especially, nutrient deficiency, drought and salt stress as well as heavy metal toxicity have been reduced or even eliminated after the inoculation of PGPG, AMF, endophytes or their combinations. Moreover, in unstressed environmental conditions the application of these inoculants revealed their beneficial effect on plant development and enhancement of productivity giving a good prospect for the increase of plant yield and the livestock nutrition and productivity.

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