Review

Pointing Out Opportunities to Increase Grassland Pastures Productivity via Microbial Inoculants: Attending the Society's Demands for Meat Production with Sustainability

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Abstract: Estimates are that land area occupied by grass pasture far exceeds that of other crops; at least half are at some stage of degradation. The use of elite plant-growth-promoting microorganisms (PGPM) as inoculants represents an important strategy to achieve qualitative and quantitative improvements in forage biomass, increasing the productivity and sustainability of livestock production. Several studies have reported the benefits of PGPM in grass pastures, with an emphasis on bacteria of the genera *Azospirillum*, *Pseudomonas*, *Bacillus*, rhizobia, and on arbuscular mycorrhiza fungi (AMF). The main grasses studied are *Urocholoa* (syn. *Brachiaria*), *Megathyrsus* (syn. *Panicum*), *Paspalum*, *Cynodon*, and *Agropyron*. Several microbial processes associated with improvements in root and shoot growth, nutrient content in biomass, and other benefits have been described. Promotion of plant growth has been associated with the synthesis of phytohormones and enzymes regulating several steps of plant development, nutrient mineralization by release of microbial molecules, biological nitrogen fixation, nutrient uptake facilitation by means of molecules such as exopolysaccharides, amongst others. Outstanding benefits of increased root growth, resulting in higher uptake of water and nutrients, either by phytohormones released by bacteria or by expanding root surface by AMF, have been reported. Biocontrol is another important property of PGPM, by a variety of mechanisms, including the synthesis of antimicrobial molecules, lytic enzymes, siderophores, and the release of specific inhibitory compounds such as hydrogen cyanide. Although improvements in forage management can enhance microbial performance, as shown for AMF, in general, inoculation with elite strains positively impacts growth parameters. Globally, the use of microbial inoculants has significantly increased in the past few years, but their application is still modest on grass pastures, which are generally degraded and would need special use of microbial inoculants for reclamation. Efforts towards increasing the use of PGPM in pastures can have deep positive environmental, economic, and social impacts worldwide.

1. Introduction

The world's growing population requires increasing food production, but the expansion of new land areas for cropping has reached its maximum, whereas land degradation advances. According to the United Nations Environment Program [1], two billion people have been affected by land degradation, and more than 12 million hectares (Mha) of arable land are annually lost to desertification. Livestock is a major sector-driven land use and, according to Ritchie et al. [2], the combination of pastures for grazing and the land used

to grow crops for animal feeding represents 77% of the global farming land. Meat consumption has increased rapidly since the 1980s, and considering the human population growth on the planet, estimated at 9.8 billion people by 2050, the increase in livestock production to meet this demand is inevitable. However, estimates are that about 49% of pasture ecosystems are under some level of degradation [3].

Land use for livestock production varies by country and can account for up to half of the total land area in continental regions [2]. In Brazil, beef livestock is a major economic activity, with pasturelands amounting to about 2.5-times of the area for other crops [4]. According to the Brazilian Association of Meat Exporting Industries (ABIEC, Associação Brasileira de Indústrias Exportadoras de Carnes), considering the inputs, services, and revenue of the whole meat business chain, livestock was responsible for 10% of the Brazilian total Gross Domestic Product (GDP) in 2019 [5]. Brazil is the largest world beef exporter, with 2.2 million tons and 14.4% of the international market share [6] and has the second-largest cattle herd, with 214.89 million heads [7]. This herd is distributed over 173 million hectares, equivalent to about 20% of the national territory, with 126 Mha composed of cultivated pastures [8,9].

Most of the Brazilian beef cattle's production occurs extensively in pastures, which depends on the forage quality and productivity [10]. The main forage grasses in these pastures are *Urochloa* (syn. *Brachiaria*) (usually referred to as brachiaria), followed by *Megathyrsus* (syn. *Panicum*), but there are also species of *Cynodon*, *Hemarthria*, *Andropogon*, *Avena*, *Pennisetum*, and *Paspalum* [11]. Based on the area used for seed production, 72.2% of the planted pasture area is occupied by *Urochloa* spp., and 25.7% by *Megathyrsus maximus* (syn. *Panicum maximum*) [9].

As in many countries with extensive pastures, inadequate management, lack of fertilization, and low use of technologies, in addition to the high occurrence of weeds and pathogens in the tropical environment, have led to the increasing degradation of pastures in Brazil. According to Dias-Filho [10], about 50% of the Brazilian pastures are considered degraded, 30% are in degradation processes, and only 20% are in good condition. Degraded pastures have low plant production and animal support capacity as well as soil physical, chemical, and biological degradation, which results in environmental degradation with negative effects on water resources, increased greenhouse gas (GHG) emissions, and desertification [10,12].

Carbon sequestration is another critical point to be considered in pasturelands. The topsoil represents the largest stock of Earth's C and contains approximately twice the C in vegetation and the atmosphere [13]. The CO_2 emissions from the soil come from the respiration of roots and soil organisms, and when respiration is greater than deposition, C is lost to the atmosphere [14]. Changes in land use, especially the conversion of forests into pastures or agricultural systems, represent the major source of CO_2 emissions in Brazil [15]. As the amount of soil C in areas of degraded pastures is lower than in well-managed areas [16], reclamation of pastures delineates a crucial scenario for C sequestration in the soil. For example, in Portugal, a recovery program of 42,000 hectares of degraded pastures over two years resulted in the sequestration of approximately 910 Gg (thousand tons) of CO_2 equivalents [17].

In addition, pasture degradation affects the economic sustainability of animal production. Considering only the fattening phase of the herd, meat productivity in a degraded pasture is around 2 at sign ha^{-1} yr^{-1} (1 at sign ~15 kg, used for cattle pricing in Brazil), while in a well-managed pasture, 12 at sign ha^{-1} yr^{-1} can be obtained [12]. With the drop in pasture productivity due to degradation, the stocking capacity and animal weight gain are reduced, leading many farmers to open new areas, resulting in significant economic and environmental losses [18]. For example, comparing zootechnical indices (birth rate, birth rate until weaning, age at the first calf, age at slaughter, and stocking) between good pastures and degraded pastures, for each hectare of recovered pasture, approximately three hectares could be released for other purposes (e.g., agricultural, forestry planting, or conservation) without reducing production [10].

With increasing political and general public pressures on sustainable food production systems, the development and use of technologies that allow increased production with less environmental impact are essential [19]. In this context, microbiological inoculants, also known as biofertilizers in some countries, are agricultural inputs composed of living microorganisms that can help the growth and development of plants by a variety of processes and have contributed to increasing the economic and environmental sustainability of food production systems [20]. Due to their benefits, the use of inoculants is now widespread globally, and impressive increases are expected in the following decade. In this scenario, Brazil is an important example, where the commercialization of inoculants went from 18.1 million doses in 2008 to 70 million in 2018 [20,21], and will soon overtake 100 million doses currently. Inoculants in Brazil have been used mainly in legume grain crops, with almost 90% for the soybean [*Glycine max* (L.) Merrill] crop [20]. However, in the past decade, the development of inoculants containing the plant-growth-promoting bacterium (PGPB) *Azospirillum brasilense* for cereals [22–24] was rapidly adopted by farmers, so that nowadays, over 10 million doses have been annually commercialized, mainly for the maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.) crops [23], in addition to co-inoculation of soybean together with *Bradyrhizobium* spp. [24].

Benefits of the inoculation of legume pastures, especially alfalfa (*Medicago sativa* L.), with nitrogen-fixing rhizobia have been well known for a long time [25]. Conversely, although grasslands represent the great majority of the global areas with pastures, research, and use of microbial inoculants for pasture grasses are still inexpressive. In Brazil, approximately five years ago, the first inoculant carrying *A. brasilense* for *Urochloa* spp. [26] reached the market and started to call the farmers´ attention. Great benefits have been reported since then, highlighting that the use of elite strains as microbial inoculants can improve pastures, promoting qualitative and quantitative increases in forage biomass and, consequently, increasing the productivity and sustainability of livestock production [20,26,27].

This review highlights the benefits of using inoculants for forage grasses, exploring the microorganisms already used in commercial inoculants and others with the potential to benefit pastures. As Brazil is a major country both in terms of the percentage of area with grassland pastures [9] and in the use of microbial inoculants [20,23], the country will be used as an example.

2. Microbial Inoculants

Microbial inoculants, also called biofertilizers in some countries, are products composed of microorganisms that can stimulate plant growth and development and are marketed in the liquid or solid form [20,28]. The first commercial inoculant was produced in 1856 in the United States of America. The first inoculant industry in Brazil was established in 1956 in the southern state of Rio Grande do Sul, initially focused on inoculants for soybean and subtropical forage legumes, such as alfalfa and clovers (*Trifolium* spp.); from the 1960s onwards, production was primarily focused on soybeans [20].

In Brazil, as in probably all countries that have used inoculants for more than 30 years, the preferred vehicle was peat, but the environmental impacts caused by the exploitation of peatlands and the increased costs of importation gave way to inoculants with liquid formulations. The first liquid inoculant was registered in Brazil in 2000, and currently, this vehicle represents more than 70% of the national market [20].

Soybean is the leading crop in the use of inoculants worldwide. In Brazil, the largest world soybean producer, annual inoculation was adopted in 80% of the total area cropped in 2019/2020 [21], leading to savings in N-fertilizer estimated at about US$ 20 billion per year [20]. As commented in the introduction section, the first inoculant for grasses in Brazil was launched in 2009 for maize and wheat, with great acceptance by the farmers [23]. However, although the area of grasslands in the country is far greater than that used for other crops [5,9], the first commercial inoculant for this sector was available only in 2016, carrying the strains Ab-V5 (=CNPSo 2083) and Ab-V6 (=CNPSo 2084) of *A. brasilense*,

for seed inoculation of brachiarias, *Urochloa brizantha* (A.Rich.) RDWebster, and *Urochloa decumbens* (Stapf) RDWebster [26].

In addition to their economic importance, inoculants play an important environmental role, as they allow the complete replacement of N-fertilizers in legume crops such as soybeans [20,29], and the partial replacement in grasses such as maize [30]. Inoculation with *A. brasilense* can provide 20–40 kg ha^{-1} of N per growing season in grasslands [26,27,31], with significant environmental benefits, as the use of each kg of N-fertilizer used results in the emission of approximately 10.5 kg of CO_2 equivalents [32]. It is also worth mentioning that in the soil, N-fertilizer derivatives, mainly nitrate (NO_3^-), with high solubility and mobility, infiltrate and reach the water table, resulting in groundwater contamination, or are leached into water bodies where they exacerbate eutrophication [33].

The use of microorganisms with biocontrol activity in inoculants has also been discussed to reduce the use of pesticides in agriculture [34]. According to de Moraes [35], the use of pesticides in Brazil rose from 58,000 tons (or megagrams, Mg) in 1991 to 375,000 Mg in 2015, representing 9.2% of global use. Pesticides can threaten human and animal health, contaminate soil and water, and lead to the selection of increasingly resistant pathogens. Microbial biocontrol agents which have antagonistic mechanisms against pathogens, such as parasitism, competition for nutrients and space, and antibiosis [34,36], are a viable alternative.

3. Plant Growth-Promoting Microorganisms

Plant-growth-promoting microorganisms (PGPM) colonize the rhizosphere, root surface, phyllosphere, and internal tissues of vegetative plant organs and promote plant growth by different mechanisms [37]. An impressive and increasing number of plant growth-promoting mechanisms have been reported for PGPM, ranging from facilitating nutrient uptake to biocontrol activity; they are discussed in this review and are summarized in Figure 1.
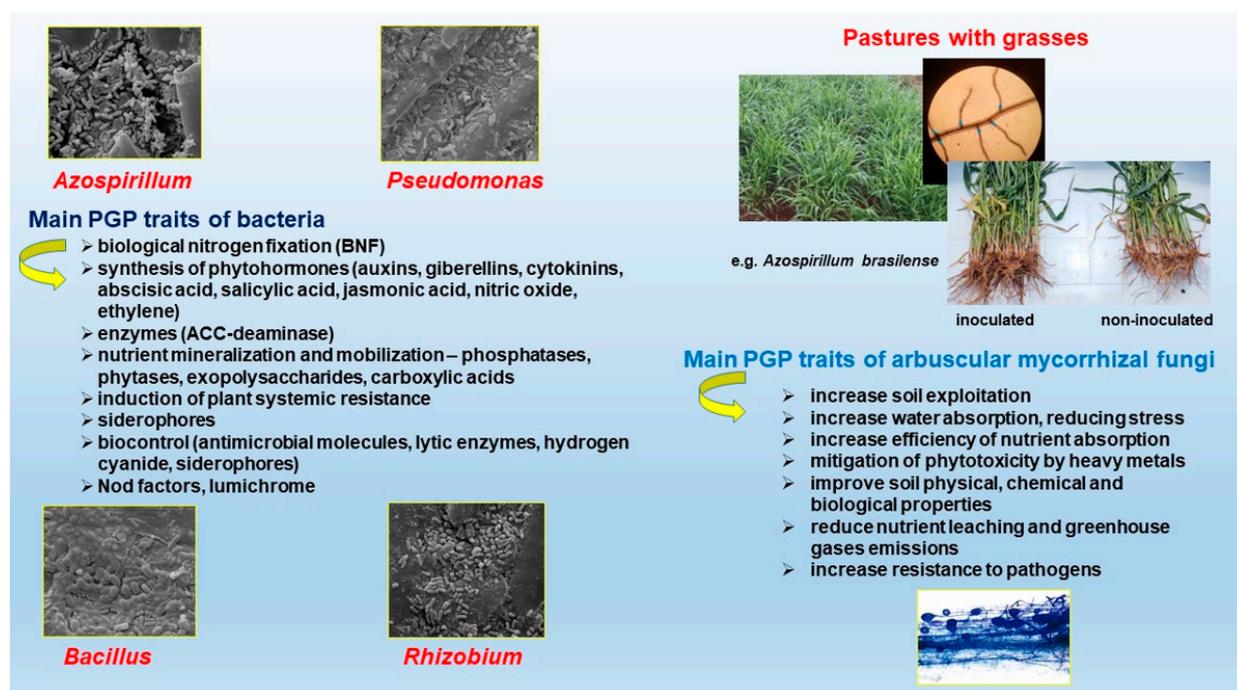
Figure 1. Main plant-growth-promoting (PGP) traits associated with the main bacteria used in studies or in commercial products for pastures with grasses, *Azospirillum*, *Pseudomonas*, *Bacillus*, *Rhizobium*, and arbuscular mycorrhizal fungi.

The main microbial processes related to plant-growth promotion include: biological nitrogen fixation (BNF); synthesis of phytohormones; (e.g., auxins, cytokinins, gibberellins, abscisic acid (ABA), and ethylene); of enzymes such as ACC (1-aminocyclopropane-1-carboxylic acid)-deaminase (which reduces ethylene levels in plants); nutrient mineralization and mobilization; solubilization of phosphorus (P); iron (Fe), and potassium (K); molecules linked to the induction of plant systemic resistance; antibiosis mechanisms [22,26,37,38].

The ability to fix atmospheric nitrogen (N_2) depends on the presence of the nitrogenase enzyme complex in the bacterium, which is composed of two subunits, Fe-protein, and MoFe-protein. In the BNF process, the Fe-protein is responsible for receiving and transferring electrons, while the MoFe-protein is the site with adequate conditions for N_2 reduction. The complex can reduce N_2 into NH_3, which is converted at physiological pH into NH_4^+, which will then be transported and assimilated by the plant [25,39].

The production of phytohormones by PGPM is one of the main factors responsible for stimulating plant growth. Auxins play a critical role in the formation of lateral roots, root hairs, shoot architecture, responses to light and gravity, and vascular development. On the other hand, gibberellins are known to stimulate cell elongation, break the dormancy of buds in stems, and promote germination and development of primordial leaves and fruits [40–42], while cytokinins act in embryogenesis, cell division, differentiation, and formation of lateral roots, and thus may affect the water and nutrient availability by the roots [43]. ABA plays a fundamental role in the seed germination process and acts on water and saline stress tolerance by inducing stomatal closure and accumulation of amino acids and soluble sugars [44]. Studies show that ethylene acts synergistically with auxin in root growth, root hair proliferation, regulation of hypocotyl elongation, and apical hook formation [45]. In addition, some PGPMs have the ability to decrease ethylene levels produced by plants during stress situations, which is beneficial, as high concentrations of ethylene inhibit plant growth due to induction of senescence [46]. The production of ACC-deaminase enzyme degrades the aminocyclopropane carboxylic acid, a precursor of ethylene [47].

Acquired systemic resistance is a plant protective mechanism against pathogens and can be constitutive or induced [48]. This protection can be induced by molecules (elicitors) produced by PGPM that act as signalers that regulate the expression of genes related to plant defense, such as salicylic acid, jasmonic acid, and ethylene [49,50]. There are also reports about the involvement of nitric oxide in mechanisms related to drought and salinity tolerance [51].

Soil microorganisms play important roles in the cycle of nutrients such as P, K, S, and Fe [52]. The increase in P availability occurs by the release of organic acids, chelation of phosphate-bound cations, or lowering of the pH in the rhizosphere [53], while P mineralization is mediated by the action of phosphatases, phytases, or lyases [54,55]. The solubilization of K occurs by the production of low molecular weight molecules such as citric, oxalic, tartaric, succinic, and malic acids [56]. The availability of S occurs by a complex process carried out by some microorganisms in which elemental-S is oxidized to sulfate [57], or organic forms are mineralized by the action of sulphatases. The increased availability of Fe relies on the ability of many organisms to reduce iron oxides [58], as Fe availability and solubility increase in the reduced state [59]. Many microorganisms can change the oxidation status of reduced Fe when using it as a substrate for energy generation or using the oxidate status as a final electron acceptor in anaerobic respiration, facilitating its availability [60].

Antibiosis mechanisms have also been associated with PGPM, via synthesis of molecules such as cyclic lipopeptides, phenazine, tropolone, and surfactins. They can produce lytic enzymes, such as chitinases, which suppress pathogens, and siderophores that chelate Fe in the rhizosphere, hindering the growth of other microorganisms, especially pathogens that have a lower ability to compete for Fe [61]. In addition, siderophores have the ability to chelate Fe, facilitating its absorption by plants [62].

Some PGPM synthesize exopolysaccharides that help root colonization, retain moisture and nutrients, and protect against pathogens. In addition, they can colonize the root surface and use nutrients, preventing the proliferation of harmful microorganisms and producing signaling molecules such as lumichrome, protecting the plant against biotic and abiotic stresses [61].

PGPM has been found associated with several species of cereals and forage grasses, with a large number of reported genera, with emphasis on *Pseudomonas*, *Bacillus*, *Rhizobium*, and *Azospirillum*, in addition to mycorrhizal fungi [22,26,63], which will be emphasized in this review.

4. Plant Growth-Promoting Bacteria (PGPB)

4.1. Azospirillum spp.

Regarding the inoculation of grasses, the species *A. brasilense* has stood out. In Brazil, especially in the past decade, there are numerous reports of yield increases in plants of agronomic interest due to inoculation with *A. brasilense* [22,26,27,64–69]. For example, inoculation with strains Ab-V5 and Ab-V6 of *A. brasilense* increased yields by 27% in maize and 31% in wheat [22]. Later, in a meta-analysis based on 103 field experiments with maize, inoculation with these two strains increased grain yield and root mass by 5.4% and 12.1%, respectively [69]. Inoculation with strains Ab-V5 and Ab-V6 of *A. brasilense* also increased yields in other crops such as rice (*Oryza sativa* L.) and sugarcane (*Sacharum* spp.) [65,67].

Azospirillum spp. may contribute to the plant's N nutrition by the BNF process [70,71] that can reach 20–40 kg ha^{-1} of N [31], allowing a reduction in the use of N-fertilizers [67]. Inoculation of *A. amazonense* (syn. *Nitrospirillum amazonense*) *A. brasilense*, and *A. lipoferum* in *U. brizantha* BRA 003719, *U. humidicola* BRA 005011, and *U. brizantha* BRA 000591 grown in concrete cylinders was responsible for providing 26.2%, 19.6%, and 24.8% of the plant accumulated N, corresponding to 7.02, 3.08, and 8.43 kg ha^{-1} of N, respectively [72]. In field trials with ten cultivars of *M. maximus*, the inoculation with *A. lipoferum*, *A. brasilense,* and *A. amazonense* supplied 5 to 10 kg ha^{-1} of N by the BNF process [73]. In another study performed under greenhouse conditions, inoculation with *A. brasilense* provided 40 kg ha^{-1} of N to M. maximus and *Digitaria decumbens* [74].

Moreover, these bacteria are able to synthesize and release phytohormones [37,75,76], in addition to inducing plant tolerance to abiotic and biotic stresses due to the production of molecules such as jasmonic and salicylic acid, and stimulating the activity of detoxifying enzymes like catalases, superoxide dismutase, and ascorbate peroxidase, as well as prolin, an osmoregulator, in both shoots and roots [20,37,77,78]. Some strains are also capable of phosphate solubilization [79]. Among these benefits, the production of phytohormones is probably the most studied and important for promoting plant growth. The synthesis of indole-3-acetic acid (IAA) by *Azospirillum* spp. [76,80] favors the growth of plant root tissues and may triplicate root growth, increasing its capacity for uptake of water and nutrients from soil [22,81,82]. In addition to IAA, molecules like gibberellins (GAs) [83,84], ethylene [85], cytokinins [86,87], and ABA [76,84,85] can contribute to plant growth.

Despite the vast majority of inoculations in grasses being carried out in important agricultural crops, it is worth mentioning that *A. brasilense* was first isolated in Brazil from the rhizosphere of the pasture *D. decumbens* Stent [88]. Another example of strain isolated from the rhizosphere of pastures is of UAP55, from *Brachiaria* (syn. *Urochloa*) mutica (Forssk.) Stapf in Mexico, which increased wheat grain yield by 43%, 15%, and 11%, in combination with different doses of N (60, 90, and 120 kg ha^{-1} of N, respectively), compared with the non-inoculated controls [89]. Another important *A. brasilense* strain commonly used is Sp7, isolated from the forage grass *Cynodon dactylon* (L.) Pers., and its variant strain Cd [90,91].

In Brazil, evaluations of *A. brasilense* strains Ab-V5 and Ab-V6 in pastures started in 2011 with *U. brizantha* and *U. decumbens*. Field trials were performed with seed inoculation and a basal level of 40 kg ha^{-1} of N. Inoculation resulted in average increases in shoot biomass by 17.3% for *U. brizantha* and 12.5% for *U. ruziziensis*, while N accu-

mulated in shoots increased by 25% [26]. The study resulted in the first commercial inoculant for pastures with brachiarias in 2016, and since then, several field trials have been performed and confirmed the positive effect of Ab-V5 and Ab-V6 strains on grass pastures in Brazil [92–96].

As most pastures in the world, including Brazil, are established with perennial grasses, farmers demanded studies to investigate the feasibility of leaf spray inoculation. Greenhouse and field experiments were performed with brachiarias inoculated with strains Ab-V5 and Ab-V6 via seeds or leaf spray; all treatments received 40 kg ha^{-1} of N at sowing and half received a second application with 40 kg ha^{-1} of N 30 days after emergence [27]. Under greenhouse conditions, inoculation with *A. brasilense* impressively increased root traits, including biomass, tissue volume and density, total and specific length, and the incidence of root hairs in *U. brizantha* and/or *U. decumbens* (syn. *Urochloa eminii*) [27]. Following, field trials were performed with *U. ruziziensis* (syn. *Urochloa eminii*), and the benefits of seed inoculation at the pasture establishment, or leaf spray in established pastures were confirmed, either when they received a basal level of 40 kg ha^{-1} of N, or when receiving another application of 40 kg ha^{-1} of N 30 days after seedling emergence. On average, shoot biomass increased by 22%, in addition to 13% of N and 10.4% of K concentrations in leaves [27].

4.2. Pseudomonas spp.

Pseudomonas are Gram-negative bacteria with a very versatile metabolism, commonly found in soil and water. They are considered aerobics but can use nitrate as a final acceptor of electrons during anaerobic respiration. The optimal temperature for growth is between 25 and 30 °C [97].

The main species referred to as a growth promoter in agriculture is *Pseudomonas fluorescens*. Among the main properties of *Pseudomonas* species are their abilities to produce auxins, notably IAA [97]. There are also reports of the production of cytokinins, gibberellins, and ACC-deaminase [98]. In a study carried out by Hungria et al. [27], inoculation of *Pseudomonas fluorescens* strain CNPSo 2719 (=CCTB 03) via seeds or leaf spray increased the total length and the number of root branches of *U. brizantha* and *U. decumbens*, which was attributed to the synthesis of phytohormones.

The synthesis of siderophores is another plant-growth-promoting trait of *Pseudomonas*. These low molecular weight molecules increase the mobility and availability of Fe, allowing its translocation through the plant cell membranes. Siderophores play an important role in plant growth and in the control of phytopathogens, preventing them in the rhizosphere by sequestering and thus limiting the Fe necessary for their development [99,100].

Suppression of pathogens by *Pseudomonas* can also occur based on other mechanisms, including the synthesis of antimicrobial molecules such as pyrrolenitrine, pyocyanin, and 2-4-diacetylphloroglucinol; competition for nutrients and space; the production of lytic enzymes, such as β-1,3-glucanases, which degrade chitin and glucans present in the cell walls of fungi; by the release of hydrogen cyanide (HCN); by degradation of toxins produced by pathogens [97]. In a study performed by Rodriguez and Pfender [101], the inoculation of *P. fluorescens* strain Pf-5 inhibited the mycelial growth of *Sclerotinia homoeocarpa* in cuts of leaves of *Agrostis* sp., while no inhibition occurred when inoculating a mutant *P. fluorescens* lacking the synthesis of antibiotics.

Phosphorus, after N, is the most limiting macronutrient for plant development participating in various metabolic processes, including cell division, photosynthesis, biosynthesis of macromolecules, energy metabolism, and signal transduction [102]. However, most of the soil P is precipitated, due to bonds with cations, immobilized in oxides and clay, adsorbed, or is in the organic form, being unavailable for plants. Considering the P present in the soil surface layer, estimated at 50 to 3000 mg P kg^{-1} of soil, only 0.1% is available to the plants [103]. In addition to mechanisms that facilitate P absorption, a crucial feature of some *Pseudomonas* strains is their ability to solubilize inorganic phosphates to forms that can be assimilated by plants. For example, the use of *Pseudomonas plecoglossicida* along with rock

phosphate in maize and wheat resulted in a higher concentration of P in shoots, roots, and grains [104]. However, it is convenient to note that many bacteria can be described as able to promote plant growth, but they may also be highly pathogenic to plants, animals, and humans. Therefore, it is mandatory to exclude these bacteria from any type of commercial use in agriculture, as is the example of *P. plecoglossicida*, first described as the causal agent of hemorrhagic in ayu fishes (*Plecoglossus altivelis*) [105], or the often-cited plant growth properties of strains of the *Burkholderia cepacia* complex, one of the most dangerous human pathogens, that are widespread in natural vegetation, such as natural ryegrass pastures in Portugal [106].

Forage grasses can benefit from inoculation with *Pseudomonas*. Under greenhouse conditions, inoculation of *U. brizantha* cv. BRS Piatã with *P. fluorescens* strain BRM-32111 increased the concentration of primary metabolites, such as carbohydrates and proteins, as well as plant biomass, N concentration, and chlorophyll concentration after 35 days of growth [107], confirming previous results on shoot and root biomass increases [108]. In another study, Begun et al. [109] inoculated *Pseudomonas grimontii* strain Bc09, *Pseudomonas veronii* strain E02, and *P. fluorescens* strain Oj24 in *Panicum* (syn. *Megathyrsus*) *virgatum* cv. Alamo and Cave-in-Rock (CIR) under cadmium (Cd) stress and reported increases in root dry biomass by 57%, 93%, and 96% in cv. Alamo, and by 70%, 137%, and 29% in CIR, and increases in the shoot dry biomass by 105%, 130%, and 105% in cv. Alamo and 97%, 169%, and 42% in CIR, respectively.

Inoculation with *P. fluorescens* strain CNPSo 2719 increased the rate of stem elongation and leaf expansion, and the number of basal tillers in *U. brizantha* [96]. In *M. maximus*, inoculation with the same strain of *P. fluorescens* resulted in increases in shoot and root dry weight, tiller number, and uptake of N and magnesium (Mg) [110]. In addition, inoculating the same strain into a hybrid of *Urochloa* spp. resulted in increases in shoot and root dry mass, as well as the number of tillers [111].

The good performance of *P. fluorescens* strain CNPSo 2719 in Brazil has resulted in its use in commercial inoculants for *Urochloa* since 2021. Inoculation of the strain via seeds or leaf spray increased shoot biomass by 15.2 and 14.2%, respectively. In addition, seed and leaf spray inoculation resulted in average increases in leaf concentration of 33.3 and 36.6% for P, and 10.6 and 13.6% for K, respectively [27].

It is also worth mentioning that *P. fluorescens* is considered a "mycorrhizal helper bacterium", capable of stimulating an increase in the rate of root colonization by arbuscular mycorrhizal fungi (AMF) [112], symbionts that increase the area of soil explored by roots and are essential for grasses to survive, grow, and reproduce in degraded tropical soils [113–115].

4.3. Bacillus spp.

In 1835, Christian Gottfried Ehrenberg cited the genus *Bacillus* for the first time. They are Gram-positive, facultative anaerobic, and endospore-forming bacteria. Because of their ability to sporulate, *Bacillus* can survive under extreme pH, temperature, and salinity [116]. These properties made them very attractive to the industry, as spore-based bioproducts may have a long shelf life, making easier the logistics of storage and distribution [117].

Many studies have demonstrated the ability of *Bacillus* to promote plant growth [116]. For example, in a study carried out with *U. brizantha*, Araujo et al. [118] reported that seed inoculation with *Bacillus* sp., previously isolated from the rhizosphere of this grass promoted, an increase in tillering and leaf expansion. Studies have also shown that *Bacillus* can improve the development, nutrient uptake, and yield of other grasses such as maize [119], wheat [79], and millet [*Pennisetum glaucum* (L.) R.Br.] [120]

Here it is worth mentioning that the taxonomy of *Bacillus* is very complex and has gone through several modifications. The last one proposed that the genus *Bacillus* should be limited to the species members of the *B. subtilis* and *B. cereus* clades, resulting in the description of the new genus *Priestia* [121]. However, for practical purposes, we will refer to the generic genus *Bacillus*, as the proper taxonomic description of several strains used in the

studies is not always clear. For updated information on the taxonomy of *Bacillus*, the website (https://lpsn.dsmz.de/genus/bacillus; accessed on 11 July 2022) should be consulted.

Several *Bacillus* are known to have the ability to produce siderophores. In addition, they can improve solubilization or facilitate the mobilization of nutrients in the soil, allowing plant absorption [122]. In some species, such as *Bacillus cereus*, *Bacillus chitinolyticus* (now *Paenibacillus chitinolyticus*), *Bacillus circulans* (now *Niallia circulans*), *Bacillus coagulans* (now *Weizmannia coagulans*), *Bacillus fusiformis* (now *Lysinibacillus fusiformis*), *Bacillus megaterium* (now *Priestia megaterium*), *Bacillus mycoides*, *Bacillus polymyxa* (now *Paenibacillus polymyxa*), *Bacillus pumilus*, and *Bacillus subtilis*, the ability to solubilize phosphates has been demonstrated [123].

Hussain et al. [124] reported that 14 *Bacillus* isolates obtained from the maize rhizosphere could solubilize zinc (Zn), and Basak and Biswas [125] observed increased K absorption in sorghum (*Sorghum vulgare* Pers.) inoculated with *Bacillus mucilaginosus* (now *Paenibacillus mucilaginosus*). In addition, *Bacillus* can make P available to plants by other mechanisms such as the production of enzymes, including phosphatases and phytases, which act as catalysts in the conversion of organic to inorganic P, that is, in the mineralization of P [126].

Bacillus species can also produce and modulate phytohormone levels in plants, thus regulating plant growth and stress responses [127]. Gas chromatography coupled to mass spectrometry analyses indicated the synthesis of auxins, cytokinins, abscisic acid, and gibberellins in *Bacillus aryabhattai* SRB02 (now *Priestia aryabhattai*) [128]. In another study, an isolate of *Bacillus* sp. producer of auxins led to greater tillering in *U. brizantha* [118]. In addition, some *Bacillus* expresses the enzyme ACC-deaminase, which helps plant growth by reducing the levels of ethylene [129].

Exopolysaccharides (EPS) produced by some *Bacillus* have shown effects on various soil properties and plant productivity. EPS can stabilize soil aggregates and regulate the movement of nutrients and water to plant roots by biofilm formation. In addition, they help in nutrient uptake, stimulating plant growth [130]. Because biofilms are negatively charged, they are effective sequesters of charged heavy metals. Therefore, the production of biofilms is relevant to salt stress as they bind to sodium (Na^+), leading to a decrease in the accumulation of this ion in plants, conferring increased salt tolerance [130,131].

Due to the production of antimicrobial molecules, lytic enzymes, and other organic molecules, *Bacillus* are the most commonly used bacteria in the biological control of plant pathogens. Concerning antimicrobial compounds, iturin synthesized by *B. subtilis* showed activity against *Aspergillus carbonarius* by affecting the fungal membrane permeability [132], and it was also very effective against several soybean seed fungi [133]. In a study carried out by Hanif et al. [134], fengicin produced by *Bacillus velezensis* strain FZB42 decreased the pathogenicity of *Fusarium graminearum* in wheat, altering the membrane permeability and fungal cell structure.

Lytic enzymes produced by some *Bacillus* are also important for the suppression of plant pathogenic microorganisms, especially fungi. They are capable of destabilizing the cell envelope, creating pores in the cell membrane, and inactivating the ribosomes of certain fungi [135]. Saxena et al. [126] showed that *B. subtilis*, *B. velezensis*, *B. cereus*, *B. thuringiensis*, *B. licheniformis*, and *B. pumilus* are producers of certain enzymes such as chitinases, glucanases, proteases, and lipases. Agarwal et al. [136] reported the antifungal activity of *B. pumilus* strain MSUA3 due to the production of chitinases and surfactin, while El-Bendary et al. [137] observed that *Bacillus* isolates 8Es, 25Sp, and 27Sp, producers of chitinases, proteases, and glucanases were able to inhibit 70–88% of the mycelial growth of the fungus *Macrophomina phaseolina* in vitro.

Apparently, bacteria belonging to the genus *Bacillus* (and their subdivisions) are the richest in plant-growth-promoting mechanisms. However, we should again call attention to their careful use in agriculture, as many species are highly pathogenic to animals and humans, such as *B. cereus* and *B. anthracis*. Therefore, the choice of proper species and

strains based on the correct taxonomic classification is mandatory for their successful use as inoculants, biofertilizers, or biopesticides.

4.4. Rhizobium spp., Bradyrhizobium spp., and Other "Rhizobia"

In 1888, the Dutch microbiologist Martinus Willem Beijerinck was the first to isolate and cultivate a microorganism present in legume nodules, later called *Rhizobium* [138]. Rhizobia is a generic term for bacteria that are symbiotic and are classified into several genera, including *Rhizobium*, *Bradyrhizobium*, *Sinorhizobium*, *Mesorhizobium*, among others. Aerobic rhizobia live saprophytically in soil, have an optimal growth temperature between 25 and 30 °C and process several mechanisms that can promote plant growth [139].

Besides the leading role of nitrogen fixation in symbiosis with legumes, and sometimes under free-living conditions [25], other mechanisms to promote non-legume growth include the solubilization of phosphates and the synthesis of phytohormones. Rhizobia are capable of producing and releasing carboxylic acids into the soil, such as citric, gluconic, oxalic, lactic, tartaric, and acetic acids, which decrease the pH of the medium and promote the release of phosphate anions from Fe, aluminum (Al), and calcium (Ca) complexes [140]. Silva et al. [141] observed an increase in shoot phosphorus concentration when inoculating maize and oat (*Avena sativa* L.) with *Bradyrhizobium* spp. isolates from *Desmodium incanum* (Sw.) DC.

The main phytohormones produced by rhizobia are auxins, cytokinins, and gibberellins [139], detected and quantified using HPLC and/or GC-MS [142,143]. Among the auxins, IAA is the most reported phytohormone. In a greenhouse experiment inoculation with auxin-producing rhizobia SEMIA 816, UFRGS Lc134, UFRGS Lc323, UFRGS Lc348, UFRGS Lc510, and UFRGS Lc524 resulted in increased shoot and root dry mass and root volume in *M. maximus*, *Paspalum saurae* (Parodi) Parodi, *U. decumbens*, and *Lolium multiflorum* Lam [144]. The effects of gibberellins were observed when inoculating canola (*Brassica napus* L.) and lettuce (*Lactuca sativa* L.) seeds with the mutant strain 127E14 of *Rhizobium leguminosarum* for the production of adenosine, the precursor molecule for gibberellin biosynthesis. In this case, there was no early root growth compared with the inoculation with the wild-type strain [145].

Other plant-growth-promoting molecules synthesized by rhizobia are lipochitooligosaccharides, also known as Nod factors. According to Souleimanov et al. [146], these molecules are involved in the cell cycle, leading to stimulation of mitotic divisions in protoplasm cultures of legumes and non-legumes. In grasses such as maize, plant growth- promotion by the addition of exogenous Nod factors synthesized by *Rhizobium tropici* and *Bradyrhizobium diazoefficiens* has been reported [147,148]. Lumichrome is another compound from rhizobia produced by the photochemical degradation of riboflavin. This molecule can induce the expression of genes responsible for cell growth and mitotic division and increase CO_2 concentrations in the rhizosphere [149]. Lumichrome has been reported as being able to promote the growth of legumes and grasses [150]. For example, the application of lumichrome to maize plants increased the photosynthetic rate [151].

Most rhizobia e.g., *Rhizobium tropici* strain CIAT 899, *Sinorhizobium* (syn. *Ensifer*) *meliloti* strain SU-47, and *R. leguminosarum* bv. trifolii strain TA-1, are well-known for their capacity of synthesizing EPS [152]. The benefits of EPS for plant growth were detailed in on the item 4.3 of *Bacillus*.

Some rhizobial species such as *R. leguminosarum*, *S. meliloti*, and *Bradyrhizobium japonicum* can suppress pathogens by competing for nutrients, or by producing antibiotics and enzymes such as chitinases and glucanases, or siderophores [139]. This capacity has been demonstrated in studies in which these bacteria were able to inhibit phytopathogens such as *M. phaseolina*, *Fusarium oxysporum*, *Fusarium solani*, *Sclerotinia sclerotiorum*, and *Rhizoctonia solani* [153,154]. In addition, some rhizobia can decrease the level of ethylene in plants by production and release of the enzyme ACC-deaminase (1-aminocycopropane-1-carboxylic acid) [139], modulating plant growth.

5. Plant Growth-Promoting Fungi

Arbuscular Mycorrhizal Fungi (AMF)

More than 80% of terrestrial plant species have their roots colonized by arbuscular mycorrhizal fungi (AMF), forming the symbiosis known as arbuscular mycorrhiza (or endomycorrhiza) [155]. In most cases, the association with AMF provides benefits to plants, such as increased resistance to pathogens [156], reduction of water stress effects [157,158], and mitigation of phytotoxicity caused by heavy metals [159]. However, the main benefits are the increase in soil exploitation and, consequently, the efficiency of nutrient absorption [160–162]. According to some studies, mycorrhizal plants absorb more efficiently N, K, Ca, Mg, Zn, copper (Cu), manganese (Mn), and especially P [160,163–167]. In addition, AMF can increase the quality and sustainability of natural ecosystems and agroecosystems as it improves soil physical, chemical, and biological attributes [168–171], and also reduces nutrient leaching and greenhouse gas emissions [167].

AMF are obligate biotrophs with coenocytic mycelium, asexual sporulation and ubiquitous distribution [155], and comprise a unique phylum, Glomeromycota [172], with 341 described species (http://www.amf-phylogeny.com/; accessed on 13 July 2022). When associated with roots, AMF presents internal hyphae, which grow in the apoplast of cortical cells, and external hyphae, which extend through the soil [162]. AMF symbiosis increases the area of soil exploited by roots because the external hyphae are longer and have a smaller diameter (between 2 μm and 10 μm) than the fine roots and the root hairs, which makes them able to explore small pores and soil regions not reached by the root system, increasing the absorption of nutrients per surface unit [162]. AMF absorbs water and nutrients from the soil through the external hyphae, transferring them to the internal hyphae and, in the arbuscles, exchanging these resources by photosynthates [155,173]. The formation and maintenance of the symbiosis requires carbon (C), so estimates point out that 4 to 20% of the total C fixed by photosynthesis can be transferred to the fungi [173,174].

Grasses, in general, have a high level of association with AMF, which becomes clear when the rate of mycorrhizal colonization in their fine roots is quantified. Under greenhouse conditions, Zangaro et al. [11] observed mycorrhizal colonization rates above 90% in the roots of the forage grasses *M. maximus*, *U. brizantha*, and *Paspalum notatum* grew in the soils of Brazilian pastures located in the Atlantic Forest biome. In the Cerrado biome, rates of colonization of 44% in *U. decumbens*, 51% in *U. brizantha*, and 52% in *U. humidicola* colonized by native AMF species (notably *Gigaspora* spp., *Scutellospora* spp., *Glomus* spp., *Acaulospora* spp., and *Entrophospora* spp.) have been reported [175]. Cavagnaro et al. [176] found mycorrhizal colonization rates of 60% for *U. brizantha* and 80% for *Paspalum dilatatum* Poir. inoculated with a mixture of three AMF species [*Rhizophagus irregularis* (syn. *Glomus intraradices*), *Simiglomus hoi* (syn. *Glomus hoi*), *and Funneliformis mosseae* (syn. *Glomus mosseae*)]. In another study, Rondina et al. [165] assessed the rate of mycorrhizal root colonization of *Sorghum* sp. and *Pennisetum purpureum* Schumach, grown in soil from the Atlantic Forest biome and reported rates of about 80%.

High mycorrhizal colonization rates are also typical in forage grassroots in the field, although the values are generally lower than those observed under greenhouse conditions. In a study carried out in Palmira, Colombia, 1000 m of altitude, with the hybrid of *Urochloa* 'Mulato' and with *U. humidicola*, the root mycorrhizal colonization was 48% and 72%, respectively [177]. However, high rates of mycorrhizal colonization, above 75% were found in pastures composed of *P. notatum*, *Cynodon* sp., and *Urochloa* spp. in the Atlantic Forest [115,178–180], and in the Pantanal [178] Brazilian biomes. In field studies conducted in the Brazilian Cerrado, Ramos et al. [181] found mycorrhizal colonization rates between 51% and 70% for *M. maximus* and 60% for *U. humidicola*. Moraes et al. [182] observed values between 36% and 60% for *U. brizantha* and *U. ruziziensis*, and Pires et al. [183] reported between 25% and 48% for *M. maximus*, and 41% and 80% for *U. brizantha*. In general, in soils under forage grasses the densities of AMF spores and external mycelium are also high and correlate positively with the rate of root mycorrhizal colonization [179,180,184,185].

Together, these data indicate a high investment of C by the host plant in the symbiosis and a high multiplication capacity of AMF by grasses [115,179].

The rate of mycorrhizal colonization in forage grassroots can be positively affected by interspecific interactions between grasses and legumes [182,183]. In a study on the crop-livestock integration system in the Cerrado, with pasture and legume intercropping in the off-season [e.g., *U. brizantha* or *M. maximus* + *Vigna unguiculata* (L.) Walp. or *Cajanus cajan* (L.) Millsp.], Pires et al. [183] found that the rate of mycorrhizal colonization in grassroots increased by up to 90% when intercropped with legumes, compared with single grass cultivation. As a result, the productivity of the soybean cropped following the intercropping was up to 16% higher, showing a significant positive relationship with the increase in the rate of mycorrhizal colonization previously verified in the pasture. Similar results were obtained by Moraes et al. [182] but using *U. ruziziensis* instead of *M. maximus* intercropped with legumes. Also, edaphic and climatic characteristics, such as pH, moisture, organic matter, and soil P availability [186,187], photoperiod, temperature, and rainfall [179,180] can affect the interaction between grasses and AMF, causing variations in the rates of root mycorrhizal colonization in the field.

Commonly, the soils occupied by pastures in Brazil, natural or planted, are acidic and have low availability of nutrients, especially P [188–191]. Although forage grasses such as *Urochloa*, *Megathyrsus*, *Paspalum*, and *Cynodon* have fine roots with typical morphological traits to exploit a large volume of soil, with total and specific root lengths, small diameter, and high incidence of long root hairs [115,178,180], studies have shown that arbuscular mycorrhizae are of great importance for the acquisition of nutrients and, thus, for the establishment, growth, and regrowth of these plants in low fertility soils [114,165,192]. Indeed, there are reports that *M. maximus*, *U. brizantha,* and *P. notatum* grown in soil with low P availability ($\approx$1.0 mg dm^{-3}) were unable to survive 20 days after emergence without mycorrhiza [114]. Similar results were obtained for *Sorghum* sp. And *P. purpureum* in soil with low available P (0.89 mg dm^{-3}) in the absence of AMF [165].

Other studies confirm the importance of colonization of pasture grasses with AMF. Cavagnaro et al. [176], in an experiment conducted in pots with sterile sand receiving nutrient solution with low nutrient content, with or without AMF inoculation, found that *P. dilatatum* and *U. brizantha* presented twice as much, and the triple production of both shoot and root biomass, respectively, compared with the non-inoculated controls. In addition, leaf P concentration and the number of tillers increased by 16% and 95%, respectively, in mycorrhizal U. brizantha plants [176]. In a study performed with *U. brizantha*, *U. decumbens*, *U. humidicola*, and *M. maximus* grown in pots containing sterilized soil and available P between 2.0 and 2.5 mg kg^{-1}, with or without inoculation with a pool of AMF species native to the Brazilian Cerrado, inoculation resulted in average increases of 67% in shoot and of 32% in root biomass [175]. Furthermore, on average, P uptake doubled in inoculated plants compared with uninoculated controls [175]. In another study to evaluate the ability of grasses growing in substrates with low P to resprout after 60% defoliation to simulate grazing, AMF inoculation promoted greater and faster regrowth of *U. brizantha* and *Agropyron elongatum* (Host) P.Beauv [192].

In low fertility soils, the nutrient requirement of grasses, in addition to their rapid growth rates, can lead to the formation of a nutrient depletion zone in the rhizosphere [115], as nutrient absorption often occurs faster than their movements in the soil and their rates of mineralization from the soil organic matter [115,193]. In this context, the symbiosis with AMF ensures that forage grasses obtain nutrients beyond the depletion zone, which helps to explain the maintenance of high rates of mycorrhizal colonization by these plant roots [115,179,180], and the high responsiveness to mycorrhization, in terms of biomass production [165,175,176,192]. Furthermore, AMF greatly influences the spread of grasses, as they can anticipate and/or increase flowering when associated with AMF [165,194]. However, when P availability is high, the AMF symbiosis can decrease the grass biomass production [114,192], a phenomenon known as "growth depression" [195]. When cultivated in sterile soil containing 32 mg kg^{-1} of P, non-inoculated *U. brizantha*, *P. nota-*

tum, and *M. maximus* showed between two and three times more shoot biomass than AMF-inoculated plants after 90 days of growth [114]. In the same soil, non-inoculated *P. purpureum* exhibited, on average, 11% more shoot biomass than inoculated individuals after 100 days of growth [165]. Cavagnaro et al. [192] observed that when cultivating *A. elongatum* in a sterile, inert substrate with a high supply of P via nutrient solution (1.0 mM), non-inoculated plants produced 47% more shoot biomass and 32% more tillers than those inoculated with AMF, 22 days after defoliation, simulating grazing. "Growth depression" events occur due to the C cost imposed on the host plant by the AMF in a condition where the fungi would not be required to obtain adequate amounts of P for the host growth [165,192,195]. As a result, when mycorrhizal colonization in the roots is high (which is frequent in grasses), the fungal demand for photosynthates can be high, and the greater allocation of C to maintain large fungal structures in the roots and soil may contribute to a lower accumulation of biomass by the mycorrhizal plant [165,196,197].

Some AMF species may be more effective than others, differing in root colonization rates, nutrient uptake, and the response levels they induce in the host plant [168,198]. The most effective species have been used, singly or in a consortium, to develop inoculants based on AMF [199,200]. Several companies worldwide have developed and marketed AMF-based inoculants for agricultural, turf, nursery, and phytoremediation applications (e.g., Rootella®, MycoApply®, Privi Mycoxol®, Mobilizer®, Myco Gold®, Root Plus ®, RISEHoP®, MYKE® Pro) [199–201]. In Brazil, Rootella® was the first commercial inoculant based on AMF (*Rhizophagus intraradices*) [202] and resulted in average increases in grain yield by 54% and 25%, for maize and soybean, respectively, as well as a reduction in the amount of P-fertilizer required to achieve high yields [203,204]. Currently, other inoculants containing AMF are under development and in the registration process in Brazil [202,205,206]. However, as far as we know, despite the potential of AMF to increase productivity and decrease the degree of soil degradation, no study on the application of commercial inoculants containing AMF in tropical forage grasses has been developed in the country to date.

6. Final Remarks

We have shown that several microorganisms, including bacteria and fungi, can highly promote plant growth, and in this review, we focused on the opportunity of improving quantitatively and qualitatively the production of forages with grasses. As grasslands occupy far more areas than crops, their improvement may not only enhance livestock production but also release land for other crops without the need to advance into deforestation. Improving pasture productivity and reducing degradation also have important social impacts, with higher economic inputs to the farmers. Environmental benefits arise from the possibility of partially replacing synthetic fertilizers and pesticides, helping to mitigate the emission of greenhouse gases in addition to decreasing pollution of water reservoirs by chemicals.

Certainly, some microorganisms may contribute to more than one mechanism, namely multifunctionality. This review points out the importance of selecting elite strains with superior performance to be applied as inoculants or biopesticides. The commercialization of microbial inoculants has significantly increased in the past few years; however, their use is still modest on pastures, which have the crops most lacking in the use of inputs to increase their quality and sustainability. One example is Brazil, where over 100 million doses of inoculants have been commercialized annually, but less than 0.1% are destined for pastures, despite outstanding results confirming the benefits of inoculation, as shown in Table 1. Therefore, efforts towards increasing the use of PGPM in pastures with grasses can have profound positive global, environmental, economic, and social impacts.

Table 1. Recent studies reporting the benefits of inoculation with plant growth-promoting microorganisms in forage grasses in Brazil.

Forage Species	Microorganism Genus/Species	Strain	Nitrogen (kg ha^{-1})	Shoot Biomass Increase (g)	Root Biomass Increase (g)	Reference
Urochloa brizantha cv. Marandu	*Azospirillum brasilense*	Ab-V5 and Ab-V6	40	24.66	-	[26]
Urochloa brizantha cv. Marandu	*Azospirillum brasilense*	Ab-V5 and Ab-V6	50	13.04	-	[207]
Urochloa brizantha cv. Marandu	*Azospirillum brasilense*	Ab-V5 and Ab-V6	25	-	81.1	[95]
Urochloa brizantha cv. Marandu	*Bacillus subtilis*	AP-3	-	27.41	13.59	[208]
Urochloa brizantha cv. Marandu	*Acaulospora muricata*	-	-	353	-	[209]
Urochloa brizantha cv. Paiaguás	*Azospirillum brasilense*	Ab-V5 and Ab-V6	50	41.25	-	[94]
Urochloa ruzizienses	*Azospirillum brasilense*	Ab-V5 and Ab-V6	40	23.26	-	[26]
Urochloa ruziziensis	*Pseudomonas fluorescens*	CNPSo 2719	0	43	60	[96]
Urochloa ruziziensis	*Pseudomonas ananatis*	AMG521	0	44	70	[96]
Urochloa ruziziensis	*Azospirillum brasilense*	Ab-V5 and Ab-V6	80	29.3	-	[27]
Urochloa ruziziensis	*Pseudomonas fluorescens*	CNPSo 2719	80	27.6	-	[27]
Urochloa brizantha	*Azospirillum brasilense*	Ab-V5 and Ab-V6	60	-	66.5	[27]
Urochloa brizantha	*Pseudomonas fluorescens*	CNPSo 2719	60	-	97.5	[27]
Urochloa decumbens	*Claroideoglomus etunicatum* and *Acaulospora morrowiae*	-	-	-	31	[210]
Megathyrsus maximus cv. Zuri	*Azospirillum brasilense*	Ab-V5 and Ab-V6	50	17.02	17	[211]
Megathyrsus maximus cv. BRS Zuri	*Pseudomonas fluorescens*	CNPSo 2719	100	7	–	[212]
Megathyrsus maximus cv. Tanzânia	*Mesorhizobium* sp.	SEMIA 816	50	-	12,5	[144]
Paspalum saurae	*Mesorhizobium* sp.	SEMIA 816	50	-	11.7	[144]
Andropogon gayanus cv. Planaltina	*Acaulospora muricata*	-	-	107	-	[213]

References

1. United Nations Environment Programme. *Annual Evaluation Report Evaluation and Oversight Unit*; United Nations Environment Programme: Nairobi, Kenya, 2000. Available online: https://wedocs.unep.org/bitstream/handle/20.500.11822/356/UNEP_Annual_Evaluation_Report_2004.pdf?sequence=1&isAllowed=y (accessed on 2 July 2021).
2. Ritchie, H.; Roses, M. Land Use. 2013. Available online: https://ourworldindata.org/land-use?fbclid=IwAR1OnVSd1Rhj7PKzA4xCejkIPKfiKJf84AXumZ2KvC4FXUBi7aLVzDwgbY4#citation (accessed on 1 April 2022).
3. Cang, C.G.; Zhou, W.; Chen, Y.; Wang, Z.; Sun, Z.; Li, Z.; Qi, J.; Odeh, I. Quantitative assessment of the contributions of climate change and human activities on global grassland degradation. *Environ. Earth Sci.* **2014**, *72*, 4273–4282. [CrossRef]
4. MAPA, Ministério da Agricultura, Pecuária e Abastecimento. *Projeções do Agronegócio: Brasil 2019/20 a 2029/30, Projeções de Longo Prazo*; Secretaria de Política Agrícola: Brasília, Brazil, 2020. Available online: https://www.gov.br/agricultura/pt-br/assuntos/politica-agricola/todas-publicacoes-de-politica-agricola/projecoes-do-agronegocio (accessed on 2 July 2021).
5. ABIEC, Associação Brasileira das Indústrias Exportadoras de Carnes. Beef Report: Perfil da Pecuária no Brasil. 2021. Available online: http://abiec.com.br/publicacoes/beef-report-2021/ (accessed on 23 November 2021).
6. FAOSTAT. 2019. FAOSTAT. Available online: https://www.fao.org/faostat/en/#data (accessed on 1 April 2022).
7. MAPA, Ministério da Agricultura, Pecuária e Abastecimento. Agropecuária Brasileira em Números. Secretaria de Política Agrícola, Brasília, Brazil. Available online: https://www.gov.br/agricultura/ptbr/assuntos/politica-agricola/todas-publicacoes-de-politicaagricola/agropecuaria-brasileira-em-numeros (accessed on 23 November 2021).
8. Novaes, R.M.L.; Tubiello, F.N.; Garofalo, D.F.T.; de Santis, G.; Pazionotto, R.A.A.; Folegatti-Matsuura, M.I.S. *Brazil's Agricultural Land, Cropping Frequency and Second Crop Area: FAOSTAT Statistics and New Estimates*; Embrapa Environment: Jaguariúna, Brazil, 2022; 26p.
9. UNIPASTO (Associação para o Fomento à Pesquisa de Melhoramento de Forrageiras). *Personal communication*. 2022. Available online: https://www.unipasto.com.br/ (accessed on 14 April 2022).
10. Dias-Filho, M.B. *Diagnóstico das Pastagens no Brasil*; Embrapa Amazônia Oriental: Belém, Brazil, 2014; 38p.
11. Machado, L.A.Z.; Lempp, B.; do Valle, C.B.; Jank, L.; Batista, L.A.R.; Postiglioni, S.R.; Resende, R.M.S.; Fernandes, C.D.; Verzignassi, J.R.; Valentim, J.F.; et al. Principais espécies forrageiras utilizadas em pastagens para gado de corte. In *Bovinocultura de Corte*, 1st ed.; Pires, A.V., Ed.; Fundação de Estudos Agrários Luiz de Queiroz: Piracicaba, Brasil, 2010; pp. 375–417.
12. Macedo, M.C.M.; Zimmer, A.H.; Kichel, N.A.; Almeida, R.G.; de Araujo, A.R. Degradação de pastagens, alternativas de recuperação e renovação, e formas de mitigação. In *Encontro de Adubação de Pastagens da Scot Consultoria-Tec-Fértil*; Scot Consultoria: Piracicaba, Brazil, 2013; pp. 158–181.
13. Anderson-Teixeira, K.J.; Davis, S.C.; Masters, M.D.; Delucia, E.H. Changes in soil organic carbon under biofuel crops. *Gcb Bioenergy* **2009**, *1*, 75–96. [CrossRef]
14. Raich, J.W.; Schlesinger, W.H. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. *Tellus B* **1992**, *44*, 81–99. [CrossRef]
15. Cerri, C.E.P.; Sparovek, G.; Bernoux, M.; Easterling, W.E.; Melillo, J.M.; Cerri, C.C. Tropical agriculture and global warming: Impacts and mitigation options. *Sci. Agric.* **2007**, *64*, 83–99. [CrossRef]
16. Cerri, C.C.; Bernoux, M.; Maia, S.M.F.; Cerri, C.E.P.; Junior, C.C.; Feilg, B.J.; Frazão, L.A.; Mello, F.F.C.; Galdos, M.V.; Moreira, C.S.; et al. Greenhouse gas mitigation options in Brazil for land-use change, livestock and agriculture. *Sci. Agric.* **2010**, *16*, 110–116. [CrossRef]
17. Watson, L. Portugal gives green light to pasture carbon farming as a recognised offset. *Aust. Farm, J.* **2010**, *1*, 44–47.
18. Terra, A.B.; Florentino, L.A.; Rezende, A.D.; Silva, N.C. Leguminosas forrageiras na recuperação de pastagens no Brasil. *Rev. Cienc. Agrícola.* **2019**, *42*, 305–313. [CrossRef]
19. United Nations, Department of Economic and Social Affairs, Population Division. World Population Prospects 2019 Highlights. Available online: https://www.un.org/sustainabledevelopment/blog/2019/06/growing-at-a-slower-pace-world-population-is-expected-to-reach-9-7-billion-in-2050-and-could-peak-at-nearly-11-billion-around-2100-un-report/# (accessed on 2 July 2021).

20. Santos, M.S.; Nogueira, M.A.; Hungria, M. Microbial inoculants: Reviewing the past, discussing the present and previewing an outstanding future for the use of beneficial bacteria in agriculture. *AMB Express* **2019**, *9*, 205. [CrossRef]

21. ANPII, Associação Nacional dos Produtores e Importadores de Inoculante. Inoculantes. 2020. Available online: http://www.anpii.org.br/wpcontent/uploads/2020/06/Global-Fert-Inoculantes.pdf (accessed on 23 November 2021).

22. Hungria, M.; Campo, R.J.; Souza, E.M.; Pedrosa, F.O. Inoculation with selected strains of *Azospirillum brasilense* and *A. lipoferum* improves yields of maize and wheat in Brazil. *Plant Soil* **2010**, *331*, 413–425. [CrossRef]

23. Santos, M.S.; Nogueira, M.A.; Hungria, M. Outstanding impact of *Azospirillum brasilense* strains Ab-V5 and Ab-V6 on the Brazilian agriculture: Lessons that farmers are receptive to adopt new microbial inoculants. *Rev. Bras. Cienc. Solo* **2021**, *45*, 1–31. [CrossRef]

24. Barbosa, J.Z.; Hungria, M.; Sena, J.V.S.; Poggere, G.; Reis, A.R.; Corrêa, R.S. Meta-analysis reveals benefits of co-inoculation of soybean with *Azospirillum brasilense* and *Bradyrhizobium* spp. in Brazil. *Appl. Soil Ecol.* **2021**, *163*, 103913. [CrossRef]

25. Ormeño-Orrillo, E.; Hungria, M.; Martínez-Romero, E. Dinitrogen-fixing prokaryotes. In *The Prokaryotes—Prokaryotic Physiology and Biochemistry*, 4th ed.; Rosemberg, E., De Long, E.F., Lory, S., Stackebrandt, E., Thompson, F., Eds.; Springer: Berlin/Heidelberg, Germany, 2013; pp. 427–451. [CrossRef]

26. Hungria, M.; Nogueira, M.A.; Araujo, R.S. Inoculation of *Brachiaria* spp. with the plant growth-promoting bacterium *Azospirillum brasilense*: An environment-friendly component in the reclamation of degraded pastures in the tropics. *Agric. Ecosyst. Environ.* **2016**, *221*, 125–131. [CrossRef]

27. Hungria, M.; Rondina, A.B.L.; Nunes, A.L.P.; Araujo, R.S.; Nogueira, M.A. Seed and leaf-spray inoculation of PGPR in *Brachiaria* (*Urochloa* spp.) as an economic and environmental opportunity to improve plant growth, forage yield and nutrient status. *Plant Soil* **2021**, *463*, 171–186. [CrossRef]

28. Hungria, M.; Loureiro, M.F.; Mendes, I.C.; Campo, R.J.; Graham, P.H. Inoculant preparation, production and application. In *Nitrogen Fixation in Agriculture, Forestry, Ecology, and the Environment*, 1st ed.; Werner, D., Newton, W.E., Eds.; Springer Science and Business Media LLC: Berlin/Heidelberg, Germany, 2005; pp. 223–253. [CrossRef]

29. Hungria, M.; Nogueira, M.A.; Araujo, R.S. Co-inoculation of soybeans and common beans with rhizobia and azospirilla: Strategies to improve sustainability. *Biol. Fertil. Soils* **2013**, *49*, 791–801. [CrossRef]

30. Martins, G.; Nogueira, W.A.; Gama, T.C.M. Influência da inoculação de *Azospirillum brasiliense* e adubação química nitrogenada no desempenho produtivo de capim braquiária Piatã. *Braz. J. Dev.* **2018**, *7*, 84508–84517. [CrossRef]

31. Fibach-Paldi, S.; Burdman, S.; Okon, Y. Key physiological properties contributing to rhizosphere adaptation and plant growth promotion abilities of *Azospirillum brasilense*. *FEMS Microbiol. Lett.* **2012**, *326*, 99–108. [CrossRef]

32. IPCC, Intergovernmental Panel on Climate Change. *IPCC Guidelines for National Greenhouse Gas Inventories 2006*; IPCC: Geneva, Switzerland, 2006. Available online: https://www.ipcc-nggip.iges.or.jp/public/2006gl/ (accessed on 9 April 2021).

33. de Castro, J.R.P.; Araujo, S. Inoculantes no agro. *AgroAnalysis* **2019**, *39*, 40–41.

34. Ramírez-Guzmán, N.; Chávez-Gonzalez, M.; Sepúlveda-Torre, L.; Torres-Léon, C.; Cintra, A.; Angulo-López, J.; Martínez-Hernández, J.L.; Aguilar, C.N. Significant advances in biopesticide production: Strategies for high-density bio-inoculant cultivation. In *Microbial Services in Restoration Ecology*, 1st ed.; Singh, J.S., Vimal, S.R., Eds.; Elsevier: Amsterdã, Germany, 2020; Volume 1, pp. 1–11. [CrossRef]

35. de Moraes, R.F. Agrotóxicos no Brasil: Padrões de uso, política da regulação e prevenção da captura regulatória. *Econ. Stor.* **2019**, *2596*, 1–85.

36. Warra, A.A.; Prasad, M.N.V. African perspective of chemical usage in agriculture and horticulture—Their impact on human health and environment. In *Agrochemicals Detection, Treatment and Remediation*, 1st ed.; Majeti, N., Vara, P., Eds.; Butterworth-Heinemann: Oxônia, UK, 2020; Volume 1, pp. 401–436. [CrossRef]

37. Fukami, J.; Cerezini, P.; Hungria, M. *Azospirillum*: Benefits that go far beyond biological nitrogen fixation. *AMB Express* **2018**, *8*, 73. [CrossRef]

38. Mariano, R.L.R.; Silveira, E.B.; Assis, S.M.P.; Gomes, A.M.A.; Nascimento, A.R.P.; Donato, V.M.T.S. Importância de bactérias promotoras de crescimento e de biocontrole de doenças de plantas para uma agricultura sustentável. *Anais Acad. Pernambucana Cienc. Agron.* **2013**, *1*, 89–111.

39. Kour, D.; Rana, K.L.; Yadav, A.N.; Yadav, N.; Kumar, M.; Kumar, V.; Vyas, P.D. Microbial biofertilizers: Bioresources and eco-friendly technologies for agricultural and environmental sustainability. *Biocatal. Agric. Biotechnol.* **2019**, *23*, 101487. [CrossRef]

40. Metivier, J.R. Giberelinas. In *Fisiologia Vegetal*, 1st ed.; Ferri, M.G., Ed.; EDUSP: São Paulo, Brazil, 1986; Volume 2, pp. 129–161.

41. Biswas, J.C.; Ladha, J.K.; Dazzo, F.B.; Yanni, Y.G.; Rolfe, B.G.R. Rhizobial inoculation influences seedling vigor and yield of rice. *Agron. J.* **2000**, *92*, 880–886. [CrossRef]

42. Radwan, T.S.D.; Mohamed, Z.K.; Reis, V.M. Aeração e adição de sais na produção de ácido indol acético por bactérias diazotróficas. *Pesq. Agropec. Bras.* **2005**, *40*, 997–1004. [CrossRef]

43. Werner, T.; Schmülling, T. Cytokinin action in plant development. *Curr. Opin. Plant Biol.* **2009**, *12*, 527–538. [CrossRef]

44. Christmann, A.; Moes, D.; Himmelbach, A.; Yang, Y.; Tang, Y.; Grill, E. Integration of abscisic acid signalling into plant responses. *Plant Biol.* **2006**, *8*, 314–325. [CrossRef]

45. Ruůžžičcka, K.; Ljung, K.; Vanneste, S.; Podhorská, R.; Beeckman, T.; Friml, J.; Benková, E. Ethylene regulates root growth through effects on auxin biosynthesis and transport-dependent auxin distribution. *Plant Cell* **2007**, *19*, 2197–2212. [CrossRef]

46. Dimkpa, C.; Weinand, T.; Asch, F. Plant–rhizobacteria interactions alleviate abiotic stress conditions. *Plant Cell Environ.* **2009**, *32*, 1682–1694. [CrossRef]

47. Penrose, D.; Glick, B. Determination of 1-aminocycopropane-1-carboxylic acid (ACC) to assess the effects of ACC deaminase-containing bacteria on roots of canola seedlings. *Can. J. Microbiol.* **2001**, *47*, 77–80. [CrossRef]
48. Diaz-Puentes, L.N. Resistencia sistémica adquirida mediada por el ácido salicílico. *Biotecnol. Sect. Agropec. Agroind* **2012**, *10*, 257–267.
49. Ballaré, C.L. Jasmonate-induced defenses: A tale of intelligence, collaborators and rascals. *Trends Plant Sci.* **2011**, *16*, 249–257. [CrossRef]
50. Pieterse, C.M.; Leon-Reyes, A.; van der Ent, S.; Van Wees, S.C. Networking by small-molecule hormones in plant immunity. *Nat. Chem. Biol.* **2009**, *5*, 308–316. [CrossRef]
51. Siddiqui, M.H.; Al-Whaibi, M.H.; Basalah, M.O. Role of nitric oxide in tolerance of plants to abiotic stress. *Protoplasma* **2011**, *248*, 447–455. [CrossRef]
52. Sahu, A.; Bhattacharjya, S.; Mandal, A.; Thakur, J.K.; Atoliya, N.; Sahu, N.; Manna, M.C.; Patra, A.K. Microbes: A sustainable approach for enhancing nutrient availability in agricultural soils. In *Role of Rhizospheric Microbes in Soil*, 1st ed.; Menna, V.S., Ed.; Springer: Singapore, 2018; Volume 1, pp. 47–75. [CrossRef]
53. Nenwani, V.; Doshi, P.; Saha, T.; Rajkumar, S. Isolation and characterization of a fungal isolate for phosphate solubilization and plant growth promoting activity. *J. Yeast Fungal Res.* **2010**, *1*, 9–14. [CrossRef]
54. Dodor, D.E.; Tabatabai, M.A. Effect of cropping systems on phosphatases in soils. *J. Plant Nutr. Soil Sci.* **2003**, *166*, 7–13. [CrossRef]
55. Yadav, R.; Tarafdar, J. Influence of organic and inorganic phosphorus supply on the maximum secretion of acid phosphatase by plants. *Biol. Fertil. Soils* **2001**, *34*, 140–143. [CrossRef]
56. Masood, S.; Bano, A. Mechanism of potassium solubilization in the agricultural soils by the help of soil microorganisms. In *Potassium Solubilizing Microorganisms for Sustainable Agriculture*, 1st ed.; Meena, V.S., Maurya, B.R., Verma, J.P., Meena, R.S., Eds.; Springer: New Delhi, India, 2016; Volume 1, pp. 137–147. [CrossRef]
57. Vidyalakshmi, R.; Paranthaman, R.; Bhakyaraj, R. Sulphur oxidizing bacteria and pulse nutrition—A review. *World J. Agric. Sci.* **2009**, *5*, 270–278.
58. Esther, J.; Sukla, L.B.; Pradhan, N.; Panda, S. Fe (III) reduction strategies of dissimilatory iron reducing bacteria. *Korean J. Chem. Eng.* **2015**, *32*, 1–14. [CrossRef]
59. Nogueira, M.A.; Nehls, U.; Hampp, R.; Poralla, K.; Cardoso, E.J.B.N. Mycorrhiza and soil bacteria influence extractable iron and manganese in soil and uptake by soybean. *Plant Soil* **2007**, *298*, 273–284. [CrossRef]
60. Coyne, M.S.; Mikkelsen, R.; Mineralization, S. Soil microorganisms contribute to plant nutrition and root health. *Better Crops* **2015**, *99*, 18–20.
61. Goswami, M.; Deka, S. Plant growth-promoting rhizobacteria—Alleviators of abiotic stresses in soil: A review. *Pedosphere* **2020**, *30*, 40–61. [CrossRef]
62. Delaporte-Quintana, P.; Lovaisa, N.C.; Rapisarda, V.A.; Pedraza, R.O. The plant growth promoting bacteria *Gluconacetobacter diazotrophicus* and *Azospirillum brasilense* contribute to the iron nutrition of strawberry plants through siderophores production. *Plant Growth Regul.* **2020**, *91*, 185–199. [CrossRef]
63. Videira, S.S.; Oliveira, D.M.; Morais, R.F.; Borges, W.L.; Baldani, V.L.D.; Baldani, J.I. Genetic diversity and plant growth promoting traits of diazotrophic bacteria isolated from two *Pennisetum purpureum* Schum. genotypes grown in the field. *Plant Soil* **2012**, *356*, 51–66. [CrossRef]
64. Fukami, J.; Nogueira, M.A.; Araujo, R.S.; Hungria, M. Accessing inoculation methods of maize and wheat with *Azospirillum brasilense*. *AMB Express* **2016**, *6*, 414–430. [CrossRef]
65. Garcia, N.F.S.; Arf, O.; Portugal, J.R.; Peres, A.R.; Rodrigues, M.; Penteado, M.d.S. Doses and application methods of *Azospirillum brasilense* in irrigated upland rice. *Rev. Bras. Eng. Agric. Ambient.* **2016**, *20*, 990–995. [CrossRef]
66. Galindo, F.S.; Teixeira Filho, M.C.M.; Buzetti, S.; Pagliari, P.H.; Santini, J.M.K.; Alves, C.J.; Megda, M.M.; Nogueira, T.A.R.; Andreotti, M.; Arf, O. Maize yield response to nitrogen rates and sources associated with *Azospirillum brasilense*. *Agron. J.* **2019**, *111*, 1985–1997. [CrossRef]
67. Guimarães, V.F.; Klein, J.; Ferreira, M.B.; Klein, D.K. Promotion of rice growth and productivity as a result of seed inoculation with *Azospirillum brasilense*. *Afr. J. Agric. Res.* **2020**, *16*, 765–776. [CrossRef]
68. Chibeba, A.M.; Guimarães, M.F.; Brito, O.R.; Araujo, R.S.; Nogueira, M.A.; Hungria, M. Co-inoculation of soybean with *Bradyrhizobium* and *Azospirillum* promotes early nodulation. *Amer. J. Plant Sci.* **2015**, *6*, 1641–1649. [CrossRef]
69. Barbosa, J.Z.; Roberto, L.A.; Hungria, M.; Corrêa, R.S.; Magri, E.; Correia, T.D. Meta-analysis of maize responses to *Azospirillum brasilense* inoculation in Brazil: Benefits and lessons to improve inoculation efficiency. *Appl. Sol. Ecol.* **2022**, *170*, 104276. [CrossRef]
70. Döbereiner, J. Fixação de nitrogênio em gramíneas tropicais. *Interciência* **1979**, *4*, 200–205.
71. Araújo, E.O.; Martins, M.R.; Vitorino, A.C.T.; Mercante, F.M.; Urquiaga, S.S. Effect of nitrogen fertilization associated with diazotrophic bacteria inoculation on nitrogen use efficiency and its biological fixation by corn determined using [15]N. *Afr. J. Microbiol. Res.* **2015**, *9*, 643–650. [CrossRef]
72. Reis, V.M.; dos Reis, F.B., Jr.; Quesada, D.M.; de Oliveira, O.C.; Alves, B.J.; Urquiaga, S.; Boddey, R.M. Biological nitrogen fixation associated with tropical pasture grasses. *Funct. Plant. Biol.* **2001**, *28*, 837–844. [CrossRef]
73. Miranda, C.H.B.; Boddey, R.M. Estimation of biological nitrogen fixation associated with 11 ecotypes of *Panicum maximum* grown in nitrogen-[15]-labeled soil. *Agron. J.* **1987**, *79*, 558–563. [CrossRef]

74. Smith, R.L.; Schank, S.C.; Bouton, J.H.; Quesenberry, K.H. Yield increases of tropical grasses after inoculation with *Spirillum lipoferum*. *Ecol. Bull.* **1978**, *26*, 380–385.

