Chapter 155

Plant growth-promoting microorganisms as mitigators of water stress in pastures: a narrative review

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ABSTRACT
Water stress is a reality present in pastoral areas throughout Brazil, and more challengingly in semi-arid regions. These climatic conditions test the tolerance to water stress of the forage species used, which despite their rusticity, markedly decrease their performance in low water availability, which limits the expression of all their productive potential. In this sense, it is important to search for sustainable technologies that help a greater resilience of animal production on pasture and that are beneficial to the environment, such as the use of microorganisms that promote plant growth, which can potentially help these species to tolerate the deleterious effects of water stress. Therefore, the objective of this review was to compile information on the use of plant growth-promoting bacteria, arbuscular mycorrhizal fungi and their co-inoculation with water stress mitigating agents in forage plants.. In view of data obtained from research platforms, the effects of inoculations with beneficial soil microorganisms on morphophysiological and productive characteristics of forage plants were addressed and how this symbiosis can potentially help plants to tolerate water stress, in addition to describing the specifics of the tripartite relationship between fungi, bacteria and forage plants. With this review, it was found that the use of microbiological inputs as modulators of species tolerance has potential use, requiring a greater volume of studies to consolidate the technique in a way that strengthens it with a sustainable and resilient alternative of livestock to pasture.

Keywords: Bacteria, Fungi, Mycorrhiza, Co-inoculation, Resilience.

1 INTRODUCTION

The conditions of pasture animal production in Brazil, predominantly in dryland, have water deficiency (common in semiarid regions) and low natural fertility of the areas, situations that put to the test the adaptation of tropical forage species to stressful growth conditions. These systems face long periods of drought, mainly due to the incidence of dry periods during the rainy season (summer), which, depending on the region, can occur at different times of the year, regardless of the season.

Such environments can cause a negative impact on forage plants, decreasing their productivity by physiological, nutritional and hormonal imbalances, limiting the productive potential of these areas and negatively reflecting on the zootechnical indices of the animals explored in this system.

In view of this situation, it is necessary to search for solutions with low environmental impact, which can optimize animal production without compromising natural resources and that provide resilience characteristics to the sector, such as reducing dependence on external inputs and increasing the efficiency of these productive systems.

Among the sustainable alternatives, the use of biological inputs based on beneficial soil microorganisms, such as plant growth-promoting bacteria (BPCP) and arbusculár mycorrhizal fungi (AMF) are among the most promising technologies to achieve the sustainability of agricultural systems, because they provide improvements ranging from characteristics to promote growth of shoots and plant roots, even improving the enzymatic protection to the conditions of biotic and abiotic stresses inherent to agricultural and livestock activity nowadays.

Plants evolved in a sophisticated way with soil microorganisms to overcome water stress and their adverse effects within cells, strengthening the intrinsic mechanisms of tolerance to plant stress, producing exopolysaccharides, phytohormones, ACC deaminase, osoliths and volatile compounds (Shaffiqueet al., 2022).

The use of this technology has great potential to become a reality in the formation and persistence of pastures, due to the great interest on the part of cattle ranchers, mainly because it is an advantageous alternative for cattle grazing, soil management and environmental quality, due to its low cost, and also for responding to society's demands for a more sustainable livestock (Mamédio et al., 2020).

According to Jiang et al. (2021), AMF are characterized by a mutualistic relationship with plant roots and, because they are mandatory biotrophic, receive carbon compounds from plants and produce an extensive network of hyphae that has access to nutrient stains outside the rhizosphere, favoring the absorption of unmobile elements in the soil such as phosphorus, seeking water in pores of the soil not accessible to the root hair.

Bpcp, as described by Fracasso et al. (2020), act through mechanisms that stimulate plant development, among which we can mention biological nitrogen fixation (BNF), amino acid and phytomonium production, as well as improvement of the availability of nutrients such as phosphorus, through phosphate solubilization processes.

Thus, in theory, the tolerance of tropical forage grasses to these negative drought events can be enhanced and/or aided by beneficial natural microorganisms, including bacteria and fungi, which through symbiotic or associative relationships, provide mitigation of biochemical and physiological disturbances caused by this condition and providing greater resilience to sustainable soil use.

However, according to Nadeem et al. (2014), although microbial inoculants are being widely used to improve plant growth under controlled field and natural conditions, the results obtained with these studies did not reach a reasonable degree of efficacy and consistency necessary for their large-scale commercialization, due to the complexity of interactions between the various factors present in these ecological relationships.

Therefore, it is important to compile information that helps better understanding of this biological process so that it can be widely used in grazing activities, providing greater resilience, food security and less environmental impact to this productive activity. In this sense, the present work aims to analyze and understand the various relationships between beneficial soil microorganisms and their ability to mitigate the deleterious effects of water stress on forage plants.

2 METHODOLOGY

This is a narrative literature review on the mitigation of water stress in tropical forage plants by the action of microorganisms that promoter plant growth.

Narrative review consists of mapping, categorization and analysis of the literature, allowing the updating of knowledge on a theme and the discussion of a given subject from a theoretical or contextual point of view, as well as the identification of approaches, gaps and perspectives for future studies (Vosgerau & Romanowski, 2014).

The searches were based on the research question: Are microorganisms promoting plant growth capable of mitigating the negative effects of water stress on pastures? The bibliographic search was performed in the Databases Scielo, Google Scholar, Scopus, Science Direct and Web of Sciences and the following descriptors were used: abiotic stress, water stress in pastures, arbuscular mycorrhizal fungi, plant growth-promoting bacteria, mitigation of water stress by beneficial soil microorganisms, tolerance to water stress, as well as their respective descriptors in the English language: abiotic stress, water stress in pastures, arbuscular mycorrhizal fungi, plant growth-promoting bacteria, of water stress by beneficial soil microorganisms, tolerance to water stress.

The inclusion criteria defined for the selection of articles were: articles published in Portuguese, English and Spanish, which in full or partially portrayed the theme of the study and indexed in these databases from 1980 to 2022. Initially, 308 articles were found, and later, through the exclusion criteria (duplicity, non-fulfillment of the objective of this review and escape from the theme) selected 114 articles that met the eligibility criteria described and composed from the initial conceptualization of terms and concepts, to the analysis and discussion of the present review.

3 RESULTS AND DISCUSSION

3.1 ABIOTIC STRESSES IN FORAGE PLANTS

Brazilian livestock farming is characterized by animal feed to pasture, extensive areas with cultivated pastures and favorable climatic conditions, which provide competitive advantages of our farms compared to other producing countries. However, climatic variations, especially those related to water availability are common in several regions and seasons, imposing a seasonal character on forage and animal production, because despite the rusticity and adaptation of tropical forage grasses, these critical conditions throughout the year affect their productivity.

According to estimates of the Intergovernmental Panel on Climate Change (Stocker, 2014) Brazil will have an increase of 2 to 7 ºC in its temperature by the year 2100, showing greater variability in precipitation scenarios, with regionalized trends of increase in maximum and minimum temperature extremes.

This situation refers to the challenges that Brazilian livestock companies face and will continue to experience in the near future, demanding the use of production systems less sensitive to these conditions, aiming at the mitigation of greenhouse gases and the adoption of animal and forage components adapted to climate change.

In this context, ecophysiology as a tool for the study of forage responses to the abiotic and biotic conditions of the pasture ecosystem can generate information that contributes to a better balance between the productive demand of the system and biological sustainability of its main factors.

The dynamics of individual plants and the pasture edby community can be altered by the conditions of the environment in which they are subject, directly affecting the structure of the lawn, as well as the adaptive mechanisms of the plant to the stress imposed by the biotic and abiotic factors of the pasture ecosystem (Lemaire, 2001).

Thus, stress can be defined as any environmental condition that prevents the plant from reaching its full genetic potential (Taiz et al., 2017), and may come from the most diverse sources of environmental variations, such as those derived from temperature (high temperatures and cold), water availability (drought and flooding), radiation (Light and UV), chemical stress (mineral salts, pollutants and toxic gases) and mechanical stress (wind, soil movement and submersion), but especially those linked to the context of climate change, being able to highlight the effects caused by the increase in temperature and water deficit that generate physiological and biochemical disorders to plants (Table 1).

Table 1. Physiological and biochemical disorders in plants caused by abiotic stress.

Environmental factor	Primary effects	Side effects
	Reduction of water potential (Ư)	Reduction of cellular/leaf expansion
Water deficit	Cellular dehydration	Reduction of cellular and metabolic activities
	Hydraulic resistance	Stomatic closure
		Photosynthetic inhibition
		Leaf abscission
		Change in carbon partition
		Cytorrise
		Cavitation
		Destabilization of membranes and proteins
		Production of EROs
		Ionic cytotoxicity
		Cell death
High temperature	Destabilization of membranes and proteins	Photosynthetic and respiratory inhibition
		Production of EROs
		Cell death

Source: Adapted from Taiz et al. (2017).

Table 1 presents the various physiological effects presented by plants submitted to the two main factors of abiotic stress (water and high temperature) and which are related to climate changes caused by the effects of global warming.

The impact of these physiological disturbances on commercial crops or livestock activities compromises the supply of food and consequently food security, especially in regions of challenging agricultural and livestock activities, such as regions with arid and semi-arid climate. This concern is not an exclusivity of agricultural systems composed of annual crops, which are comparatively more affected by climatic extremes.

Tropicalforage grasses, Plants of C4 metabolism, with high efficiency in the use of natural resources with light and temperature, also present physiological disturbances to this stress conditions, and have developed throughout their evolution some morphophysiological adaptations that help them to tolerate these conditions to some degree of disturbance.

In a review by Pimentel et al. (2016) the main factors of abiotic and biotic stress and their respective adaptive characteristics are listed (Chart 1).

Table 1. Stress caused by biotic and abiotic factors and adaptive response of tropical forage grasses.

Factors	Stress to the plant	Plant response
Compaction	Impairs root growth	Issue of lateral roots Thickening of roots
Flooding	Low ATP availability Reactive oxygen species Toxic levels of the elements Lower stomatic conductance	Formation of Adventitious roots Reduction of root biomass
Drought	Reactive oxygen species Lower carbon assimilation	Decreased stomatic opening Reduction of stomata diameter Osmotic cell adjustment Deepening of roots
Grazing	Decrease of photosynthetic appenditis	Source/Drain Ratio Changes Change in the population of childchildren
Shadow	Decrease in solar radiation	Increase in shoot/root ratio Decrease in peresoning Increase in leaf-specific surface Increase in chlorophyll content
Nutrient deficiency	Lack of essential elements	Accelerates root growth Increases surface and root length

Source: Pimentel et al. (2016).

Chart 1 gathered information on stress caused in forage plants by several factors in the pastoral environment and their respective adaptive response, which demonstrates that forage grasses evolved to adapt through physiological and morphological adjustments in an attempt to minimize the effect of these stress situations.

Water stress in forage plants

Water deficit is a situation common to the production of many crops worldwide, a phenomenon that is associated with factors such as occurrence and distribution of rainfall, evaporative demand and capacity to store soil water (Pimentel et al., 2016).

According to Naing & Kim, (2021) drought stress is considered one of the most severe abiotic stresses to crop yield, impairing normal plant growth by disturbance of cell division, leaf surface and stem growth, and root cell proliferation negatively affecting plant growth.

Water stress can be described as all water content of a tissue or cell that is below the maximum water content displayed when the plant is in the state of highest hydration, and this water deficit (insufficient water availability) occurs in most natural or agricultural habitats and is mainly caused by intermittent periods until continuous without precipitation, drought is the meteorological term for a period of insufficient precipitation that results in water deficit for the plant (Taiz et al., 2017).

The main consequences of drought in cultivated plants are the reduced rate of cell division and expansion, leaf size, stem elongation, root proliferation, stomatic oscillations, change in water and nutrient relationships in plants, providing lower crop productivity, and inefficiency in water use (Li et al. 2009).

Severe water restrictions promote stoppage of the growth and death of the aerial part of the plant and limit animal production, both due to low quality and forage availability. On the other hand, mild water deficiencies reduce the growth speed of plants, slowing the formation of stems and result in plants with higher leaf proportions and potentially digestible nutrient content (Santos et al., 2011).

In addition to all the effects on crop productivity in general, drought decreases the access of plants to available and essential resources for their growth, such as nutrients present in the rhizosphere that need water to be absorbed. With limited water supply, the absorption of nutrients by the roots decreases because a decline in soil water potential slows the rate of nutrient diffusion between the soil matrix and the root surface (Farooq et al., 2009).

Another important aspect is the effects of lower water availability of plants on their CO2 assimilation and, consequently, on their photosynthetic rate. Reductions in leaf area (size and number) and stomatic closure, impaired activities of carboxylaization enzymes and ATP synthesis and destruction of photosynthetic devices are among the main factors that decrease carbon fixation in drought (Yamance et al., 2003).

Severe drought limits photosynthesis due to a decline in ribulose-1 activities, 5-bisphosphate carboxylase / oxygenase (Rubisco), Phosphoenolpyruvate carboxylase enzyme (PEPCase), NADP-Mallica enzyme (NADP-ME), fructose-1, 6-bisphosphatase (FBPase) and pyruvate phosphate dikinase (PPDK), and limits the photosynthetic area due to reduced leaf expansion and number of leaves. In addition, the transport of non-cyclic electrons corresponds to the reduced requirements of NADPH production and thus reduces the synthesis of ATP (Farroq et al., 2012).

The condition of low water availability for plants disturbs the balance between production of Reactive Oxygen Species (REOs) and antioxidant defense causing accumulation of OU, which induces oxidative stress. With stomatic closure, the CO2 influx and its internal reduction in leaves not only directly reduces carboxylation, but also directs more electrons to form OU And promotes photorespiration.

In tropical forage plants there are several effects of water stress reported in the scientific literature of the area, which can mention the work carried out by Carrizo et al. (2021) evaluating the effects of water stress and recovery in two lines of buffel grass (*Cenchrus ciliaris*), which had the water supply interrupted until the soil reached 20% of the soil moisture content. The authors found a reversible decrease in leaf water ratio and damage to photosystem II, leading to an increase in the generation of reactive oxygen species, lipid peroxidation and the additional development of lignified tissues and bulliform cells and a greater thickness of the axial epidermis.

Maranhão et al. (2019) studying the effects of water restriction (30, 60, 90 and 120% of reference evapotranspiration – Eto) on buffel grass cv. Gayndah obtained a lower photosintetic foliar rate, stomatic conductance, leaf transpiration rate and a higher leaf temperature in the water slide correcting at 30% of Eto, which demonstrates the impact of water stress even in a forage considered as drought tolerant.

Siddique et al. (2016) studying the physiological responses of water stress on two species (*Halopyrum mucronatum* and *Cenchrus ciliaris*), observed in conditions of low water availability, reductions in chlorophyll, carotenoid, stomatic conductance and increase in free proline content in the two studied species.

Tommasino et al. (2018) evaluating the simultaneous stress of low water availability (30% of soil water content) and high temperatures (45 ºC) on two buffel grass genotypes, found oxidative damage caused by reduced activity of antioxidant enzymes, directly impacting the growth of the cultivars studied.

Therefore, there are several physiological disturbances caused by water stress in tropical forage grasses, including in a species considered tolerant to water stress, such as buffel grass.

Mechanisms for adapting plants to drought

Plants throughout their evolution have developed several morphological and biochemical adaptations to tolerate events of low water availability, as a way to mitigate or escape from disturbances caused by the lack of available water.

According to Farooq et al. (2009), plants throughout their evolution developed several mechanisms that allowed them to live with water stress, including morphological adaptations, osmotic adjustment, optimization of water resources, antioxidant systems that reduce the effects of reactive oxygen species (ROS) linked to drought, and the induction of a variety of genes and proteins that respond to stress.

Drought tolerance is a complex phenomenon associated with cuticle thickness, stomatic regulation, root system, hormonal balances, antioxidant defense system, osmotic adjustment and maintenance of water content in tissue, etc. (Farooq et al., 2012).

In general, the mechanisms of drought resistance by plants can be divided into physiological, morphological and aspects adaptations related to molecular mechanisms.

Among the adaptations to drought we can mention the ability of some species to "escape" from the period of lower water availability, either by the short life cycle (corresponding to the rainy season) or going into dormancy before scarcity, as several species of plants of the Caatinga biome do to survive.

Another form of adaptation is the prevention of drought by phenotypic flexibility, when the plant has the ability to maintain high water status or cellular hydration under water deficit, performing this mechanism either by capturing more water from the soil or minimizing water loss through transpiration (Blum, 2005).

As for morphological aspects, Wang & Yamauchi (2006) describe root plasticity as an important aspect to avoid drought, through a greater depth of rooting, root proliferation and root length density.

Regarding physiological adaptations, several are the metabolic modifications made by plants to face the low level of water in their tissues, being able to mention the most important, with osmotic adjustment, synthesis of plant growth substances (plant hormones) and antioxidant defenses.

Accumulation of organic and inorganic solutes under drought and/or salinity, which help decrease water potential without decreasing water content, is referred to as osotic adjustment or osmoregulation (Serraj & Sinclair, 2002). However, these solutes do not cause harmful effects on membranes, enzymes and other macromolecules, even at higher concentrations, so they are also called compatible solutes (Kiani et al., 2007).

Biosynthesis and accumulation of compatible solutes, such as the amino acid proline, occur in the vacuola or cytosol, with osmoprotective function, which maintains the water balance and preserves the cellular integrity of proteins, enzymes and membranes, for the continuity of vital activities, and is one of the adaptive strategies of vegetables to the multiple effects caused by stresses (Abdul Jaleel et al., 2007).

These compatible solutes include soluble sugars, sugar alcohols, proline, glycinobetain (GB), organic acids, trerealosis, etc. These compatible solutes not only help maintain turgor pressure, but also to protect enzymes and cell macromolecules from the harmful effects of OU (Farooq et al. 2009).

Osmotic adjustment is the main defense mechanism of the plant capable of reducing cellular water potential (Guirra et al. (2022). It is performed by accumulating biomolecules (sugars, amino acids, proline, etc.) in the cytosol without poisoning the cell (Butt et al., 2017).

Another physiological aspect in the adaptation of plants to drought is the action of plant hormones, which in low concentrations can inhibit, modify or promote howtoand qualitatively plant growth.

Auxins, Giberelines, Cytokinins, Ethylene, and Abscisic Acid (ABA) are the most studied phytomoniums in higher plants. Of these, Giberelins and Cytokinins promote plant growth (growth promoters), while Ethylene and ABA have inhibitory effects (growth retarders) (Taiz et al., 2017). Water stress alters the endogenous synthesis of these growth substances. Generally, under stress conditions, the concentration of growth retarders increases at the expense of growth promoters to regulate the water budget of plants (Farooq et al., 2009).

According to Taiz et al. (2017), under water deficit conditions there is the accumulation of abscisic acid (ABA) in the roots, inducing the leaves to decrease the opening of the stomata, reducing gas exchange, inhibiting photosynthesis, and thus producing reactive oxygen species (ROS) that can promote damage to

DNA and cell membranes.

Limited water supply promotes oxidative stress with overproduction of REOs. Influx of CO_2 declined with stomatic closure or impaired activities of enzymes and photosynthetic devices damaged under water stress deregulate photosynthesis, leading to the generation of a variety of OU, such as O_2^-, $^1O_2$, H_2O_2, HO_2^- and HO^- (Lawlor & Cornic, 2002).

According to Naing & Kim (2021), these EROS are highly reactive and toxic, and their overproduction causes oxidative damage to membranes (e.g., lipid peroxidation), proteins, RNA, and DNA and other macromolecules in the absence of any protective mechanism, which ultimately lead to plant death.

The plants developed enzymatic and non-enzymatic defense mechanisms capable of neutralizing the cytotoxicity of THE (Barbosa et al., 2014). The antioxidant defense cell system begins with an enzymatic cascade, but also involves non-enzymatic components, among which are ascorbate (AsA), glutathione (GSH), β-carotene and α-tocooferol. Such antioxidants can prevent the formation of free radicals, kidnap them or promote their degradation, preventing the occurrence of damage to plant cells (Serkedjieva, 2011).

Of the enzymatic antioxidants, superoxide dismutase (SOD), catalase (CAT), peroxidase (POX), glutathione reductase (GR) and ascorbate peroxidase (APX), non-enzymatic antioxidants, ascorbic acid, α -tocopherol, reduced glutathione, β -carotene salicylates, solutes compatible as proline accumulate in higher plants under water stress to avoid oxidative damage (Ozkur et al., 2009).

3.2 BENEFICIAL SOIL MICROORGANISMS AS MODULATORS OF TOLERANCE TO WATER STRESS IN PLANTS

One of the alternatives to help plants cope with low water availability is the use of microbial communities associated with plants, such as arbuscular mycorrhizal fungi (AMF) and plant growth-promoting bacteria (BPCP), which optimize plant growth and development under different types of abiotic and biotic stresses.

The application of microorganisms such as BPCP and FMA are useful for and improving the sustainability of agriculture and environmental stability (Kumar & Verma, 2018).

Plant Growth Promoting Bacteria (BPCP)

The definition of plant growth-promoting bacteria (BPCV), plant growth-promoting bacteria (BPCP) or even plant growth-promoting rhizobacteria (PCRP) encompasses groups of free-living or epiphytic microorganisms with the ability to establish symbiotic, associative or non-associative relationships with plants (Glick, 2012).

The study of the interactions between plant and microorganisms has intensified in recent years in order to understand the various factors involved for the selection of strains of bacteria efficient in promoting growth of large crops (Ferreira et al., 2014).

PCBPs have been found in association with a large number of forage cereal and grass species, with a wide range of genera described, *including Pseudomonas, Burkholderia, Bacillus, Bradyrhizobium, Rhizobium, Gluconacetobacter, Herbaspirillum and Azospirillum* (Hungary et al., 2010; Vine et al. , 2012).

The mechanisms by which bacteria can influence plant growth differ between species and strains, so there is no single mechanism to promote plant growth. Studies have been conducted in relation to the abilities of various bacteria to promote plant growth, including endophytic bacteria (Souza et al., 2015).

Endophytes are conventionally defined as bacteria or fungi that colonize the internal tissues of plants, can be isolated from the plant after surface disinfection and do not cause negative effects on plant growth (Gaiero et al., 2013).

According to Souza et al. (2015), BPCP has been reported for their improvement in plant development because they provide a number of benefits through several mechanisms such as: biological nitrogen fixation, production of indole compounds, production of iron-quelant siderophores that at high concentrations can inhibit the growth of phytopathogens, acc deaminase activity and solubilization of organic and inorganic phosphates.

Many beneficial microorganisms, including bacteria and fungi that live in the soil and those associated with plant roots, are able to solubilize insoluble phosphorus from the soil (Bechtaoui et al., 2020).

Bacteria often solubilize mineral phosphorus (P) (inorganic) by synthesizing low molecular weight organic acids, such as golucionic acid and citric acid (Rodriguez et al., 2004). Phosphate solubilizing bacteria solubilize inorganic forms of phosphates, such as Ca3(PO4)2, FePO4 and AlPO4, through the production of organic acids, siderophores and hydroxyls. Phosphate binds with hydroxyl groups and quelifying carboxyls and thereby releases cations that induce soil acidification, resulting in the release of soluble phosphate (Kpomblekou & Tabatabai, 1994).

Iron, despite being one of the most abundant elements in the earth's crust, in the soil, is often in a form not available for direct assimilation by plants and microorganisms, due to the low solubility of the iron ion (Fe3+) (predominant form in nature). To improve the absorption of this nutrient, plants and some bacteria produce low molecular weight compounds that bind and sequester to available forms of soil iron. Bacteria synthesize low molecular weight siderophores, molecules with a very high affinity for Fe3+ and membrane receptors that can bind to the Fe-siderophore complex, thus allowing the absorption of iron by bacteria (Neilands, 1981).

The siderophores produced by plants bind with a lower affinity to iron when compared to the siderophores produced by bacteria, and bacterial ferro-siderophore complexes can be absorbed and used by plants (Wang et al., 1993).

In addition to these aspects of promoting growth in plants under adequate conditions of cultivation, these microorganisms present several mechanisms that can help plants in their tolerance to the impact caused by water deficit.

According to Kaushal & Wani (2016), the application of growth-promoting bacteria (BPC) mitigates the negative effects of drought on plants through various physiological and biochemical processes in plants, including changes in phytomonium levels, activation of the antioxidant defense system and the accumulation of various compatible organic solutes such as sugars, amino acids and polyamines. Potential mechanisms include (1) production of phytomoniums such as Indoleacetic Acid (AIA), Cytokinins and Abscisic Acid (ABA), (2) exopolysaccharides, (3) ACC deaminase and (4) induction of systemic tolerance (Kumar & Verma, 2018).

Goswami et al. (2015) report the importance of AIA, an auxin that regulates the differentiation of vascular tissue, adventitious and lateral root, cell division and bud growth during water stress. ABA is an important growth regulator during water stress. When the seed or plant is inoculated with BPCP, aba concentration increases and regulates plant physiology to tolerate water stress. This phytomonium mitigates water stress by regulating the transcription of the gene related to drought and hydraulic conductivity of the root (Jiang et al., 2013).

Hormones such as auxins, giberelins, kinetin and ethylene are produced specifically by these microorganisms and play an important role in root strengthening (Ahemad & Kibret, 2014).

According to Bal et al. (2013), the organisms that produce the enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase, responsible for the degradation of ACC (ethylene precursor) in ammonia and α-ketobutyrate, are able to promote plant growth by reducing ethylene levels in the plant.

By facilitating the formation of long roots and the protection of plants under stress, due to the deleterious effects of the presence of ethylene, these bacteria can increase survival and protect the yield of a plant variety, especially during the first days after sowing, where plants are generally more vulnerable to damage by various environmental stresses (Glick, 2004).

The presence of bacteria can also lead to the production of osmorphic substances by the plant and thus act synergistically, mediating changes in the elasticity of root cell walls, contributing to drought tolerance (Dimkpa et al., 2009).

And among the wide range of species and strains of plant growth-promoting bacteria, those of the *genus Azospirillum* have been widely tested in forage grasses, with satisfactory results in the nutrition of host plants, such as those observed by Hungary et al. (2021) and abiotic stress mitigators, as contacted by Bulegon et al. (2017).

Azospirillum are the most studied BPCP, mainly because of their ability to produce growth regulatory compounds, such as indole-3-acetic acid (IAA) and giberelins, and to exert growth-promoting effects on a diverse set of hosts (Cortés-Patiño et al., 2021).

Bulengon et al. (2016) studying the effects of water stress on *Brachiaria ruzziziensis* associated *with A. brasilense*, noted that the bacterium favors the maintenance of chlorophyll content in leaves, helping plants to tolerate this abiotic stress.

The *bacterium A. brasilense* can minimize oxidative damage caused by water stress by increasing the contents of chlorophylls and carotenoides in inoculated plants, under water deficit (Bulegon et al., 2016) and by synthesizing 1-carboxylic amino cyclopropane acid (ACC) deaminase that degrades ACC, precursor substrate of ethylene synthesis (Glick, 2014).

Leite et al. (2019) evaluating the performance of Capim Marandu under different doses of N and inoculations with Azospirillum brasilense in different seasons, observed a 20% reduction in the need for nitrogen adduction and a higher performance in various productive parameters at dry season of the year with microbiological inoculation.

Bulegon et al. (2019) evaluating the effect of inoculation of *the bacterium Azospirillum brasilense* in *urochoa ruzziziensis* grass under water stress, observed the increase in the relative water content, under water deficit conditions, with less reduction in the rate of liquid assimilation of CO2 and reduction of damage to cell membranes. This process is mediated by stimulating the production and release of compounds such as plant hormones, mainly auxin and abscisic acid, but also compounds such as betaine osoliths, proline and amino acids.

And also Fukami et al. (2018) evaluating mechanisms of stress resistance, concluded that *the bacterium Azospirillum* provides protection to corn plants by increasing their antioxidant defense, through the activities of catalase (CAT), superoxide dismutase (SOD) and malondialdehyde (MDA) in leaves, and ascorbate peroxidase (APX) in the roots.

Mamédio et al. (2020) in a literature review on the influence of BPCP on the persistence of tropical pastures in water deficit concluded the use of these biological inputs in tropical grasses is an alternative for the maintenance of pasture growth and development, even when the soil nutritional profile does not meet the needs of grasses and environmental conditions are adverse. However, there are not many studies testing inoculants in tropical grasses under water deficit conditions and reaffirmed the need for studies with the most exploited grass species in animal production, as well as more detailed analyses of the efficiency of this technology, in order to better employ these products in grasses in a context of water deficit.

Arbuscular mycorrhais fungi (AMFs)

Arbuscular mycorrhizal fungi (AMF) form one of the most common associations in nature, arbuscular mycorrhaza (MA), a symbiotic relationship formed between these fungi and the roots of 82% of plant species, including crops of economic importance exerting great influence on various agroecological and ecosystem processes (Silvana et al., 2020).

This interaction is mainly based on the carbon exchange of the host plant and nutrients from fungi to the host plant in a symbiotic system (Atul-Nayyar et al., 2009).

Mycorrhhas can be ectomycorrhzas, in which the fungus covers the root, but does not penetrate it or arbuscular mycorrhazas, in which the hyphae of the fungus enter the root and penetrate the cell wall of the root cells forming arbuscular structures, inside the cell wall, but outside the plasma membrane (Sadava et al., 2009).

Recently, it was observed that the symbiotic interaction of plants with AMF, besides being important from the agricultural and ecological point of view (Yang et al., 2008), could be a sustainable mitigation practice for water deficit (Aroca, 2012).

According to Gamalero et al. (2009), the main mechanisms used by arbuscular mycorrhazas to help plants overcome the effects of drought include: (A) Better water absorption; Arbuscular mycorrhaza effectively extend the roots of plants providing a more efficient water catchment. (B) Better mineral nutrition, especially phosphorus, as a consequence of the effective extension of plant roots. In fact, arbuscular mycorrhities can provide the main mechanism for phosphorus absorption in many plants, with CVBP possibly acting as a secondary or adjuvant mechanism of mycorrhazas in terms of absorption of P. (C) Changes in root architecture. (D) Modification of some physiological and enzymatic activities, especially those involved in antioxidant responses of the plant. (E) induction of the plant hormone Abscisic Acid (ABA), which may play an important role in mediatingsome plant responses to different stresses including drought (Danneberg et al., 1992).

It has been reported that the effect of AMF increases with the intensity of water deficit (Miransari et al., 2007); however, the effect is not predictable and the magnitude and type of response depend on AMF and plant species and the degree of stress prevalent in water deficit (Zhongqun et al., 2007).

One of the possible mechanisms for improving the tolerance of mycorrhizal plants to water deficit may be related to increased hydraulic conductivity of the roots (Augé et al., 2008).

Live hyphae that are involved in the transport of water (Allen, 2009) have a diameter between 2 μm and 5 μm and can penetrate the smaller pores of the soil that are inaccessible to the lateral root (10 μm to 20 μm in diameter) and thus absorb water that is not available for non-mycorrhizal plants (Marulanda et al., 2003). In addition, AMF demonstrated beneficial effect on soil structures, specifically generating aggregates due to the production of a glycoprotein known as glomalin (Wu et al., 2008).

Glomalin is a glycoprotein that is released by the arbuscular mycorrhizo fungus after its death, containing 2-5% Fe, 4-6% O, 0.03–0.1% P, 36–59% C, 33–49% H and 3–5% N (Wright et al., 1999). Due to its high adesivity and hydrophobicity, it plays an important role as a cementing material with soil particles and acts as a highly stable form of organic carbon storage, which represents an important fraction of the total organic matter present in the soil (Bhale et al., 2018).

According to Fernández-Lizarazo & Moreno-Fonseca (2016) regarding aid in antioxidant defense, two mechanisms were proposed to explain the low oxidative damage in plants submitted to water deficits and inoculated with AMF. The first consists of the direct absorption of water by the hyphae and their transfer to the host plant, increasing the water content and decreasing the generation of reactive oxygen species (REOs). The second mechanism implies an increase in the production of enzymatic and non-enzymatic antioxidants induced by symbiosis with AMF (Abbaspour et al., 2012), especially in water deficit conditions (Amiri et al., 2015).

Under conditions of water and saline stresses, plants accumulate some organic solutes (proline, soluble sugars, betaine glycine, among others) and inorganic ions to maintain greater osmotic adjustment

(Yang et al., 2009).

As for the improvement of nutrient absorption by the symbiotic relationship between mycorrhizal fungi and plants, much is due to the expansion of the root contact area, due to the greater coverage provided by fungal hyphae. As colonization develops within the roots, fungal hyphae grow abroad at distances that can extend up to about 25 cm, depending on the genotype of fungi and soil conditions (Jakobsen et al., 1992).

As phosphorus is less mobile in soils with little water, an increase in its acquisition as a consequence of association with AMF is important for improving the nutrition of host plants (Augé, 2004).

The main function of AMF is to provide phosphorus to plant roots through phosphate conveyors present in the hyfal membrane. Extra-radical and filamentous hyphae networks of AMF assist in the absorption of freely available phosphates. This symbiotic interaction results in the hydrolysis of organic phosphates that are present in the soil and provide soluble phosphates to the host plant through hyphae (Bagyaraj et al., 2015).

Ruiz-Lozano et al. (2012) emphasize the existence of clear evidence that the symbiosis of the plants to water stress, by altering various physiological effects or ecological processes, which are summarized in Chart 2, including the improvement of soil water retention properties and the ability of hyphae to absorb water from inaccessible sources to roots and the transfer of this water to the host plant, with contributions of up to 20% more in the total absorption of water by plants.

There are several studies that report the effects of the use of mycorrhazas as mitigating water stress in plants, presenting effects of decreased oxidative stress (Chen et al., 2020), increase in proline levels and chlorophyll content of leaves (Tyagi et al., 2017), water potential and steamatic conduction of leaves (Li et al., 2014) and rate of liquid photosynthesis (Fracasso et al., 2020).

Table 2. Representation of the integral physiological processes by which FM A can improve the tolerance of the host plant to drought.

Physiological effects	Processes involved
Protection against oxidative damage	Antioxidant production
Maintains gas exchange and plant growth	Stomatic conductance and hormonal ballast
Reduction of osmotic potential in tissues. Avoiding water loss	Osmotic adjustment
Search for water in sources inaccessible to the roots	Water retention capacity and water absorption by hyphae
Water absorption and maintenance of the hydraulic properties of the roots	Regulation of aquaporin

Source: Adapted from Cheng et al. (2021).

Odokonyero et al., (2017), for example, evaluating the effects of endophytic fungus, *Acremonium implicatum*, in the growth and physiological responses of five brachiaria cultivars (Basilisk, Tully, Marandu, Cayman and Mulato II) in well-irrigated and drought-stressed conditions (irrigation suspended for 21 days), verified that plants in symbiosis with endophyte fungus significantly increased the stomatic conductance of the leaf and reduced the xylem diameter. However, the smallest leaf area was found in plants inoculated in three cultivars, compared to the control and both in well-irrigated conditions and in water stress, which indicates a cost of infection of endophytes for host cultivars.

Grasses, in general, have a high level of association with AMF, which is clear when the rate of mycorrhizal colonization in their fine roots is quantified (Guimarães et al., 2022). Table 3 shows significant rates of mycorrhizal colonization in roots of different tropical forage grasses, which demonstrates their high symbiotic affinity with these species, and the need for further research that explores all this potential with the selection of species/strains to make up biological inoculants.

Table 3. Mycorrhizal colonization rate identified in different tropical forage grasses and in different localities in Brazil.

Tropical forage grass	Mycorrhizal colonization rate	Locality	Reference
Megathyrsus maximus, Urochloa brizantha and Paspalum notatum	90%	Greenhouse	Zangaro et al., (2018)
Urochloa Decumbens	44%	Cerrado biome	Kanno et al., (2006)
Humidicola Urochloa	60%	Cerrado biome	Ramos et al., (2012)
Sorghum sp. and Pennisetum purpureum	80%	Atlantic forest	Rondina et al., (2014)
Ruziziensis	60%	Cerrado biome	Morais et al., (2019)
Cynodon sp.	75%	Pantanal Biome	Zangaro et al., (2012)

Adapted from Guimarães et al., (2022).

Although the potential of arbuscular mycorrhazic fungi naturally colonize forage plants, as presented in Chart 3, and increase their productivity, decreasing the degree of soil degradation and improving the resilience of forage plants to water stress, no study on the application of commercial inoculants containing AMF in tropical forage grasses has been developed in Brazil to date (Guimarães et al., 2022).

Co-inoculation of BPCP and FMA

The rhizosphere is a highly dynamic ecosystem that differs in biological composition depending on the physical and chemical conditions of the soil, native microorganisms and plants that are inserted in different biomes. Some of the important interactions include plant-plant interactions, root-microorganism interactions, and microbe-microbe interactions (Lau & Lennon, 2011). Synergism and antagonism in response to these interactions depend on the nature of the microbial strains involved in these interactions, as well as on plant species.

The growth promotion mechanisms provided by BPCP and mycorrhazas can be very useful for improving plant growth using these microbial populations together, particularly under stressful environments (Nadeem et al., 2014).

Figure 1 describes several plant growth promotion mechanisms used by arbuscular mycorrhizal fungi (AMF), plant growth promoting bacteria (BPCP) and example of their synergism. It is important to highlight that plant growth-promoting microorganisms act in different ways and their combinations and their results will depend on the host plant, compatibility between microorganisms and abiotic conditions.

Bacteria can produce compounds to increase cell permeability so as to increase the rate of root exudation, which stimulates hifal growth and facilitates the penetration of roots by the fungus (Jeffries et al., 2003). On the other hand, mycorrhazas help the plant to resist against abiotic stress, increasing the surface area of the roots for nutrient acquisition or through more specific mechanisms (Sikes, 2010). In addition, BPCP improves the development of microsymbionts and facilitates the colonization of plant roots by AMF (Jaderlund et al., 2008). The presence of BPCP supports the establishment of mycorrhazas and improves the ability to perform various functions properly.

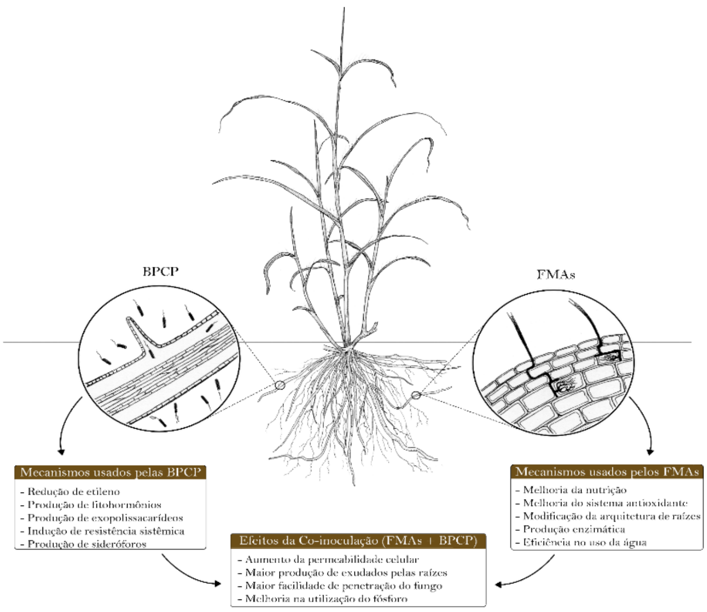
In the case of AMF the interaction with bacteria of the *genus Azospirillum* occurs directly, providing a niche and / or habitat or indirectly modifying the morphophysiology of the host plant. This communication in the soil can be beneficial for both microorganisms and the host plant (Domínguez-Núñez et al., 2015).

Colonization generated by both microbial groups stimulates the hydrolysis of cell wall hemicellulose and generates oligosaccharides that will be used in the nutrition process. The enzymes generated during this process are responsible for morphological changes that begin on the surface and end in the inner regions of the cortex. These results suggest that bacteria associated with fungi use metabolites produced by plant cells and microsymbionts that interact with them (Domínguez-Núñez et al., 2015).

Miyauchi et al. (2008) showed that mycorrhizal colonization increased colonization of diazotrophic bacteria in corn roots. The bacterium did not affect mycorrhizal morphology and colonization. This result suggests a beneficial effect of the action of AMF in helping diazotrophic bacteria penetrate and colonize plant roots (Raimam et al., 2007).

Fungal structures have been shown to be used by bacteria as intermediates to reach the root tissue epidermis, and that the production of phytomoniums by them stimulates root growth and, in fact, mycorrhizal colonization (Villarreal et al., 2016).

Figure 1. Mechanisms used to promote plant growth, provided by the association between rhizobacteria and arbuscular mycorrhizal fungi under water stress.



Source: Adapted from Nadeem et al. (2014); Revillini et al. (2016).

The entry of diazotrophic bacteria into plants can occur through AMF spores (Bhowmik & Singh, 2004) or bacterial colonization in extra-root hyphae of AMF (Toljander et al., 2006). THE AMF, in addition to providing nutrients for the bacteria that colonize the surfaces or inside the spores, provide protection against desiccation, radiation, predation and salinity (Levy et al., 2009). During the process of penetration of infective hyphae, there is greater exudation of nutrients by the plant, accelerating the growth of bacteria (Paula et al., 1991).

However, antagonistic interactions may also occur due to competition for nutrients and other essential resources for the life of these microorganisms.

Bauer et al. (2012) found no interactions between FMAs and N_2 fixers in Panicum communities or monocultures, indicating that in the short term the effects of these microbial functional groups would not be additive.

The interactions of microorganisms can be more than just competitive. Bellone & Carrizo de Bellone (2012) described the process of *colonization by Azospirillum brasilense* and *Glomus intraradices* in sugarcane roots, mainly in young roots and its subsequent introduction into xylem and phloem, favored by the endodermal disorganization of the cell that occurs during the growth of future lateral roots.

Also according to the authors, in the root sites with maximum colonization, fungi strongly decrease the cell wall, which allows better exchanges of metabolites between bacteria and fungi. In the lumen of xylem vessels, bacteria randomly colonize and the presence of intracellular hyphae increases the colonization of bacteria, which occupy the intercellular spaces generated by fungi.

