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Article

Arbuscular Mycorrhizal Fungi in Cerrado: An Overview of Scientific Production, Trends, and Gaps

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RESUMO

Os fungos micorrizicos arbusculares (FMA) são fungos biotróficos obrigatórios do filo *Glomeromycota*, esses fungos estão intimamente relacionados a biomassa vegetal. Entretanto, pouco se sabe sobre esses fungos uma vez que vivem abaixo do solo, ainda mais em domínios tão ameaçados e importantes como o Cerrado. