Revista Ciência Agronômica, v. 56, e202393665, 2025
Centro de Ciências Agrárias - Universidade Federal do Ceará, Fortaleza, CE
www.ccarevista.ufc.br

Scientific Article
ISSN 1806-6690

Arbuscular mycorrhizal fungi on the development and productivity of grain sorghum cultivars[1]

Eduardo Canepelle[2]*, Rodrigo Ferreira da Silva[3], Andréa da Rocha Giovenardi[4], Felipe Bonini da Luz[4], Ana Paula da Silva[5], Sinara Barros[6]

ABSTRACT - Arbuscular mycorrhizal fungi increase water and nutrient absorption from the soil by plants. However, its benefits to plants vary depending on the inoculated species. This study aimed to determine the influence of different species of mycorrhizal fungi on the development and productivity of grain sorghum cultivars. The experiment was conducted in a greenhouse in a completely randomized design in a 2 x 5 factorial scheme, consisting of two sorghum cultivars (BRS 310 and BRS 330) and five treatments (control without inoculation and four species of arbuscular mycorrhizal fungi: *Gigaspora margarita*, *Glomus formosanum*, *Acaulospora scrobiculata*, and *Scutellospora pellucida*), with four replications. Plant height, stem diameter, leaf area, length, volume, specific surface area, root diameter, shoot dry mass, root dry mass, thousand-grain weight, grain productivity, colonization, dependence, and mycorrhizal efficiency were evaluated. The results showed that inoculation with the species *S. pellucida* induced higher root and shoot development of plants of the cultivar BRS 310, as well as higher productivity of sorghum grains. The cultivar BRS 330 showed higher root development when inoculated with the species *G. formosanum* and a higher shoot development when inoculated with the species *A. scrobiculata*. Mycorrhizal dependence for grain productivity was low and varied with the inoculated species of mycorrhizal fungi. The mycorrhizal efficiency for shoot dry mass was higher with the inoculation of *A. scrobiculata* and *S. pellucida* in the cultivar BRS 310 and *A. scrobiculata* and *G. margarita* in the cultivar BRS 330.

Key words: *Acaulospora scrobiculata*. *Gigaspora margarita*. *Glomus formosanum*. Grain. *Scutellospora pellucida*.

DOI: 10.5935/1806-6690.20250015
Editor-in-Chief: Prof. Adriel Fonseca - adrielff@gmail.com
*Author for correspondence
Received for publication 06/05/2023; approved on 02/10/23
[1]Article extracted from part of the first author's dissertation, presented to the Postgraduate Course in Agronomy – Agriculture and Environment, Federal University of Santa Maria (UFSM), Frederico Westphalen Campus, Frederico Westphalen – RS, Brazil
[2]Postgraduate Program in Agronomy – Agriculture and Environment, Federal University of Santa Maria (UFSM), Frederico Westphalen Campus, Frederico Westphalen-RS, Brazil, eduardocanepelle@gmail.com (ORCID ID 0000-0002-4029-5558)
[3]Department of Agricultural and Environmental Sciences, Federal University of Santa Maria (UFSM), Frederico Westphalen Campus, Frederico Westphalen-RS, Brazil, rodrigosilvaufsm@gmail.com (ORCID ID 0000-0002-1747-2149)
[4]Federal University of Santa Maria (UFSM), Frederico Westphalen Campus, Frederico Westphalen-RS, Brazil, giovenardiandrea@gmail.com (ORCID ID 0000-0002-9800-1874), felipe.b.luz@ufsm.br (ORCID ID 0000-0002-4427-2396)
[5]Undergraduate Course in Agronomy, Federal University of Santa Maria (UFSM), Frederico Westphalen Campus, Frederico Westphalen-RS, Brazil, dasilvaanapaula2019@gmail.com (ORCID ID 0000-0003-4311-0069)
[6]Farroupilha Federal Institute - Frederico Westphalen Campus, Frederico Westphalen-RS, Brazil, sinarabarros@yahoo.com.br (ORCID ID 0000-0003-0466-4544)

INTRODUCTION

Grain sorghum cultivation has been expanding in Brazil, with an area of 1.032 million hectares cultivated in the 2021/2022 growing season, but the national mean productivity in this season was only 2,763 kg ha^{-1}, which is below the crop production potential of up to 7,000 kg ha^{-1} (CONAB, 2023; Menezes *et al.*, 2021). The small investment in base and top dressing fertilization contributes to the low sorghum productivity, as nutrient availability directly affects its production potential (Biesdorf *et al.*, 2018; Menezes *et al.*, 2018).

The nutritional requirements of sorghum are met with inorganic fertilizers, but only between 10 and 40% of the applied fertilization is used by the plants, and the rest is lost in the system, which increases its production cost due to the high acquisition value of fertilizers (Franco; Ramirez; Cháirez, 2019). In this scenario, there is a need to develop agronomic practices aiming to increase sorghum productivity, and inoculation of arbuscular mycorrhizal fungi (AMF) in plants would be a promising alternative (Franco, Hernández; Del Río, 2008; Franco *et al.*, 2014).

AMF form a mutualistic symbiotic association with 80% of plant species, allowing plants to increase water and nutrient absorption because the external fungal mycelium acts as an extension of the root system, expanding the soil exploration capacity (Novais *et al.*, 2017). Moreover, AMF provide host plants with a reduction in the effects of adverse abiotic conditions, production of phytohormones that stimulate plant growth, and protective action against some soil phytopathogens (Franco; Ramirez; Cháirez, 2019; Rodrigues; Barroso; Fiqueiredo, 2018). AMF inoculation in grain sorghum leads to an increase in root dry mass (Pérez; Rodríguez; Suárez, 2018), plant height, stem diameter (Franco; Ramirez; Cháirez, 2019), and also increases shoot dry matter, grain weight, grain production, and leaf contents of N, P, K, Zn, and Cu (Bressan *et al.*, 2001), being an alternative to promoting the growth and productivity of this crop.

However, the benefits to host plants may vary depending on the species of mycorrhizal fungus. Thus, enabling the use of AMF in plants is essential to selecting and isolating fungi that can improve their development and productivity (Franco *et al.*, 2014; Moreira; Siqueira, 2006). Nevertheless, doubts persist about which AMF species promote growth and productivity in different grain sorghum cultivars fertilized with inorganic fertilizer. This study aimed to determine the influence of different species of mycorrhizal fungi on the development and productivity of grain sorghum cultivars.

MATERIAL AND METHODS

The experiment was conducted from October 2021 to March 2022 in a greenhouse belonging to the Department of Agricultural and Environmental Sciences of the Federal University of Santa Maria, on the Campus of Frederico Westphalen. The soil was collected from the 0.00–0.20 m layer and characterized as an Oxisol (Latossolo Vermelho distrófico) (Santos *et al.*, 2018). After collection, the soil was sieved through a 0.002-m mesh opening sieve and mixed with fine sand at the proportion of 0.65 kg of soil with 0.35 kg of fine sand to facilitate root assessments. The soil was then sterilized in an autoclave at 121 °C during three cycles of 1,800 s. Subsequently, a sample of this sterilized soil was taken for analysis of chemical and physical attributes, which presented the following characteristics: 460 g kg^{-1} of clay, 5.3 of pH in water, 4.6 mg dm^{-3} of P (Mehlich-1), 27.5 mg dm^{-3} of K, 10 g kg^{-3} of OM, 1.7 cmol$_c$ dm^{-3} of Ca, 1 cmol$_c$ dm^{-3} of Mg, and 4.9 cmol$_c$ dm^{-3} of H+Al.

Liming was carried out 62 days before sowing based on soil analysis, consisting of the application of dolomitic limestone to reach a pH of 6.5 in water. After this procedure, the soil was placed in sterilized 0.005-m^3 plastic pots. Planting and top dressing fertilizations were conducted according to the crop requirements interpreted from soil analysis, following the recommendation of the Liming and Fertilization Manual for the States of RS and SC (CQFS, 2016), aiming for a production potential of 5,000 kg ha^{-1}. Fertilization consisted of 20 kg ha^{-1} of nitrogen (ammonium sulfate), 125 kg ha^{-1} of phosphorus (triple superphosphate), 130 kg ha^{-1} of potassium (potassium chloride), applied at the time of sowing, and 70 kg ha^{-1} of nitrogen (urea), applied as top dressing 35 days after plant emergence.

The experimental design was completely randomized, with four replications, in a 2 x 5 factorial scheme, consisting of two grain sorghum cultivars (BRS 310 and BRS 330) and five treatments (control without inoculation and four species of arbuscular mycorrhizal fungi: *Gigaspora margarita*, *Glomus formosanum*, *Acaulospora scrobiculata*, and *Scutellospora pellucida*). Each pot containing a sorghum plant was considered an experimental unit in this study.

The isolates of arbuscular mycorrhizal fungi were obtained from the collection of the Brazilian Agricultural Research Corporation (Embrapa Agrobiology, Seropédica, RJ, Brazil). The fungi were inoculated 300 seconds before sowing, with 30 spores of each isolate being applied to each pot in the holes opened in the soil to place the seeds corresponding to the cultivar to be sown (BRS 310 or BRS 330).

Sowing was carried out on October 7 th, with five seeds per pot. Thinning was conducted ten days later, leaving only one plant per pot until the end of the experiment. The seeds were previously disinfected with 2% sodium hypochlorite for ten minutes and washed three times in sterilized water. The plants were grown in plastic pots with a 0.005-m^3 capacity filled with 5 kg of the soil and sand mixture. Plants were irrigated daily using an automatic sprinkler irrigation system, maintaining moisture at 80% of field capacity.

Leaf area (LA) was evaluated at the full flowering stage (88 days after sowing) by the triangle/trapezoid method, as proposed by Sousa *et al.* (2015). Moreover, the following traits were evaluated at the end of the crop cycle (152 days after sowing): plant height (PH), obtained with a graduated ruler, measuring the distance from the plant collar to the panicle insertion; stem diameter (SD), determined with a digital caliper (Black Jack Tools®, Campinas, SP, BR); thousand-grain weight (TGW), determined by manual separation and counting of a thousand grains; and grain productivity (GP), obtained through the grains existing in the plant's panicle, being extrapolated to a population of 180,000 plants ha^{-1}, which were weighed on an analytical balance, with moisture corrected to 13%.

After collecting the plants (152 days after sowing), the shoot was separated from the root in the collar region, the roots were separated from the soil by washing with running water using sieves with a mesh size of 0.0005 m, the root volume (RV) was determined by the graduated cylinder method (Turchetto *et al.*, 2022), and the root system fresh mass (RSFM) was obtained through weighing on an analytical balance. The total root length (RL) was determined by the Tennant (1975) method using a sample of 0.005 kg of RSFM. The specific root surface area (SSA) and mean root diameter (D) were determined according to Schenk and Barber (1979). The RSFM and the shoot were dried in an oven at 65 ± 1 °C until constant mass and weighed on an analytical balance to determine the root dry mass (RDM) and shoot dry mass (SDM).

The mycorrhizal colonization was evaluated with 0.001 kg of fresh roots using the technique of clarifying and staining roots with 0.05% Trypan Blue (Phillips; Hayman, 1970), and the percentage of colonization estimated in six replications per plant using the checkerboard method, as described by Giovannetti and Mosse (1980).

The results of grain production and shoot dry mass were used to determine mycorrhizal dependence (MD) and mycorrhizal efficiency (ME), respectively. Mycorrhizal dependence was determined according to Miranda (2012) by Equation (1):

$$MD(\%) = \frac{grain\ production\ with\ mycorrhiza - grain\ production\ without\ mycorrhiza}{grain\ production\ with\ mycorrhiza} \times 100 \quad (1)$$

Mycorrhizal dependence was classified as very high, when > 75%, high, from 51 to 75%, medium, from 26 to 50%, low, from 1 to 25%, and null, when = 0% (MIRANDA, 2012). Mycorrhizal efficiency was determined according to Silva *et al.* (2011b) by Equation (2):

$$ME(\%) = \frac{shoot\ dry\ mass\ with\ mycorrhiza - shoot\ dry\ mass\ without\ mycorrhiza}{shoot\ dry\ mass\ without\ mycorrhiza} \times 100 \quad (2)$$

The results were subjected to analysis of variance. The effect of inoculum sources was compared within each cultivar and between cultivars when there was a significant interaction. The single effects of variation factors were analyzed through the test of Scott Knott mean comparison at 5% probability ($p \leq 0.05$) when there was no significant interaction. The analyses were carried conducted using the SISVAR statistical program (Ferreira, 2011). Moreover, principal component analysis (PCA) was carried out between inoculation treatments with arbuscular mycorrhizal fungi (AMF) in the two grain sorghum cultivars (BRS 310 and BRS 330), using the computer program PAST version 2.17c (Hammer; Harper; Ryan, 2001).

RESULTS AND DISCUSSION

The results showed a significant interaction between inoculum and grain sorghum cultivars for RDM, RV, RL, D, SSA, and SDM. The RDM of sorghum plants of the cultivar BRS 310 was higher with the inoculation of *G. formosanum* and *S. pellucida* and the cultivar BRS 330 with the inoculation of *G. formosanum* and *G. margarita* (Table 1). This result corroborates other studies (Franco; Ramirez; Cháirez, 2019; Pérez; Rodríguez; Suárez, 2018), being attributed to the production of phytohormones by AMF during the symbiosis, as well as the formation of fungal hyphae in the roots of plants, which expand the root absorption area (Franco *et al.*, 2014; Moreira; Siqueira, 2006).

The RV of the cultivars BRS 310 and BRS 330 was higher with *S. pellucida* and *G. formosanum* inoculations, respectively (Table 1). Nunes *et al.* (2019) also observed increased root volume with AMF inoculation in corn. It occurs due to the external mycelium produced by AMF, which increases root volume, enabling plants to explore a larger area of soil (Moreira; Siqueira, 2006; Novais *et al.*, 2017).

The RL of sorghum plants of the cultivar BRS 310 was higher with AMF inoculations, particularly *S. pellucida* and *G. formosanum*. Inoculation of *G. formosanum* in the cultivar BRS 330 also stood out (Table 1). Turchetto *et al.* (2022) analyzed the wheat root system and also found an increase in root length with AMF inoculation. AMF produce external hyphae on plant roots, which function as an extension of the plant's root system (Novais *et al.*, 2017), which may contribute to a higher RL of plants inoculated with AMF.

The D of sorghum plants of the cultivar BRS 310 was lower with the inoculation of the fungi *A. scrobiculata*, *G. formosanum*, *G. margarita*, and *S. pellucida*, while plants of the cultivar BRS 330 had a lower D value when inoculated with *G. formosanum* (Table 2). The reduction in D results in a predominance of fine roots, which together with external fungal hyphae increase nutrient absorption by plants due to access to small-diameter soil pores (Moreira; Siqueira, 2006). Furthermore, the AMF species that caused a decrease in D (Table 2) also significantly increased their RL (Table 1).

The SSA of the cultivar BRS 310 was higher when inoculated with *S. pellucida* and *G. formosanum*, not differing from the cultivar BRS 330, and was significantly higher in this cultivar than the other inocula (Table 2). This increase occurs because AMF increases root length and reduces its diameter, as thinner and longer roots have higher specific surface area The external hyphae produced by mycorrhizal fungi next to the roots of the host plant also contribute to the increase in the root area of mycorrhized plants, as they are very thin (Novais *et al*., 2017).

SDM of the cultivar BRS 310 was higher with the AMF *A. scrobiculata* and *S. pellucida* relative to the control but lower than in BRS 330, which had a higher SDM with the inocula *G. margarita* and *A. scrobiculata*, with an increase of 15.15 and 11.24%, respectively, compared to the control (Table 2). The increase in sorghum SDM due to AMF inoculation has also been reported in other studies (Franco; Ramirez; Cháirez, 2019; Pérez; Rodríguez; Suárez, 2018). The nutritional and

Table 1 - Root dry mass (RDM), root volume (RV), and root length (RL) of two grain sorghum cultivars inoculated with the mycorrhizal fungi *Acaulospora scrobiculata*, *Glomus formosanum*, *Gigaspora margarita*, and *Scutellospora pellucida* and control (without inoculation)

Inoculum	Cultivar					
	BRS 310	BRS 330	BRS 310	BRS 330	BRS 310	BRS 330
	RDM (g)		RV (cm^3)		RL (m)	
Control	21.75 Ab	22.00 Ab	133.25 Ac	92.50 Bd	6.26 Bc	7.58 Ab
A. scrobiculata	22.50 Ab	22.25 Ab	142.75 Ac	93.25 Bd	7.31 Ab	7.55 Ab
G. formosanum	26.75 Ba	32.25 Aa	151.00 Bb	167.75 Aa	8.55 Ba	9.50 Aa
G. margarita	23.75 Bb	30.00 Aa	135.00 Bc	147.50 Ab	7.57 Bb	8.41 Ab
S. pellucida	28.00 Aa	23.75 Bb	165.00 Aa	121.25 Bc	9.38 Aa	8.12 Bb
CV %	9.88		4.91		7.91	

CV = coefficient of variation. Means followed by the same lowercase letter in the column and uppercase letter in the row within each variable do not differ from each other by the Scott-Knott test at a 5% probability of error

Table 2 - Root diameter (D), specific root surface area (SSA), and shoot dry mass (SDM) of two grain sorghum cultivars inoculated with the mycorrhizal fungi *Acaulospora scrobiculata*, *Glomus formosanum*, *Gigaspora margarita,* and *Scutellospora pellucida*, and a control (without inoculation)

Inoculum	Cultivar					
	BRS 310	BRS 330	BRS 310	BRS 330	BRS 310	BRS 330
	D (mm)		SSA (m^2)		SDM (g)	
Control	0.99 Aa	0.91 Ba	0.19 Bc	0.22 Ab	18.16 Bb	30.70 Ab
A. scrobiculata	0.92 Ab	0.91 Aa	0.21 Ab	0.22 Ab	22.37 Ba	34.15 Aa
G. formosanum	0.86 Ac	0.82 Ab	0.23 Aa	0.24 Aa	19.25 Bb	32.33 Ab
G. margarita	0.90Ab	0.86 Aa	0.22 Ab	0.22 Ab	19.27 Bb	35.35 Aa
S. pellucida	0.83 Ac	0.88 Aa	0.24 Aa	0.22 Bb	22.17 Ba	31.97 Ab
CV (%)	3.92		4.37		6.23	

CV = coefficient of variation. Means followed by the same lowercase letter in the column and uppercase letter in the row within each variable do not differ from each other using the Scott-Knott test at a 5% probability of error non-nutritional benefits provided by AMF induce plant development and enable a higher SDM production (Moreira; Siqueira, 2006; Pérez; Rodríguez; Suárez, 2018). Thus, SDM of sorghum cultivars varies depending on the inoculated AMF species, with *A. scrobiculata* being efficient in increasing this parameter in both cultivars.

The results showed no significant interaction between inoculum sources and sorghum cultivars for PH, SD, LA, TGW, and GP, but a significant single effect of the sources of variation was observed, except for SD for inoculum and PH for cultivars.

Inoculation of the AMF *A. scrobiculata* provided a significant increase in PH relative to the other treatments (Table 3). The hyphae produced by fungi increase the soil volume explored by the root system of inoculated plants, providing higher efficiency in water and nutrient absorption, and resulting in higher vegetative growth (Abreu *et al*., 2018; Novais *et al*., 2017).

Inoculation with the AMF *A. scrobiculata*, *G. margarita*, and *S. pellucida* resulted in 33.26, 23.23, and 19.14% higher LA relative to the control, respectively (Table 3). The increase in LA caused by arbuscular mycorrhizal fungi provides an expansion of the photosynthetic area, which benefits carbon assimilation by plants and, consequently, their development (Lessa *et al*., 2018).

TGW was significantly higher with *S. pellucida* inoculation, being 33.10% higher than the control (Table 3). AMF provide plants with higher nutrient absorption, including nitrogen (Novais *et al*., 2017). Nitrogen has a direct influence on sorghum grain production and, therefore, its availability to plants affects the weight of its grains (Goes *et al*., 2011; Nakao *et al*., 2014).

Plants of the cultivar BRS 330 presented SD and LA values 3.62 and 53.43% higher, respectively, than those of the cultivar BRS 310 (Table 3). A higher SD makes plants less susceptible to lodging (Nakao *et al*., 2014), while LA is a morphological parameter used to estimate the photosynthetic capacity of plants and predict SDM production (Borrego *et al*., 2021). This relationship was also evidenced in this study in the cultivar BRS 330, which presented higher LA (Table 3) and SDM (Table 2) than the cultivar BRS 310.

TGW of the cultivar BRS 310 was significantly 24.08% higher than that of the cultivar BRS 330 (Table 3). Almeida *et al*. (2015) observed a variation in sorghum TGW between hybrids, while Silva *et al*. (2011a) found a variation between cultivars. Grain weight is an important component of sorghum production, as it directly reflects its final productivity (Nakao *et al*., 2014). However, this component is influenced by the cultivar, and the cultivar BRS 310 stood out in this study for providing the highest TGW.

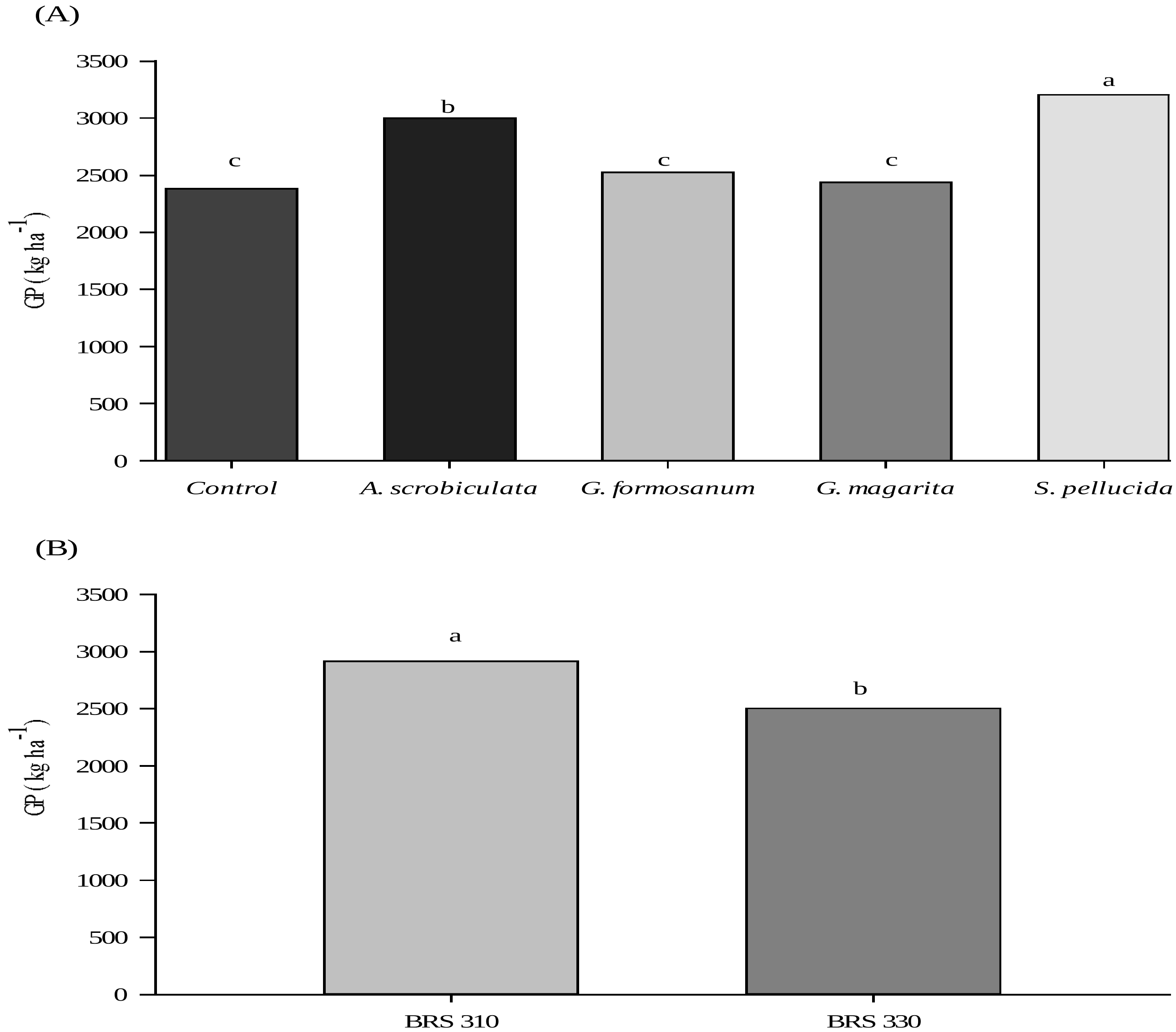
GP with *S. pellucida* inoculation was 34.57% higher than the control (Figure 1A). The inoculation of this isolate provided productivity of 3,204 kg ha^{-1}, which is also 15.97% higher than the national mean for the 2021/2022 growing season. Research results have also shown an increase in sorghum grain productivity with AMF inoculation (Franco; Hernández; Del Río, 2008; Franco; Ramirez, Cháirez, 2019). It occurs because the external mycelium of the fungus expands the plant's ability to explore the soil, improving its nutrition and providing an increase in development and productivity (Franco; Ramirez, Cháirez 2019; Novais *et al*., 2017).

Table 3 - Single effect of mycorrhizal inoculum (*Acaulospora scrobiculata*, *Glomus formosanum*, *Gigaspora margarita*, and *Scutellospora pellucida*) and the control (without inoculation) on plant height (PH), leaf area (LA), thousand-grain weight (TGW), and cultivars (BRS 310 and BRS 330) on stem diameter (SD), leaf area (LA), and thousand-grain weight (TGW) of grain sorghum

Inoculum	PH (m)	LA (m^2)	TDW (g)
Control	1.13 b	0.13 b	15.62 c
A. scrobiculata	1.19 a	0.17 a	19.24 b
G. formosanum	1.14 b	0.14 b	16.42 c
G. margarita	1.12 b	0.15 a	15.88 c
S. pellucida	1.14 b	0.15 a	20.79 a
CV (%)	3.68	14.75	5.01
Cultivar	SD (mm)	LA (m2)	TGW (g)
BRS 310	17.15 b	0.12 b	19.48 a
BRS 330	17.77 a	0.18 a	15.70 b
CV (%)	4.36	14.75	5.01

CV = coefficient of variation. Means followed by the same lowercase letter in the column do not differ from each other by the Scott-Knott test at a 5% probability of error

Figure 1 - Single effect of mycorrhizal inoculum (*Acaulospora scrobiculata*, *Glomus formosanum*, *Gigaspora margarita*, and *Scutellospora pellucida*), as well as the control (without inoculation) (A), and cultivars (BRS 310 and BRS 330) (B) on sorghum grain productivity (GP)

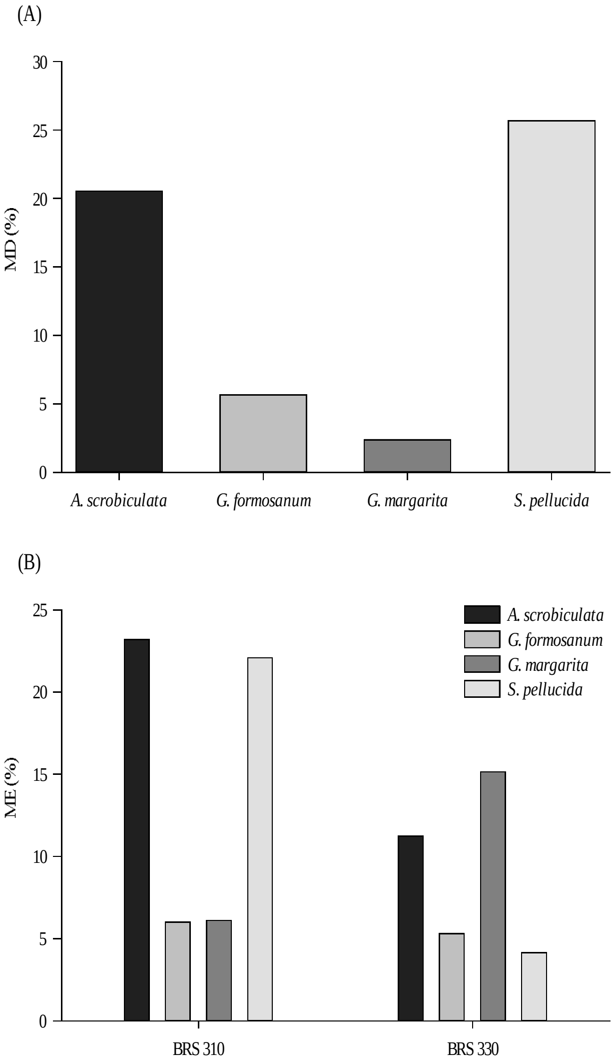


Means followed by the same lowercase letter do not differ from each other by the Scott-Knott test at a 5% probability of error

GP of the cultivar BRS 310 was 16.47% higher than that of the cultivar BRS 330 (Figure 1B). The production variability of grain sorghum is related to the cultivars, among other factors (May *et al.*, 2011). In this sense, Andrade *et al.* (2016) and Mota, Bevilaqua, and Menezes (2016) also observed that the GP of grain sorghum varied significantly between cultivars, with some of them being more productive than others.

Grain sorghum MD for grain productivity was positive, reaching 20.55, 5.67, 2.38, and 25.69% with *A. scrobiculata*, *G. formosanum*, *G. margarita*, and *S. pellucida* inoculation, respectively (Figure 2A). These results demonstrated that the MD of grain sorghum was low (Miranda, 2012), but they highlight that grain sorghum presents a higher MD with *A. scrobiculata* and *S. pellucida* inoculation (Figure 2A), which provides a significant increase in grain productivity. Sorghum MD is broadly classified as high but variations in its degree may occur depending on the cultivars and/or varieties and the inoculated species of mycorrhizal fungi (Berude *et al.*, 2015; Miranda, 2012; Miranda; Miranda, 2004). In this sense, grain sorghum MD is altered depending on the species of fungus inoculated to the plants.

Figure 2 - Mycorrhizal dependence (MD) in grain production of grain sorghum (A) and mycorrhizal efficiency (ME) in the shoot dry mass of grain sorghum cultivars (B) inoculated with the fungi *Acaulospora scrobiculata, Glomus formosanum, Gigaspora margarita* and *Scutellospora pellucida*



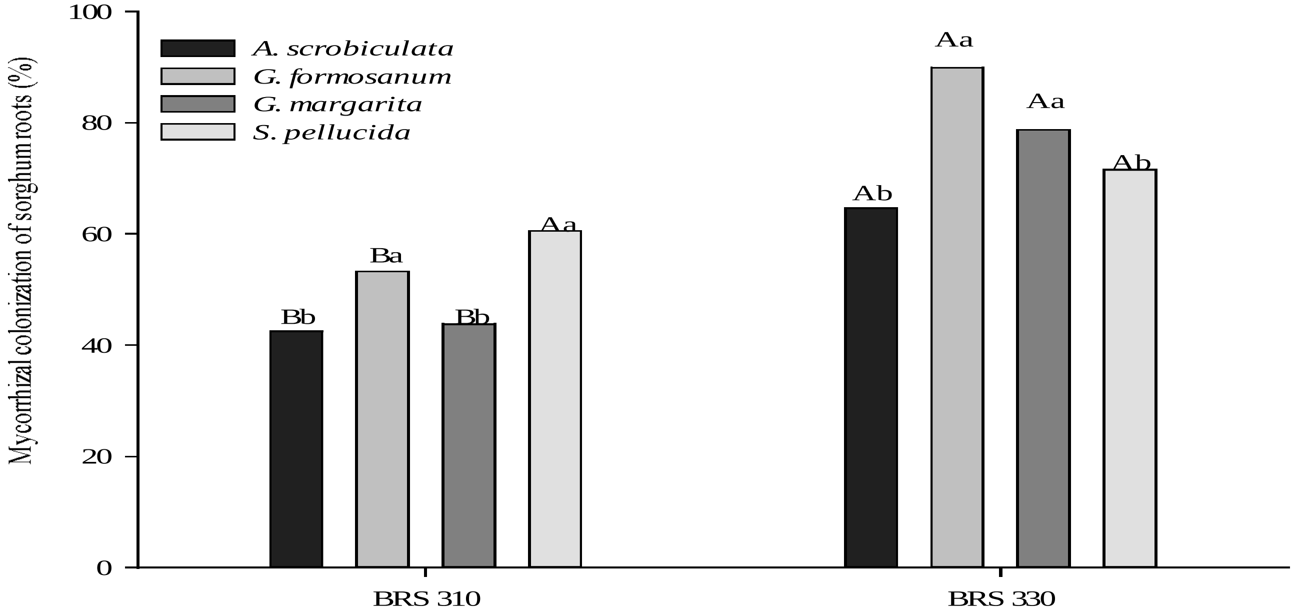
ME for the shoot dry mass of the grain sorghum cultivar BRS 310 was higher for the species *A. scrobiculata* and *S. pellucida*, with values of 23.18 and 22.08%, respectively, while the species *G. formosanum* and *G. margarita* had efficiencies of 6.00 and 6.11%, respectively. In the cultivar BRS 330, the species *A. scrobiculata* and *G. margarita* had higher efficiency, with values of 11.24 and 15.15%, respectively, while *G. margarita* and *S. pellucida* presented efficiencies of 5.31 and 4.13%, respectively (Figure 2B). These results demonstrated that the tested species of mycorrhizal fungi are efficient in improving the development of grain sorghum, especially *A. scrobiculata* and *S. pellucida* in the BRS 310 cultivar and *A. scrobiculata* and *G. margarita* in BRS 330. Variations in ME between AMF species during the plant development occur because the species present different compatibility with the host plant, and the inoculum efficiency depends on the compatibility of the inoculated fungus with the host plant. Therefore, efficiency is higher with species that have higher compatibility with the host plant (Moreira; Siqueira, 2006).

The percentage of mycorrhizal colonization was higher in the cultivar BRS 310 with *G. formosanum* and *S. pellucida* inoculation, not differing from BRS 330, which was significantly higher than the others (Figure 3). Bressan *et al.* (2001) also observed variations in mycorrhizal colonization of sorghum roots between AMF species. It happens because the compatibility between the plant and the fungus varies among AMF species, with the percentage being higher in species that have higher compatibility (Moreira; Siqueira, 2006). Therefore, the percentage of mycorrhizal colonization varied between AMF species and sorghum cultivars tested in this study, and *S. pellucida* and *G. formosanum* inoculation is recommended for BRS 310 and *G. formosanum* and *G. margarita* for BRS 330.

The construction of the principal component analysis (PCA) (Figure 4) used inoculation treatments with AMF added to control treatments in both grain sorghum cultivars (BRS 310 and BRS 330) as gradients to analyze the attributes that presented or did not present a significant interaction. A total of 46% of the data variability was explained by principal component 1 (PC1) and 26% by principal component 2 (PC2). The indices and measures that showed a significant interaction when analyzed in PCA tended to maintain a relationship with *S. pellucida* and *G. formosanum* in the cultivar BRS 310. Similarly, production parameters that did not present significant interactions showed interactions related to *A. scrobiculata* and *G. margarita* in the cultivar BRS 310, as well as plant height. In contrast, the metric parameters leaf area and stem diameter showed a trend toward relationships with *G. formosanum* and *G. margarita* for the cultivar BRS 330. In general, there is an indication of a grouping related to cultivars with certain fungi, demonstrating specificities between them. The controls of both cultivars showed no relationship with the other analyzed parameters.

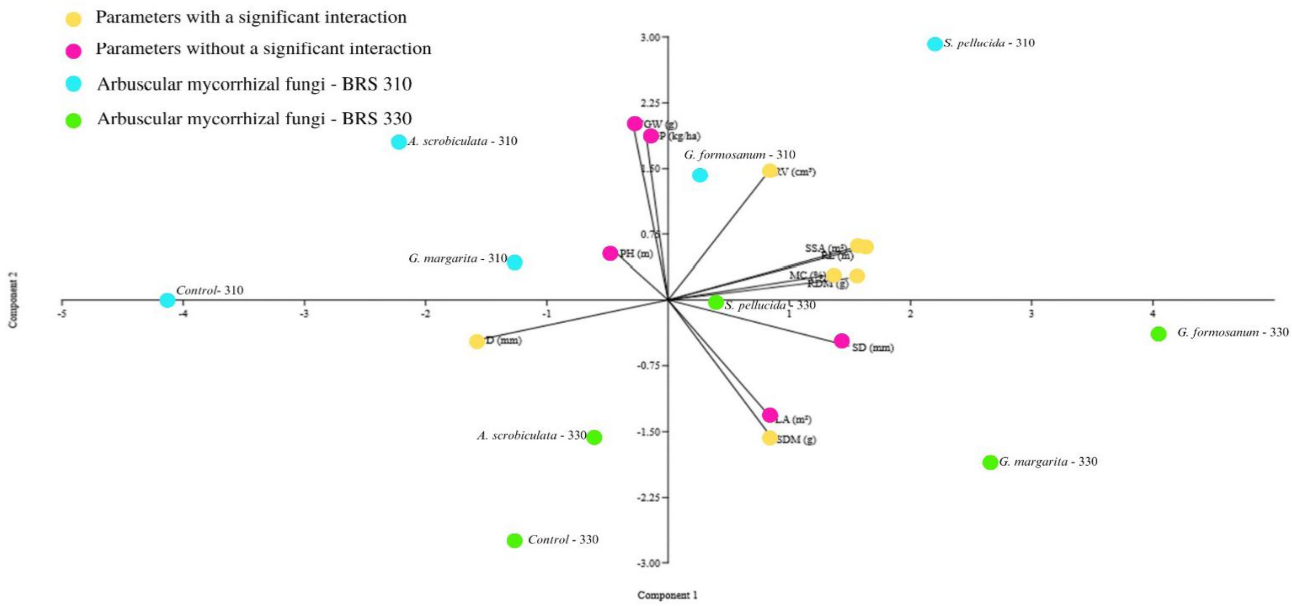
The fungus *S. pellucida* increased the grain productivity of grain sorghum and the development of the shoot and root of plants of the cultivar BRS 310. The fungus *G. formosanum* induced a better root development in plants of the cultivar BRS 330, whereas *A. scrobiculata* induced a better shoot development. The cultivar BRS 310 showed higher grain productivity than BRS 330. In addition, this cultivar showed a higher productivity than the national average when inoculated with the fungus *S. pellucida*. Thus, in this study carried out in a greenhouse, the cultivar BRS 310 stood out as the most productive, and the species *S. pellucida* as the most efficient in increasing the development and grain productivity of this grain sorghum cultivar. However, there is still a need to evaluate this association under field conditions to ensure its efficiency.

Figure 3 - Mycorrhizal colonization of roots of the sorghum cultivars BRS 310 and BRS 330 inoculated with the mycorrhizal fungi *Acaulospora scrobiculata*, *Glomus formosanum*, *Gigaspora margarita*, and *Scutellospora pellucida*



Means followed by the same uppercase letter between sorghum cultivars and lowercase letters within each cultivar do not differ from each other by the Scott-Knott test at a 5% probability of error

Figure 4 - Principal component analysis (PCA) of inoculation treatments with arbuscular mycorrhizal fungi (AMF) in two grain sorghum cultivars (BRS 310 and BRS 330) and quantitative and productivity attributes



Gradients: *Acaulospora scrobiculata*, *Glomus formosanum*, *Gigaspora margarita*, *Scutellospora pellucida*, and control without inoculation in two grain sorghum cultivars (BRS 310 and BRS 330). Attributes: RDM = root dry mass (g); RV = root volume (cm^3); RL = root length (m); D = root diameter (mm); SSA = specific root surface area (m^2); SDM = shoot dry mass (g); PH = plant height (m); LA = leaf area (m^2); TGW = thousand-grain weight (g); SD = stem diameter (mm); GP = grain productivity (kg/ha); MC = mycorrhizal colonization (%)

CONCLUSIONS

1. Inoculation of the species *Scutellospora pellucida* induced higher root and shoot development of sorghum plants of the cultivar BRS 310, as well as higher sorghum grain productivity;
2. Inoculation of the species *Glomus formosanum* induced higher root development in the cultivar BRS 330, while inoculation of *Acaulospora scrobiculata* induced a higher shoot development.

ACKNOWLEDGMENTS

To the Federal University of Santa Maria, campus of Frederico Westphalen, for providing the necessary facilities to carry out this study, and the Coordination for the Improvement of Higher Education Personnel – Brazil (CAPES) – Financing Code 001, for financial support.

REFERENCES

ABREU, G. M. *et al*. Crescimento inicial e absorção de fósforo e nitrogênio de *Enterolobium contortisiliquum* inoculada com fungos micorrízicos arbusculares. **Revista de Ciências Agrárias**, v. 41, n. 1, p. 156-164, 2018.

ALMEIDA, E. F. *et al*. Desempenho agronômico de híbridos de sorgo granífero na safrinha em Jataí-GO. **Scientia Plena**, v. 11, n. 12, p. 1-7, 2015.

ANDRADE, L. C. *et al*. Avaliação de produtividade, adaptabilidade e estabilidade genotípica de sorgo granífero em três ambientes. **Revista Agropecuária Técnica**, v. 37, n. 1, p. 36-43, 2016.

BERUDE, M. C. *et al.* Micorrizas e sua importância agroecológica. **Enciclopédia Biosfera**, v. 11, n. 22, p. 132-146, 2015.

BIESDORF, E. M. *et al.* Efeito inibitório do sorgo granífero na cultura da soja semeada em sucessão. **Revista Brasileira de Milho e Sorgo**, v. 17, n. 3, p. 445-459, 2018.

BORREGO, F. Z. *et al*. Efeito de diferentes níveis de evapotranspiração sobre a área foliar, temperatura superficial, potencial hídrico e produtividade de sorgo forrageiro. **Terra Latinoamericana**, v. 39, p. 1-14, 2021.

BRESSAN, W. *et al*. Fungos micorrízicos e fósforo, no crescimento, nos teores de nutrientes e na produção do sorgo e soja consorciados**. Pesquisa Agropecuária Brasileira**, v. 36, p. 315-323, 2001.

COMISSÃO DE QUÍMICA E FERTILIDADE DO SOLO-RS/SC (CQFS-RS/SC). **Manual de calagem e adubação para os estados do Rio Grande do Sul e de Santa Catarina**. 11. ed. Porto Alegre: Sociedade Brasileira de Ciência do Solo, 2016. 375 p.

COMPANHIA NACIONAL DE ABASTECIMENTO (CONAB). **Portal de informações agropecuárias. Produção agrícola: safras-estimativas-grãos**. 2023. Disponível em: https://portaldeinformacoes.conab.gov.br/safra-estimativa-de-evolucao-graos.html. Acesso em: 24 jan. 2023.

FERREIRA, D. F. Sisvar: sistema computacional de análise estatística. **Ciência e agrotecnologia**, v. 35, n. 6, p. 1039-1042, 2011.

FRANCO, A. D. *et al*. Características de planta, suelo y productividad entre sorgo fertilizado e inoculado con micorriza arbuscular. **Revista mexicana de ciencias agrícolas**, v. 5, n. 3, p. 379-390, 2014.

FRANCO, A. D.; HERNÁNDEZ, C. J.; DEL RÍO, M. A. P. Productividad de sorgo en campo asociada con micorriza arbuscular y *Azospirillum brasilense*. **Universidad y ciencia**, v. 24, n. 3, p. 229-237, 2008.

FRANCO, A. D.; RAMIREZ, M. E.; CHÁIREZ, F. E. O. Reducción de la fertilización inorgánica mediante micorriza arbuscular en Sorgo. **Revista internacional de contaminación ambiental**, v. 35, n. 3, p. 683-692, 2019.

GIOVANNETTI, M.; MOSSE, B. An evaluation of techniques for measuring vesiculararbuscular mycorrhizal infection in roots. **New Phytologist**, v. 84, n. 3, p. 489-500, 1980.

GOES, R. J. *et al.* Fontes e doses de nitrogênio em cobertura, no sorgo granífero na safrinha. **Revista Brasileira de Milho e Sorgo**, v. 10, n. 2, p. 121-129, 2011.

HAMMER, Ø.; HARPER, D. A. T.; RYAN P. D. PAST: Paleontological Statistics software package for education and data analysis. **Palaeontologia Electronica**, v. 4, n. 1, p. 9, 2001.

LESSA, B. F. T. *et al*. Modelos matemáticos para a estimativa da área foliar total em sorgo sacarino. **Energia na Agricultura**, v. 33, n. 2, p. 175-182, 2018.

MAY, A. *et al*. **Cultivares de sorgo para o mercado brasileiro na safra 2011/2012**. 1. ed. Sete Lagoas: Embrapa Milho e Sorgo, 2011. 28 p.

MENEZES, C. B. *et al*. É Possível Aumentar a Produtividade de Sorgo Granífero no Brasil?. *In*: PAES, M. D. A; VINHO, R. G.; MOREIRA, S. G. (ed.). **Livro de palestras: Soluções integradas para os sistemas de produção de milho e sorgo no Brasil**. Sete Lagoas: Associação Brasileira de Milho e Sorgo, 2018. p. 106-139.

MENEZES, C. B. *et al.* Importância do sorgo para o abastecimento de grãos, forragem e bioenergia no Brasil. *In:* MENEZES, C. B. (ed). **Melhoramento Genético de Sorgo**. Brasília: Embrapa, 2021. p.13-58.

MIRANDA, J. C. C. **Cerrado micorriza arbuscular manejo e ocorrência**. 2. ed. Brasília: Embrapa Cerrado, 2012. 169 p.

MIRANDA, J. C. C.; MIRANDA, L. N. **Dependência micorrízica de diferentes culturas anuais, adubos verdes e pastagens em solos de cerrado**. 1. ed. Planaltina: Embrapa Gado de corte, 2004. 3 p. (Comunicado Técnico, 114).

MOREIRA, F. M. S.; SIQUEIRA, J. O. **Microbiologia e Bioquímica do solo**. 2. ed. Lavras: Editora UFLA, 2006. 729 p.

MOTA, J. H.; BEVILAQUA, L. K. A.; MENEZES, C. B. Avaliação de cultivares de sorgo granífero na safrinha em Jataí, GO. **Revista de Agricultura**, v. 91, n. 3, p. 240-248, 2016.

NAKAO, A. *et al*. Resposta do sorgo granífero à aplicação de diferentes doses e épocas de inoculante (*Azospirillum brasilense*) via foliar. **Enciclopédia Biosfera**, v. 10, n. 18, p. 2702-2714, 2014.

NOVAIS, C. B. *et al*. **Técnicas Básicas em Micorrizas Arbusculares**. Lavras: Ed.UFLA, 2017.132 p.

NUNES, A. B. C. *et al*. Steel slag and phosphate nutrition of corn inoculated with arbuscular mycorrhizal fungi. **Pesquisa Agropecuária Brasileira**, v. 54, p. 1-9, 2019.

PÉREZ, Y. M.; RODRÍGUEZ, J. M. D. A.; SUÁREZ, K. F. Evaluación de la infectividad de *Glomus cubense* en formulación líquida sometida a diferentes presiones hidrostáticas. **Cultivos Tropicales**, v. 39, n. 4, p. 86-90, 2018.

PHILLIPS, J. M.; HAYMAN, D. S. Improved proceduresfor clearing roots and staining parasitic and vesicular-arbuscularmycorrhizal fungi for rapid assessment of infection. **British Mycological Society Transactions**, v. 55, n. 1, p. 158-161, 1970.

RODRIGUES, L. A.; BARROSO, D. G.; FIQUEIREDO, F. A. M. M. A. Fungos micorrízicos arbusculares no crescimento e na nutrição mineral de mudas de *Tectona grandis* LF. **Ciência Florestal**, v. 28, n. 1, p. 25-34, 2018.

SANTOS, H. G. *et al*. **Sistema Brasileiro de classificação de solos**. 5. ed. Brasília: Embrapa, 2018. 356 p.

SCHENK, M. K.; BARBER, S. A. Absorção de fosfato pelo milho em função das características do solo e morfologia radicular. **Soil Science Society of America Journal**, v. 43, n. 5, p. 880-883, 1979.

SILVA, K. J. *et al*. **Ensaio de Competição Entre Cultivares de Sorgo Granífero Para a Região Sudeste de Minas Gerais**. 2011a. Disponível em: https://ainfo.cnptia.embrapa.br/digital/bitstream/item/40591/1/ensaio-competicao.pdf. Acesso em: 23 mar. 2023.

SILVA, R. F. *et al*. Ectomicorrização em quatro espécies florestais nativas do Rio Grande do Sul e sua eficiência em solo contaminado por cobre. **Ciência e Natura**, v. 33, n. 2, p. 95-109, 2011b.

SOUSA, L. F. *et al*. Método prático e eficiente para estimar a área foliar de gramíneas forrageiras tropicais. **Archivos de Zootecnia**, v. 64, n. 245, p. 83-85, 2015.

TENNANT, D. A test of a modified line intersect method of estimating root length. **Journal of Ecology**, v. 63, n. 3, p. 995-1001, 1975.

TURCHETTO, R. *et al*. Arbuscular mycorrhizal fungi in wheat grown in copper contaminated soil. **Semina: ciências agrárias**, v. 43, n. 4, p. 1579-1594, 2022.