Associative diazotrophics, on the other hand, are not separated from mycelium from endomyrrhic fungi. These nitrogen fasteners can function both inside and outside the lateral structures of AMFs. This can result in a competition for nutrients between the two microsymbionts. The success and failure of co-inoculation *of Azospirillum* and AMF may therefore depend on the physiological stage of the host, the time of infections or the nutrient demands of the microsymbiont partners (Biró et al., 2000).

According to Ferrera-Cerrato & Alarcón (2004), there are numerous factors that can influence the symbiotic efficacy of microorganisms in plants, such as the strain used, the host plant and the edaphical conditions. It is important to understand this when dealing with such factors in order to optimize plant growth.

Behrooz et al. (2019), evaluating the effect of co-inoculation of arbuscular mycorrhizal fungi (*Glomus mosseae*, *G. etunicatum* and a mixture of these) and plant growth-promoting bacteria (*Azotobacter chroococcum* + *Azospirillium lipoferum*) as relievers of the effect of water stress on Walnut seedlings, observed the reduction of growth (plant height, root length, number of leaves and fresh weight), leaf nutrient content (N, P and Zn) and in contrast, increase in proline values, total soluble sugar, activity of the starch peroxidase enzyme and total phenolic content of the leaves under this stress.

In forage plant, Ronseax et al. (2020) evaluating the co-inoculation *of Azospirillum brasilenses and R. intraradices* and fertilization with N in Mulatto II grass, observed with biofertilization (without N) values similar to the dose of 100 kg/ha.

And Ruiz-Sanches et al. (2011) evaluating microbiological inoculations (*Azospirillum brasilenses*, *Glomus intraradices, A. brasilenses* + *G. intraradices* and control without inoculation) in rice plants under water stress, observed positive effect of co-inoculation of microorganisms on the colonization of plant roots by the fungus mycorrhizal, indicating beneficial effect of the bacterium on propagule germination and the micellar growth of mycorrhide. Also on these results, the authors observed that plants under water stress (two weeks with 50% wc and two weeks with 25%) and inoculated with mycorrhancy and co-inoculated had higher photosynthetic efficiency and stomatic conductance compared to the other treatments, as well as effects on higher shoot and root production.

In general, there are few studies evaluating the effectiveness of the joint use of microorganisms and forage grasses, thus requiring trials that generate information to understand this tripartite relationship between fungi, bacteria and host plants and the use of their benefits in pastoral environments, especially in conditions of water deficiency.

3.4 EXAMPLES OF PASTURE USE SITUATIONS OR STEPS THAT CAN BENEFIT FROM INOCULATIONS OF MICROBIOLOGICAL INPUTS TO ATTENUATE WATER STRESS

Despite little information on the possibilities of using these biological inputs pastoral environments, in addition to those already conceptualized, as growth promoters and in place of chemical fertilization, it is possible to infer about the potentialities of actions and modulation effect of microbiological inoculations on forage plants in various stages of pasture use, and can mention:

Phase of implantation or formation of pasture

The planting window in dryland crops is concentrated in a short period of time depending on the operationalization and planning of the activity. In this time window, the seed comes into contact with soil moisture and the process of embebition and subsequent germination occurs, which depend on the relationship between the water potential of the seed and the soil so that there is adequate transfer of water from soil to seed.

Particularly in tropical forage grasses, which most plantations are carried out to toss, the little contact of the soil with the seed can delay the embebition, tinting and emergence of seedlings, and added to this, this phase can be preceded by water scarcity, which can impair the formation of an initial plant stand per square meter, compromising the initial use of pasture;

Water stress soon after sowing is one of the abiotic factors that most influence the germination process, directly interfering in the enzymatic activities of the plant minimizing productive yield, mainly due to the low recovery capacity after abiotic stress (Francisco et al., 2016). This low recovery capacity can be mitigated by inoculating with plant growth-promoting microorganisms, which can aid the mechanisms of tolerance to water stress imposed on seedlings.

Use of pasture in semiarid regions

Extreme weather events due to climate change are already causing disturbances in animal production systems and the projections for the near future are of aggravation of these disturbances, especially those associated with increased air temperature, concentration of rains, longer dry season and higher frequency of summers (Ambrosio et al., 2018).

The semiarid and arid regions are the most vulnerable to suffer from the impacts of global and regional climate change (Marengo et al., 2016), mainly because they are characterized by rainfall irregularities and low rainfall rates, compromising animal feed and persistence of forage species in the long term.

Livestock, developed predominantly in pastures in these regions, faces marked nationality of pasture production, concentrating greater availability of forage in the rainy season and scarcity in the dry season, which compromises the support capacity throughout the year and hinders the stable annual dimensioning of the herd, which can lead to supergrazing at the time of lower forage supply and, therefore, compromising the perenity of pastures (Porto et al., 2022).

Water stress mitigation technologies are very important for semiarid regions, which naturally present a water balance between evapotranspiration and annual precipitation, which limit the persistence and plant sustainability of many species in these regions. Thus, these interventions provided that they are proven effective have a potential for resilience of agricultural activities in these challenging areas for the durability of many forage species.

Occurrence of "summer" periods

Rainfall irregularity in pasture areas in Brazil is a common situation faced every year by grazing livestock activity, imposing a seasonal character in the food supply of animals, generating challenges in planning throughout the year and added to this, the phenomena of summer (Dry Spells) often occur, which are defined as a period of five or more consecutive days without rain within the rainy season of a given region (Magalhães) et al., 2020). Veranicos can compromise the stocking rates of these areas at a time, theoretically of greater water security.

The water stress mitigation characteristics discussed in the present review can improve the tolerance system of forage plants at this time (unpredictable) of low water supply in the soil, through improvement of morphophysiological adaptations of plants at a time that usually presents adequate temperature and luminosity for pasture growth.

Use of pasture in periods of dry water transition:

Forage production concentrates its growth between 70 and 80% in the water period and 20 to 30% in the dry season (Reis et al., 2011), for this reason throughout the year, in addition to the water and drought periods, it can also be subdivided into two transition periods: dry water transition and dry-water transition

(Roth et al., 2017). Such transitions allow better to understand the changes that the pasture undergoes and consequently the supply of fodder to the animals, facilitating the management of grazing and correction of its deficiencies via nutritional supplementation.

Specifically, the transition waters - drought is the period of the year situated between the rainy and dry season, is an intermediate period of growth and nutritional value of plants, which presents progressive decrease in rainfall, temperatures and photoperiod, which alters the pattern of pasture growth and compromises forage production and progressively decreases its nutritional value and digestibility for animals.

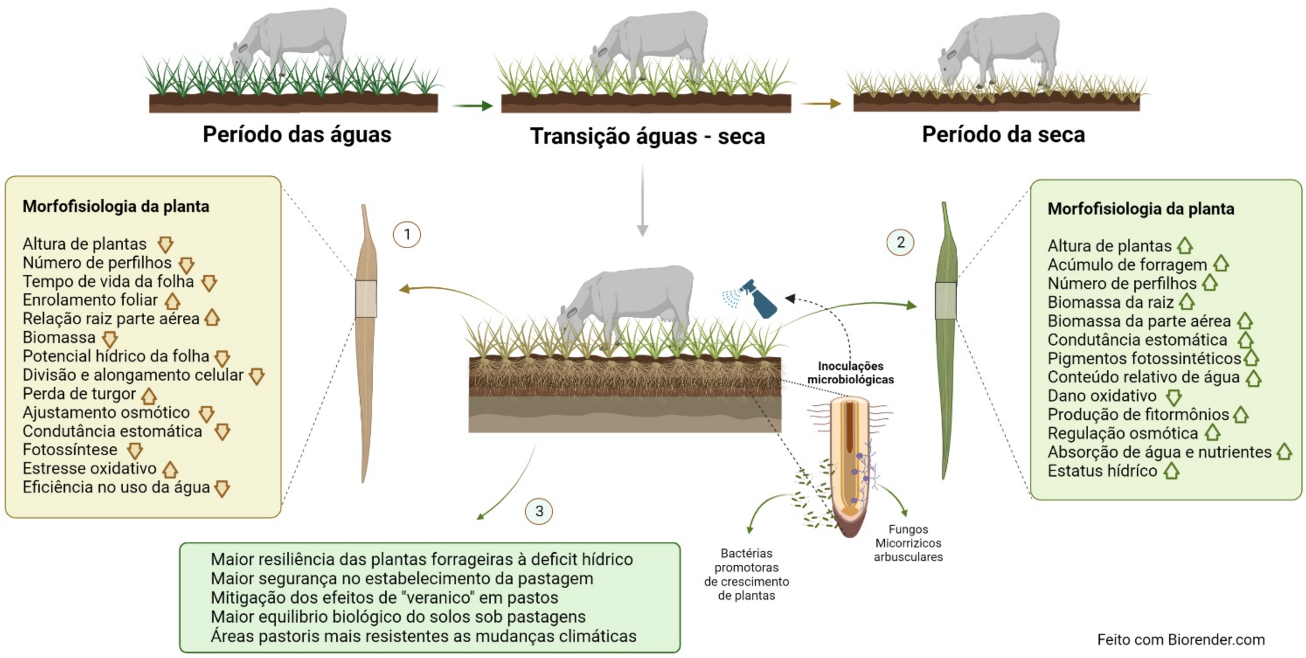
Pasture in early autumn presents good quality and a lot of mass and as the season progresses, due to the reduction of rains and temperatures, the fodder begins to senescence and present low nutritional quality, especially due to the aging of plant tissues. Another marked change in canopy structure is the accumulation of stem and senescent material, causing a decrease in the quality of forage and, consequently, a reduction in the consumption and performance of animals (Roth et al., 2017).

Lima et al. (2012) describe that, with the advance in the transition period and, consequently, advance in the physiological age of the plants, there is a decrease in cp content and dry matter digestibility (DM), an increase in neutral detergent fiber (NDF) and acid detergent fiber (ADF).

Bioinput technology could help grazing management in the transition period, in theory by slowing the morphophysiological seasonality of the species with the decrease in water availability and would add to other grazing management strategies in this period, such as the deferred use of pasture. The deferred use of pasture consists of sealing an aisland of the pasture in the final third of the water period, for use in the dry period of the year, providing greater accumulation of fodder during the autumn period (in central Brazil) and would maintain the physiological activities of the plants, such as the content of photosynthetically active pigments for example, which would help a characteristic "stay green", where the plant would remain longer green and maintaining its photosynthetic metabolism for longer as the dry season progresses.

This possibility could decrease the production and quality seasonality that occurs in most tropical forage grass species. Figure 2 describes the effects of water stress on tropical forage grasses and the improvement of the tolerance of these species with inoculation with plant growth-promoting microorganisms that may contribute to greater resilience of pastures in conditions of decreased rainfall in the period known as the water-dry transition.

Figure 2. Main morphophysiological responses of forage plants in water stress condition (1), effects of mitigation of this stress modulated by plant growth-promoting microorganisms (2) and potential benefits of microbiological inoculation of pastures under water deficit conditions (3).



Adapted from Mamédio et al. (2020); Bulegon et al. (2017 and 2019) and Odokonyero et al. (2017).

All these situations could benefit from the relationships between microorganisms and forage plants, enhancing the characteristics of tolerance to water stress of these species and providing greater resilience of this productive system with low environmental impact. According to Walker et al. (2004), resilient pastures are those that incur a smaller reduction in production and recover more rapidly after a stress event such as drought/flood, pest pressure/disease.

Despite the several microbiological mechanisms described in the present review, which may in theory improve the tolerance of tropical forage species to water deficit events, scientific studies in the literature that address the behavior of these inoculated plants under water stress conditions or throughout the seasons are incipient. Chart 4 describes the scientific articles selected to make up the corpus of the review and that specifically address forage species inoculated in conditions of water stress and the characteristics that helped mitigate water stress in these pastures.

Table 4. Articles selected to make up the Research Corpus of this review that specifically address the mitigation of the effects of water stress by the use of microbiological inoculants in tropical forage grass species.

Tropical Forage Grass	Microorganism (Species)	Water stress mitigation characteristic	Reference
Ruziziensis	*Azospirillum*	Increased activity of antioxidant enzymes and protection of photosynthesizing pigments	Bulegon et al. (2016)
Cultivars of Urochloa (Basilisk, Tully, Marandu, Cayman and Mulato II)	*Acremonium implicatum* (FMA)	Maintenance of stomatic conductance of the sheet and reduced xylem diameter	Odokoniero et al., (2017)

Urochloa brizantha cv. Marandu	*Azospirillum*	Greater tillering and root biomass	Leite et al., (2019)
Ruziziensis	*Azospirillum*	Maintenance of the relative content of water, net assimilation rate of CO_2, and absolute integrity of the cell membrane membranes;	Bulegon et al., (2019)

It is necessary to advance research that addresses forage plants in field conditions under situations of multiple stress and with a greater competition between microorganisms inoculated with the native microbiota of these areas, to improve the effectiveness of these biological inputs in pastoral environments.

According to Guimarães et a., (2022) despite the increased commercialization of microbial inoculants in Brazil, their use in pastures is still modest, representing less than 0.1% of the doses sold annually, this demonstrates the long way to go to realize the adoption of this technology in areas that are traditionally more lacking in the use of agricultural inputs.

4 FINAL CONSIDERATIONS

In view of the research conducted in this study, it is observed that there is great potential to use the benefits of symbiotic relationships between forage plants and beneficial soil microorganisms to improve the tolerance to water stress of tropical forage grasses.

However, there are few studies with the use of microorganisms in forage plants mainly under field conditions (under different conditions of abiotic stress), to advance the knowledge of the interrelationships between inoculations (isolated or with a polymicrobial character), forage plants and grazing animals.

Although known microbial interventions are promising, their dose, frequency and time still require practical validation.

Based on this information, new studies with selection of species/strains of microorganisms and their combinations, which have the potential to modulate tolerances of tropical forage grass species should be conducted, in addition to the need for studies addressing the effectiveness of biological inputs in different forage species and in practical situations of pasture use cited in this review, such as the implantation phase, management in semiarid regions with incidence of dry spells and strategic use of pasture in times of dry water transition.

It is also necessary to understand the characteristics of competition or mutual assistance among microorganisms that can potentially be used together, since each of them has different characteristics of growth promotion and improvement of tolerance to water stress in forage plants.

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