75. Tien, T.M.; Gaskins, M.H.; Hubbel, D.H. Plant growth substances produced by *Azospirillum brasilense* and their effect on the growth of pearl millet (*Pennisetum americanum* L.). *Appl. Environ. Microbiol.* **1979**, *37*, 1016–1024. [CrossRef]

76. Fukami, J.; Ollero, F.J.; Megías, M.; Hungria, M. Phytohormones and induction of plant stress tolerance and defense genes by seed and foliar inoculation with *Azospirillum brasilense* cells and metabolites promote maize growth. *AMB Express* **2017**, *7*, 1–13. [CrossRef]

77. Cerezini, P.; Kuwano, B.H.; Santos, M.B.; Terassi, F.; Hungria, M.; Nogueira, M.A. Strategies to promote early nodulation in soybean under drought. *Field Crop. Res.* **2016**, *196*, 160–167. [CrossRef]

78. Fukami, J.; Ollero, F.J.; De La Osa, C.; Valderrama-Fernández, R.; Nogueira, M.A.; Megías, M.; Hungria, M. Antioxidant activity and induction of mechanisms of resistance to stresses related to the inoculation with *Azospirillum brasilense*. *Arch. Microbiol.* **2018**, *200*, 1191–1203. [CrossRef]

79. Turan, M.; Gulluce, M.; von Wirén, N.; Sahin, F. Yield promotion and phosphorus solubilization by plant growth-promoting rhizobacteria in extensive wheat production in Turkey. *J. Plant Nutr. Soil Sci.* **2012**, *175*, 818–826. [CrossRef]

80. Fallik, E.; Okon, Y.; Epstein, E.; Goldman, A.; Fischer, M. Identification and quantification of IAA and IBA in *Azospirillum brasilense*-inoculated maize roots. *Soil Biol. Biochem.* **1989**, *21*, 147–153. [CrossRef]

81. Rondina, A.B.L.; Sanzovo, A.W.S.; Guimarães, G.S.; Wendling, J.R.; Nogueira, M.A.; Hungria, M. Changes in root morphological traits in soybean co-inoculated with *Bradyrhizobium* spp. and *Azospirillum brasilense* or treated with *A. brasilense* exudates. *Biol. Fertil. Soils* **2020**, *56*, 537–549. [CrossRef]

82. Santos, M.S.; Rondina, A.B.; Nogueira, M.A.; Hungria, M. Compatibility of *Azospirillum brasilense* with pesticides used for treatment of maize seeds. *Int. J. Microbiol.* **2020**, *2020*, 8833879. [CrossRef]

83. Janzen, R.A.; Rood, S.B.; Dormaar, J.F.; McGill, W.B. *Azospirillum brasilense* produces gibberellin in pure culture on chemically-defined medium and in co-culture on straw. *Soil Biol. Biochem.* **1992**, *24*, 1061–1064. [CrossRef]

84. Cohen, A.C.; Travaglia, C.N.; Bottini, R.; Piccoli, P.N. Participation of abscisic acid and gibberellins produced by endophytic *Azospirillum* in the alleviation of drought effects in maize. *Botany* **2009**, *87*, 455–462. [CrossRef]

85. Perrig, D.; Boiero, M.L.; Masciarelli, O.A.; Penna, C.; Ruiz, O.A.; Cassán, F.D.; Luna, M.V. Plant-growth-promoting compounds produced by two agronomically important strains of *Azospirillum brasilense*, and implications for inoculant formulation. *Appl. Microbiol. Biotechnol.* **2007**, *75*, 1143–1150. [CrossRef]

86. Strzelczyk, E.; Kampert, M.; Li, C.Y. Cytokinin-like substances and ethylene production by *Azospirillum* in media with different carbon sources. *Microbiol. Res.* **1994**, *149*, 55–60. [CrossRef]

87. Abbasi, K.; Mir-Mahmoodi, T.; Jalilnezhad, N. Effects of *Azospirillum* bacteria and cytokinin hormone on morphology, yield and yield components of corn (*Zea mays* L.). *Int. J. Biol. Sci.* **2015**, *6*, 378–386. [CrossRef]

88. Day, J.M.; Döbereiner, J. Physiological aspects of N_2-fixation by a *Spirillum* from *Digitaria* roots. *Soil Biol. Biochem.* **1976**, *8*, 45–50. [CrossRef]

89. Caballero-Mellado, J.; Carcano-Montiel, M.G.; Mascarua-Esparza, M.A. Field inoculation of wheat (*Triticum aestivum*) with *Azospirillum brasilense* under temperate climate. *Symbiosis* **1992**, *13*, 243–253.

90. Eskew, D.L.; Focht, D.D.; Ting, I.P. Nitrogen fixation, denitrification, and pleomorphic growth in a highly pigmented *Spirillum lipoferum*. *Appl. Environ. Microbiol.* **1977**, *34*, 582–585. [CrossRef]

91. Pereg, L.; Luz, E.; Bashan, Y. Assessment of affinity and specificity of *Azospirillum* for plants. *Plant Soil* **2015**, *399*, 389–414. [CrossRef]

92. Aguirre, P.F.; Olivo, C.J.; Rodrigues, P.F.; Falk, D.R.; Adams, C.B.; Schiafino, H.P. Forage yield of Coastcross-1 pastures inoculated with *Azospirillum brasilense*. *Acta Sci. Anim. Sci.* **2018**, *40*, e36392. [CrossRef]

93. Leite, R.D.C.; Santos, A.C.D.; Santos, J.G.D.D.; Leite, R.D.C.; Oliveira, L.B.T.D.; Hungria, M. Mitigation of mombasa grass (*Megathyrsus maximus*) dependence on nitrogen fertilization as a function of inoculation with *Azospirillum brasilense*. *Rev. Bras. Cienc. Solo* **2019**, *43*, 1–14. [CrossRef]

94. Rocha, A.F.S.; Costa, R.R.G.F. Desempenho de *Urochloa brizantha* cv Paiaguás inoculada com *Azospirillum brasilense* e diferentes doses nitrogênio. *Glob. Sci. Technol.* **2018**, *11*, 177–186.

95. Heinrichs, R.; Meirelles, G.C.; Santos, L.P.M.; Lira, M.C.S.; Lapaz, A.M.; Nogueira, M.A.; Bonini, C.S.B.; Soares Filho, C.V.; Moreira, A. *Azospirillum* inoculation of 'Marandu' palisade grass seeds: Effects on forage production and nutritional status. *Semina. Cienc. Agrar.* **2020**, *41*, 465–478. [CrossRef]

96. Duarte, C.F.D.; Cecato, U.; Hungria, M.; Fernandes, H.J.; Biserra, T.T.; Galbeiro, S.; Toniato, A.K.B.; Silva, D.R. Morphogenetic and structural characteristics of *Urochloa* species under inoculation with plant growth-promoting bacteria and nitrogen fertilization. *Crop Pasture Sci.* **2020**, *71*, 82–89. [CrossRef]

97. David, B.V.; Chandrasehar, G.; Selvam, P.N. Pseudomonas fluorescens: A plant-growth-promoting rhizobacterium (PGPR) with potential role in biocontrol of pests of crops. In *New and Future Developments in Microbial Bbiotechnology and Bioengineering: Crop Improvement through Microbial Biotechnology*, 1st ed.; Prasad, R., Gill, S.S., Tuteja, N., Eds.; Elsevier: Nova Deli, India, 2018; Volume 1, pp. 221–243. [CrossRef]

98. Prasad, R.; Kumar, M.; Varma, A. Role of PGPR in soil fertility and plant health. In *Plant Growth-Promoting Rhizobacteria (PGPR) and Medicinal Plants*, 1st ed.; Egamberdieva, D., Shrivastava, S., Varma, A., Eds.; Springer: Cham, Switzerland, 2015; Volume 42, pp. 247–260. [CrossRef]

99. Kumar, V.; Menon, S.; Agarwal, H.; Gopalakrishnan, D. Characterization and optimization of bacterium isolated from soil samples for the production of siderophores. *Resour.-Effic. Technol.* **2017**, *4*, 434–439. [CrossRef]

100. Hesse, E.; O'brien, S.; Tromas, N.; Bayer, F.; Luján, A.M.; Veen, E.M.; Hodgson, D.J.; Buckling, A. Ecological selection of siderophore producing microbial taxa in response to heavy metal contamination. *Ecol. Lett.* **2018**, *21*, 117–127. [CrossRef]

101. Rodriguez, F.; Pfender, W.F. Antibiosis and antagonism of *Sclerotinia homoeocarpa* and *Drechslera poae* by *Pseudomonas fluorescens* Pf-5 in vitro and in planta. *Phytopathology* **1997**, *87*, 614–621. [CrossRef]

102. Khan, M.S.; Zaidi, A.; Ahemad, M.; Oves, M.; Wani, P.A. Plant growth promotion by phosphate solubilizing fungi—Current perspective. *Arch. Agron. Soil Sci.* **2010**, *56*, 73–98. [CrossRef]

103. Zhu, J.; Li, M.; Whelan, M. Phosphorus activators contribute to legacy phosphorus availability in agricultural soils: A review. *Sci. Total. Environ.* **2018**, *612*, 522–537. [CrossRef]

104. Kaur, G.; Reddy, M.S. Effects of phosphate-solubilizing bacteria, rock phosphate and chemical fertilizers on maize-wheat cropping cycle and economics. *Pedosphere* **2015**, *25*, 428–437. [CrossRef]

105. Nishimori, E.; Kita-Tsukamoto, K.; Wakabayashi, H. *Pseudomonas plecoglossicida* sp. nov. the causative agent of bacterial haemorrhagic ascites of ayu, *Plecoglossus altivelis*. *Int. J. Syst. Evol. Microbiol.* **2000**, *50*, 83–89. [CrossRef]

106. Castanheira, N.; Dourado, A.C.; Kruz, S.; Alves, P.I.L.; Delgado-Rodríguez, A.I.; Pais, I.; Semedo, J.; Scotti-Campos, P.; Sánchez, C.; Borges, N.; et al. Plant growth-promoting *Burkholderia* species isolated from annual ryegrass in Portuguese soils. *J. Appl. Microbiol.* **2016**, *120*, 724–739. [CrossRef]

107. Lopes, M.J.S.; Dias-Filho, M.B.; Castro, T.H.R.; Gurgel, E.S.C.; da Silva, G.B. Efficiency of biostimulants for alleviating shade effects on forage grass. *J. Agric. Studies* **2021**, *9*, 14–30. [CrossRef]

108. Lopes, M.J.S.; Dias-Filho, M.B.; Castro, T.H.R.; Silva, G.B. Light and plant growth-promoting rhizobacteria effects on *Brachiaria brizantha* growth and phenotypic plasticity to shade. *Grass Forage Sci.* **2017**, *73*, 493–499. [CrossRef]

109. Begum, N.; Afzal, S.; Zhao, H.; Lou, L.; Cai, Q. Shoot endophytic plant growth-promoting bacteria reduce cadmium toxicity and enhance switchgrass (*Panicum virgatum* L.) biomass. *Acta Physiol. Plant.* **2018**, *40*, 170. [CrossRef]

110. Sá, G.C.R.; Hungria, M.; Carvalho, C.L.M.; Moreira, A.; Nogueira, M.A.; Heinrichs, R.; Soares Filho, C.V. Nutrients uptake in shoots and biomass yields and roots and nutritive values of Zuri Guinea grass inoculated with plant growth-promoting bacteria. *Commun. Soil Sci. Plant Anal.* **2019**, *50*, 2927–2940. [CrossRef]

111. Sá, G.C.R.; Carvalho, C.L.M.; Moreira, A.; Hungria, M.; Nogueira, M.A.; Heinrichs, R.; Soares Filho, C.V. Biomass yield, nitrogen accumulation and nutritive value of Mavuno grass inoculated with plant growth-promoting bacteria. *Commun. Soil Sci. Plant Anal.* **2019**, *50*, 1931–1942. [CrossRef]

112. Frey-Klett, P.; Garbaye, J.; Tarkka, M. The mycorrhiza helper bacteria revisited. *New Phytol.* **2007**, *176*, 22–36. [CrossRef]

113. Zangaro, W.; Rondina, A.B.L. Arbuscular mycorrhizas in different successional stages in some Brazilian ecosystems. In *Recent Advances on Mycorrhizal Fungi*, 1st ed.; Pagano, M.C., Ed.; Springer: Cham, Switzerland, 2016; Volume 1, pp. 47–62. [CrossRef]

114. Zangaro, W.; Lescano, L.E.A.M.; Matsuura, E.M.; Rondina, A.B.L.; Nogueira, M.A. Interactions between arbuscular mycorrhizal fungi and exotic grasses differentially affect the establishment of seedlings of early-and late-successional woody species. *Appl. Soil Ecol.* **2018**, *124*, 394–406. [CrossRef]

115. Rondina, A.B.L.; Tonon, B.C.; Lescano, L.E.A.M.; Hungria, M.; Nogueira, M.A.; Zangaro, W. Plants of distinct successional stages have different strategies for nutrient acquisition in an Atlantic Rain Forest ecosystem. *Int. J. Plant. Sci.* **2019**, *180*, 186–199. [CrossRef]

116. Govindasamy, V.; Senthilkumar, M.; Magheshwaran, V.; Kumar, U.; Bose, P.; Sharma, V.; Annapurna, K. Bacillus and *Paenibacillus* spp.: Potential PGPR for sustainable agriculture. In *Plant Growth and Health Promoting Bacteria*, 1st ed.; Maheshwari, D., Ed.; Springer: Berlin/Heidelberg, Germany, 2010; Volume 18, pp. 333–364. [CrossRef]

117. Gurung, N.; Ray, S.; Bose, S.; Rai, V. A broader view: Microbial enzymes and their relevance in industries, medicine, and beyond. *BioMed Res. Int.* **2013**, *2013*, 329121. [CrossRef]

118. Araujo, F.F.; Guaberto, L.M.; Silva, I.F. Bioprospecção de bactérias promotoras de crescimento em *Brachiaria brizantha*. *Rev. Bras. Zootec.* **2012**, *41*, 521–527. [CrossRef]

119. Lima, F.F.; Nunes, L.A.; Figueiredo, M.; de Araújo, F.F.; Lima, L.M.; de Araújo, A.S. Effect of *Bacillus subtilis* inoculation and nitrogen fertilization on maize yield. *Rev. Bras. Ciênc. Agrar.* **2011**, *6*, 657–661. [CrossRef]

120. Ribeiro, V.P.; Marriel, I.E.; Sousa, S.M.; Lana, U.G.P.; Mattos, B.B.; Oliveira, C.A.; Gomes, E.A. Endophytic *Bacillus* strains enhance pearl millet growth and nutrient uptake in low-P. *Braz. J. Microbiol.* **2018**, *49*, 40–46. [CrossRef]

121. Gupta, R.S.; Patel, S.; Saini, N.; Chen, S. Robust demarcation of 17 distinct *Bacillus* species clades, proposed as novel *Bacillaceae* genera, by phylogenomics and comparative genomic analyses: Description of *Robertmurraya kyonggiensis* sp. nov. and proposal for an emended genus *Bacillus* limiting it only to the members of the *subtilis* and *cereus* clades of species. *Int. J. Syst. Evol. Microbiol.* **2020**, *70*, 5753–5798. [CrossRef]

122. Bhattacharyya, P.N.; Jha, D.K. Plant growth-promoting rhizobacteria (PGPR): Emergence in agriculture. *World J. Microbiol. Biotechnol.* **2012**, *28*, 1327–1350. [CrossRef]

123. Sharma, S.B.; Sayyed, R.Z.; Trived, M.H.; Gobi, T.A. Phosphate solubilizing microbes: Sustainable approach for managing phosphorus deficiency in agricultural soils. *SpringerPlus* **2013**, *2*, 587. [CrossRef]

124. Hussain, A.; Arshad, M.; Zahir, Z.A.; Asghar, M. Prospects of zinc solubilizing bacteria for enhancing growth of maize. *Pak. J. Agric. Sci.* **2015**, *52*, 915–922. [CrossRef]

125. Basak, B.B.; Biswas, D.R. Influence of potassium solubilizing microorganism (*Bacillus mucilaginosus*) and waste mica on potassium uptake dynamics by sudan grass (*Sorghum vulgare* Pers.) grown under two Alfisols. *Plant Soil* **2009**, *317*, 235–255. [CrossRef]

126. Saxena, A.K.; Kumar, M.; Chakdar, H.; Anuroopa, N.; Bagyaraj, D.J. *Bacillus* species in soil as a natural resource for plant health and nutrition. *J. Appl. Microbiol.* **2020**, *128*, 1583–1594. [CrossRef]

127. Kundan, R.; Pant, G.; Jadon, N.; Agrawal, P.K. Plant growth promoting rhizobacteria: Mechanism and current prospective. *J. Fertil. Pestic.* **2015**, *6*, 9. [CrossRef]

128. Park, Y.G.; Mun, B.G.; Kang, S.M.; Hussain, A.; Shahzad, R.; Seo, C.W.; Kim, A.Y.; Lee, S.U.; Oh, K.Y.; Lee, D.Y.; et al. *Bacillus aryabhattai* SRB02 tolerates oxidative and nitrosative stress and promotes the growth of soybean by modulating the production of phytohormones. *PLoS ONE* **2017**, *12*, e0173203. [CrossRef]

129. Chinnaswamy, A.; Coba De La Peña, T.; Stoll, A.; De La Peña Rojo, D.; Bravo, J.; Rincón, A.; Lucas, M.M.; Pueyo, J.J. A nodule endophytic *Bacillus megaterium* strain isolated from *Medicago polymorpha* enhances growth, promotes nodulation by *Ensifer medicae* and alleviates salt stress in alfalfa plants. *Ann. Appl. Biol.* **2018**, *172*, 295–308. [CrossRef]

130. Awasthi, S.; Srivastava, P.; Mishra, P.K. Application of EPS in agriculture: An important natural resource for crop improvement. *Agric. Res. Technol.* **2017**, *8*, 22–24. [CrossRef]

131. Tiwari, S.; Lata, C. Heavy metal stress, signaling, and tolerance due to plant- associated microbes: An overview. *Front. Plant Sci.* **2018**, *9*, 452. [CrossRef]

132. Jiang, C.; Li, Z.; Shi, Y.; Guo, D.; Pang, B.; Chen, X.; Shao, D.; Liu, Y.; Shi, J. *Bacillus subtilis* inhibits *Aspergillus carbonarius* by producing iturin A, which disturbs the transport, energy metabolism, and osmotic pressure of fungal cells as revealed by transcriptomics analysis. *Int. J. Food Microbiol.* **2020**, *330*, 108783. [CrossRef]

133. Araujo, F.F.; Henning, A.A.; Hungria, M. Phytohormones and antibiotics produced by *Bacillus subtilis* and their effects on seed pathogenic fungi and on soybean root development. *World J. Microbiol. Biotechnol.* **2005**, *21*, 1639–1645. [CrossRef]

134. Hanif, A.; Zhang, F.; Li, P.; Li, C.; Xu, Y.; Zubair, M.; Zhang, M.; Jia, D.; Zhao, X.; Liang, J.; et al. Fengycin produced by *Bacillus amyloliquefaciens* FZB42 inhibits *Fusarium graminearum* growth and mycotoxins biosynthesis. *Toxins* **2019**, *11*, 295. [CrossRef]

135. Hong, T.Y.; Meng, M. Biochemical characterization and antifungal activity of an endo-1, 3-β-glucanase of *Paenibacillus* sp. isolated from garden soil. *Appl. Microbiol. Biotechnol.* **2003**, *61*, 472–478. [CrossRef]

136. Agarwal, M.; Dheeman, S.; Dubey, R.C.; Kumar, P.; Maheshwari, D.K.; Bajpai, V.K. Differential antagonistic responses of *Bacillus pumilus* MSUA3 against *Rhizoctonia solani* and *Fusarium oxysporum* causing fungal diseases in *Fagopyrum esculentum* Moench. *Microbiol. Res.* **2017**, *205*, 40–47. [CrossRef]

137. El-Bendary, M.A.; Hamed, H.A.; Moharam, M.E. Potential of *Bacillus* isolates as bio-control agents against some fungal phytopathogens. *Biocatal. Agric. Biotechnol.* **2016**, *5*, 173–178. [CrossRef]

138. Theunissen, B. The beginnings of the "Delft Tradition" revisited: Martinus, W. Beijerinck and the genetics of microorganisms. *J. Hist. Biol.* **1996**, *29*, 197–228. [CrossRef]

139. Verma, R.; Annapragada, H.; Katiyar, N.; Shrutika, N.; Das, K.; Murugesan, S. Rhizobium. In *Beneficial Microbes in Agro-Ecology*, 1st ed.; Amaresan, N., Annapurna, K., Sankaranarayanan, A., Kumar Senthil, M., Kumar, K., Eds.; Academic Press: Cambridge, MA, USA, 2020; Volume 1, pp. 37–54. [CrossRef]

140. Deubel, A.; Merbach, W. Influence of microorganisms on phosphorus bioavailability in soils. In *Microorganisms in Soils: Roles in Genesis and Function*, 1st ed.; Buscot, F., Varma, A., Eds.; Springer: Berlin, Germany, 2005; Volume 3, pp. 177–191. [CrossRef]

141. Silva, F.B.; Winck, B.; Borges, C.S.; Santos, F.L.; Bataiolli, R.D.; Backes, T.; Bassani, V.L.; Borin, J.B.M.; Frazzon, A.P.G.; Sá, E.L.S. Native rhizobia from southern Brazilian grassland promote the growth of grasses. *Rhizosphere* **2020**, *16*, 100240. [CrossRef]

142. Atzorn, R.; Crozier, A.; Wheeler, C.T.; Sandberg, G. Production of gibberellins and indole-3-acetic acid by *Rhizobium phaseoli* in relation to nodulation of *Phaseolus vulgaris* roots. *Planta* **1988**, *175*, 532–538. [CrossRef]

143. Upadhyaya, N.M.; Parker, C.W.; Letham, D.S.; Scott, K.F.; Dart, P.J. Evidence for cytokinin involvement in *Rhizobium* (IC3342)-induced leaf curl syndrome of pigeonpea (*Cajanus cajan* Millsp.). *Plant Physiol.* **1991**, *95*, 1019–1025. [CrossRef]

144. Machado, R.G.; Sá, E.L.S.; Bruxel, M.; Giongo, A.; Santos, S.N.; Nunes, A.S. Indoleacetic acid producing rhizobia promote growth of tanzania grass (*Panicum maximum*) and Pensacola grass (*Paspalum saurae*). *Int. J. Agric. Biol.* **2013**, *15*, 827–834.

145. Noel, T.C.; Sheng, C.; Yost, C.K.; Pharis, R.P.; Hynes, M.F. *Rhizobium leguminosarum* as a plant growth-promoting rhizobacterium: Direct growth promotion of canola and lettuce. *Can. J. Microbiol.* **1996**, *42*, 279–283. [CrossRef]

146. Souleimanov, A.; Prithiviraj, B.; Smith, D.L. The major Nod factor of *Bradyrhizobium japonicum* promotes early growth of soybean and corn. *J. Exp. Bot.* **2002**, *53*, 1929–1934. [CrossRef]

147. Marks, B.B.; Megías, M.; Nogueira, M.A.; Hungria, M. Biotechnological potential of rhizobial metabolites to enhance the performance of *Bradyrhizobium japonicum* and *Azospirillum brasilense* inoculants with the soybean and maize crops. *AMB Express* **2013**, *3*, 21. [CrossRef]

148. Marks, B.B.; Megías, M.; Ollero, F.J.; Nogueira, M.A.; Araujo, R.S.; Hungria, M. Maize growth promotion by inoculation with *Azospirillum brasilense* and metabolites of *Rhizobium tropici* CIAT 899 enriched on lipo-chitooligossacharides (LCOs). *AMB Express* **2015**, *5*, 71. [CrossRef]

149. Phillips, D.A.; Joseph, C.M.; Yang, G.P.; Martínez-Romero, E.; Sanborn, J.R.; Volpin, H. Identification of lumichrome as a *Sinorhizobium* enhancer of alfalfa root respiration and shoot growth. *Proc. Natl. Acad. Sci. USA* **1999**, *96*, 12275–12280. [CrossRef]

150. Matiru, V.N.; Dakora, F.D. Potencial use of rhizobial bacteria as promoters of plant growth for increased yield in landraces of African cereal crops. *Afr. J. Biotechnol.* **2004**, *3*, 1–7. [CrossRef]

151. Khan, W.; Prithiviraj, B.; Smith, D.L. Nod factor [Nod Bj V (C18:1, MeFuc)] and lumichrome enhance photosynthesis and growth of corn and soybean. *J. Plant Physiol.* **2008**, *165*, 1342–1351. [CrossRef]

152. Staudt, A.K.; Wolfe, L.G.; Shrout, J.D. Variations in exopolysaccharide production by *Rhizobium tropici*. *Arch. Microbiol.* **2011**, *194*, 197–206. [CrossRef]

153. Plett, J.M.; Solomon, J.; Snijders, F.; Marlow-Conway, J.; Plett, K.L.; Bithell, S.L. Order of microbial succession affects rhizobia-mediated biocontrol efforts against *Phytophthora* root rot. *Microbiol. Res.* **2021**, *242*, 126628. [CrossRef]

154. Jemai, N.; Gargouri, S.; Hemissi, I.; Ben Mahmoud, K.; Ksouri, M.F.; Jemmali, A. *Rhizoctonia solani* affecting micropropagated Garnem (*Prunus amygdalus* × *Prunus persica*) rootstock-characterization and biocontrol with *Rhizobia*. *J. Plant Pathol.* **2021**, *103*, 207–215. [CrossRef]

155. Smith, S.E.; Read, D.J. *Mycorrhizal Symbiosis*, 3rd ed.; Academic Press: London, UK, 2008; pp. 1–769. ISBN 978-0-12-370526-6.

156. Wehner, J.; Antunes, P.M.; Powell, J.R.; Mazukatow, J.; Rillig, M.C. Plant pathogen protection by arbuscular mycorrhizas: A role for fungal diversity? *Pedobiologia* **2010**, *53*, 197–201. [CrossRef]

157. Augé, R.M. Water relations, drought and vesicular-arbuscular mycorrhizal symbiosis. *Mycorrhiza* **2001**, *11*, 3–42. [CrossRef]

158. Zou, Y.N.; Wu, Q.S.; Kuča, K. Unravelling the role of arbuscular mycorrhizal fungi in mitigating the oxidative burst of plants under drought stress. *Plant Biol.* **2021**, *23*, 50–55. [CrossRef]

159. Riaz, M.; Kamran, M.; Fang, Y.; Wang, Q.; Cao, H.; Yang, G.; Deng, L.; Wang, Y.; Zhou, Y.; Anastopoulos, I.; et al. Arbuscular mycorrhizal fungi-induced mitigation of heavy metal phytotoxicity in metal contaminated soils: A critical review. *J. Hazard. Mater.* **2021**, *402*, 123919. [CrossRef] [PubMed]

160. Marschner, H.; Dell, B. Nutrient uptake in mycorrhizal symbiosis. *Plant Soil* **1994**, *59*, 89–102. [CrossRef]

161. Smith, S.E.; Smith, F.A. Roles of arbuscular mycorrhizas in plant nutrition and growth: New paradigms from cellular to ecosystem scales. *Annu. Rev. Plant Biol.* **2011**, *62*, 227–250. [CrossRef]

162. Smith, S.E.; Jakobsen, I.; Grølund, M.; Smith, F.A. Roles of arbuscular mycorrhizas in plant phosphorus nutrition: Interactions between pathways of phosphorus uptake in arbuscular mycorrhizal roots have important implications for understanding and manipulating plant phosphorus acquisition. *Plant Physiol.* **2011**, *156*, 1050–1057. [CrossRef]

163. Clark, R.B.; Zeto, S.K. Mineral acquisition by arbuscular mycorrhizal plants. *J. Plant Nutr.* **2000**, *23*, 867–902. [CrossRef]

164. Lehmann, A.; Veresoglou, S.D.; Leifheit, E.F.; Rillig, M.C. Arbuscular mycorrhizal influence on zinc nutrition in crop plants—A meta-analysis. *Soil Biol. Biochem.* **2014**, *69*, 123–131. [CrossRef]

165. Rondina, A.B.L.; Lescano, L.E.A.M.; Alves, R.A.; Matsuura, E.M.; Nogueira, M.A.; Zangaro, W. Arbuscular mycorrhizas increase survival, precocity and fowering of herbaceous and shrubby species of early stages of tropical succession in pot cultivation. *J. Trop. Ecol.* **2014**, *30*, 599–614. [CrossRef]

166. Lehmann, A.; Rillig, M.C. Arbuscular mycorrhizal contribution to copper, manganese and iron nutrient concentrations in crops—A meta-analysis. *Soil Biol. Biochem.* **2015**, *81*, 147–158. [CrossRef]

167. Qiu, Q.; Bender, S.F.; Mgelwa, A.S.; Hu, Y. Arbuscular mycorrhizal fungi mitigate soil nitrogen and phosphorus losses: A meta-analysis. *Sci. Total Environ.* **2022**, *807*, 150857. [CrossRef]

168. van der Heijden, M.G.A.; Boller, T.; Wiemken, A.; Sanders, I.R. Different arbuscular mycorrhizal fungal species are potential determinants of plant community structure. *Ecology* **1998**, *79*, 2082–2091. [CrossRef]

169. Leifheit, E.F.; Veresiglou, S.D.; Lehmann, A.; Morris, E.K.; Rillig, M.C. Multiple factors influence the role of arbuscular mycorrhizal fungi in soil aggregation—A meta-analysis. *Plant Soil* **2014**, *374*, 523–537. [CrossRef]

170. Cavagnaro, T.R.; Bender, S.F.; Asghari, H.R.; van der Heijden, M.G.A. The role of arbuscular mycorrhizas in reducing soil nutrient loss. *Trends Plant Sci.* **2015**, *20*, 283–290. [CrossRef] [PubMed]

171. Santos, A.; Silva, C.F.; Gama-Rodrigues, E.F.; Gama-Rodrigues, A.C.; Sales, M.; Faustino, L.L.; Barreto-Garcia, P.A.B. Glomalin in soil aggregates under different forest and pasture systems in the North of Rio de Janeiro state, Brazil. *Environ. Sustain. Indic.* **2020**, *8*, 100088. [CrossRef]

172. Schüβler, A.; Schwaezott, D.; Walker, C. A new fungal phylum, the *Glomeromycota*: Phylogeny and evolution. *Mycol. Res.* **2001**, *105*, 1413–1421. [CrossRef]

173. Kiers, E.T.; Duhamel, M.; Beestty, Y.; Mensah, J.A.; Franken, O.; Verbruggen, E.; Fellbaum, C.R.; Kowalchuk, G.A.; Hart, M.M.; Bago, A.; et al. Reciprocal rewards stabilize cooperation in the mycorrhizal symbiosis. *Science* **2011**, *333*, 880–882. [CrossRef]

174. Lynch, J.P.; Ho, M.D. Rhizoeconomics: Carbon costs of phosphorus acquisition. *Plant Soil* **2005**, *269*, 45–56. [CrossRef]

175. Kanno, T.; Saito, M.; Ando, Y.; Macedo, M.C.M.; Nakamura, T.; Miranda, C.H.B. Importance of indigenous arbuscular mycorrhiza for growth and phosphorus uptake in tropical forage grasses growing on an acid, infertile soil from the Brazilian savannas. *Trop. Grassl.* **2006**, *40*, 94–101.

176. Cavagnaro, R.A.; Oyarzabal, M.; Oesterheld, M.; Grimoldi, A.A. Screening of biomass production of cultivated forage grasses in response to mycorrhizal symbiosis under nutritional deficit conditions. *Grassl. Sci.* **2014**, *60*, 178–184. [CrossRef]

177. Teutscherova, N.; Vazquez, E.; Arevalo, A.; Pulleman, M.; Rao, I.; Arango, J. Differences in arbuscular mycorrhizal colonization and P acquisition between genotypes of the tropical *Brachiaria* grasses: Is there a relation with BNI activity? *Biol. Fertil. Soils* **2019**, *55*, 325–337. [CrossRef]

178. Zangaro, W.; Alves, R.A.; Lescano, L.E.; Ansanelo, A.P.; Nogueira, M.A. Investment in fine roots and arbuscular mycorrhizal fungi decrease during succession in three Brazilian ecosystems. *Biotropica* **2012**, *44*, 141–150. [CrossRef]

179. Zangaro, W.; Rostirola, L.V.; Souza, P.B.; Alves, R.A.; Lescano, L.E.A.M.; Rondina, A.B.L.; Nogueira, M.A.; Carrenho, R. Root colonization and spore abundance of arbuscular mycorrhizal fungi in distinct successional stages from an Atlantic rainforest biome in southern Brazil. *Mycorrhiza* **2013**, *23*, 221–233. [CrossRef] [PubMed]

180. Zangaro, W.; Alves, R.A.; Souza, P.B.; Rostirola, L.V.; Lescano, L.E.A.M.; Rondina, A.B.L.; Nogueira, M.A. Succession and environmental variation influence soil exploration potential by fine roots and mycorrhizal fungi in an Atlantic ecosystem in southern Brazil. *J. Trop. Ecol.* **2014**, *30*, 237–248. [CrossRef]

181. Ramos, M.L.G.; Konrad, M.D.F.; Silva, D.E.; Ribeiro Junior, W.Q.; Batista, L.M.T. Mycorrhizal fungus diversity and radicular colonization, on single and consorciation with maize. *Biosci. J.* **2012**, *28*, 235–244.

182. Moraes, J.M.A.S.; Zanchi, C.S.; Pires, G.C.; Moretti, C.F.; Barbosa, M.V.; Silva, A.O.; Pacheco, L.P.; Carneiro, M.A.C.; Oliveira, R.L.; Kemmelmeier, K.; et al. Arbuscular mycorrhizal fungi in integrated crop livestock systems with intercropping in the pasture phase in the Cerrado. *Rhizosphere* **2019**, *11*, 100165. [CrossRef]

183. Pires, G.C.; Lima, M.E.; Zanchi, C.S.; Freitas, C.M.; Souza, J.M.A.; Camargo, T.A.; Pacheco, L.P.; Wruck, F.J.; Carneiro, M.A.C.; Kemmelmeier, K.; et al. Arbuscular mycorrhizal fungi in the rhizosphere of soybean in integrated crop livestock system with intercropping in the pasture phase. *Rhizosphere* **2021**, *17*, 100270. [CrossRef]

184. Stürmer, S.L.; Siqueira, J.O. Species richness and spore abundance of arbuscular mycorrhizal fungi across distinct land uses in Western Brazilian Amazon. *Mycorrhiza* **2011**, *21*, 255–267. [CrossRef]

185. Rubin, J.G.K.R.; Stürmer, S.L. Potencial de inóculo micorrízico e importância do comprimento do micélio para a agregação de solos de ambiente fluvial. *Rev. Bras. Cienc. Solo* **2015**, *39*, 59–68. [CrossRef]

186. Posada, R.H.; Franco, L.A.; Ramos, C.; Plazas, L.S.; Suárez, J.C.; Álvarez, F. Effect of physical, chemical and environmental characteristics on arbuscular mycorrhizal fungi in *Brachiaria decumbens* (Stapf) pastures. *J. Appl. Microbiol.* **2008**, *104*, 132–140. [CrossRef]

187. Johnson, N.C.; Miller, R.M.; Wilson, G.W.T. Mycorrhizal interactions with climate, soil parent material and topography. In *Mycorrhizal Mediation of Soil: Fertility, Structure and Carbon Storage*, 1st ed.; Johnson, N.C., Gehring, C., Jansa, J., Eds.; Elsevier: Amsterdam, Germany, 2017; Volume 1, pp. 47–66. [CrossRef]

188. Corazza, E.J.; Brossard, M.; Muraoka, T.; Coelho-Filho, M.A. Spatial variability of soil phosphorus of a low productivity *Brachiaria brizantha* pasture. *Sci. Agric.* **2003**, *60*, 559–564. [CrossRef]

189. Oliveira, O.C.; Oliveira, I.P.; Alves, B.J.R.; Urquiaga, S.; Boddey, R.M. Chemical and biological indicators of decline/degradation of *Brachiaria* pastures in the Brazilian Cerrado. *Agric. Ecosyst. Environ.* **2004**, *103*, 289–300. [CrossRef]

190. Oliveira, L.B.; Tiecher, T.; Quadros, F.L.F.; Trindade, J.P.P.; Gatiboni, L.C.; Brunetto, G.; Santos, D.R. Formas de fósforo no solo sob pastagens naturais submetidas à adição de fosfatos. *Rev. Bras. Cienc. Solo* **2014**, *38*, 867–878. [CrossRef]

191. Dias-filho, M.B. Os desafios da produção animal em pastagens na fronteira agrícola brasileira. *Rev. Bras. Zootec.* **2011**, *40*, 243–252.

192. Cavagnaro, R.A.; Oyarzabal, M.; Oesterheld, M.; Grimoldi, A.A. Species-specific trade-offs between regrowth and mycorrhizas in the face of defoliation and phosphorus addition. *Fungal Ecol.* **2021**, *51*, 101058. [CrossRef]

193. Koide, R.T. Nutrient supply, nutrient demand and plant response to mycorrhizal infection. *New Phytol.* **1991**, *117*, 365–386. [CrossRef]

194. Koide, R.T. Mycorrhizal symbiosis and plant reproduction. In *Arbuscular Mycorrhizas: Physiology and Function*, 1st ed.; Koltai, H., Kapulnik, Y., Eds.; Springer: Dordrecht, The Netherlands, 2010; Volume 1, pp. 297–320. [CrossRef]

195. Johnson, N.C.; Graham, J.H.; Smith, F.A. Functioning of mycorrhizal associations along the mutualism-parasitism continuum. *New Phytol.* **1997**, *35*, 575–585. [CrossRef]

196. Graham, J.H.; Abbott, L.K. Wheat responses to aggressive and nonaggressive arbuscular mycorrhizal fungi. *Plant Soil* **2000**, *220*, 207–218. [CrossRef]

197. Ryan, M.H.; van Herwaarden, A.F.; Angus, J.F.; Kirkegaard, J.A. Reduced growth of autumn-sown wheat in a low-P is associated with high colonization by arbuscular mycorrhizal fungi. *Plant Soil* **2005**, *270*, 275–286. [CrossRef]

198. Klironomos, J.N. Variation in plant response to native and exotic arbuscular mycorrhizal fungi. *Ecology* **2003**, *84*, 2292–2301. [CrossRef]

199. Basiru, S.; Mwanza, H.P.; Hijri, M. Analysis of arbuscular mycorrhizal fungal inoculant benchmarks. *Microorganisms* **2021**, *9*, 81. [CrossRef] [PubMed]

200. Srivastava, S.; Johny, L.; Adholeya, A. Review of patents for agricultural use of arbuscular mycorrhizal fungi. *Mycorrhiza* **2021**, *31*, 127–136. [CrossRef]

201. Islam, M.N.; Germida, J.J.; Walley, F.L. Survival of a commercial AM fungal inoculant and its impact on indigenous AM fungal communities in field soils. *Appl. Soil Ecol.* **2021**, *166*, 103979. [CrossRef]

202. Messa, V.R.; Savioli, M.R. Improving sustainable agriculture with arbuscular mycorrhizae. *Rhizosphere* **2021**, *19*, 100412. [CrossRef]

203. Stoffel, S.C.G.; Soares, C.R.F.S.; Meyer, E.; Lovato, P.E.; Gianchini, A.J. Yield increase of corn inoculated with a commercial arbuscular mycorrhizal inoculant in Brazil. *Cienc. Rural* **2020**, *50*, 1–10. [CrossRef]

204. Stoffel, S.C.G.; Soares, C.R.F.S.; Meyer, E.; Lovato, P.E.; Gianchini, A.J. Yield increase of soybean inoculated with a commercial arbuscular mycorrhizal inoculant in Brazil. *Afr. J. Agric. Res.* **2020**, *16*, 702–713. [CrossRef]

205. Cely, M.V.T.; Oliveira, A.G.; Freitas, V.F.; Luca, M.B.; Barazetti, A.R.; Santos, I.M.O.; Gionco, B.; Garcia, G.V.; Prete, C.E.C.; Andrade, G. Inoculant of arbuscular mycorrhizal fungi (*Rhizophagus clarus*) increase yield of soybean and cotton under field conditions. *Front. Microbiol.* **2016**, *7*, 720. [CrossRef]

206. Barazetti, A.R.; Simionato, A.S.; Navarro, M.O.P.; Santos, I.M.O.; Modolon, F.; Andreata, M.F.L.; Liuti, G.; Cely, M.V.T.; Chryssafidis, A.L.; Dealis, M.L.; et al. Formulations of arbuscular mycorrhizal fungi inoculum applied to soybean and corn plants under controlled and field conditions. *Appl. Soil Ecol.* **2019**, *142*, 25–33. [CrossRef]

207. Leite, R.C.; Santos, J.G.D.; Silva, E.L.; Alves, C.R.C.R.; Hungria, M.; Leite, R.C.; Santos, A.C. Productivity increase, reduction of nitrogen fertiliser use and drought-stress mitigation by inoculation of Marandu grass (*Urochloa brizantha*) with *Azospirillum brasilense*. *Crop Pasture Sci.* **2018**, *70*, 61–67. [CrossRef]

208. Manrique, A.E.R.; Mazzuchelli, R.D.C.L.; Araujo, A.S.F.; Araujo, F.F.D. Conditioning and coating of *Urochloa brizantha* seeds associated with inoculation of *Bacillus subtilis*. *Pesq. Agropec. Trop.* **2019**, *49*, 1–8. [CrossRef]

209. Costa, N.L.; Paulino, V.T.; Costa, R.S.C.; Pereira, R.G.D.; Townsend, C.R.; Magalhães, J.A. Efeito de micorrizas arbusculares sobre o crescimento e nutrição mineral de *Brachiaria brizantha* cv. Marandu. *Cienc. Anim. Bras.* **2012**, *13*, 406–411. [CrossRef]

210. Sales, L.R.; Silva, G.N.D.; Siqueira, R.H.D.S.; Carneiro, M.A.C.; Faquin, V. Influência de fungos micorrícos arbusculares na biomassa e na nutrição de *Urochloa decumbens* em diferentes densidades do solo. *Pesq. Agropec. Bras.* **2018**, *53*, 943–951. [CrossRef]

211. Picazevicz, A.A.C.; Shockness, L.S.F.; Santos Filho, A.L.; Nascimento, I.R.; Maciel, L.D.; Silva, L.R.; Costa, G.E.G. Crescimento de *Panicum maximum* cv. BRS Zuri em resposta a rizobactéria e nitrogênio. *Rev. Bras. Agropecuária Sustentável* **2020**, *10*, 33–37. [CrossRef]

212. de Carvalho, C.L.M.; Duarte, A.N.M.; Hungria, M.; Nogueira, M.A.; Moreira, A.; Soares Filho, C.V. Nitrogen in shoots, number of tillers, biomass yield and nutritive value of zuri guinea grass inoculated with plant-growth promoting bacteria. *Int. J. Innov. Res.* **2020**, *8*, 437–463. [CrossRef]

213. Costa, N.D.L.; Townsend, C.R.; Magalhães, J.A.; Paulino, V.T.; Rodrigues, A.N.A.; Nascimento, L.D.S.; Rodrigues, M.D.A. Resposta de *Andropogon gayanus* cv. Planaltina a inoculação de micorrizas arbusculares e fertilização com fosfato de rocha. *PubVet* **2015**, *9*, 405–409. [CrossRef]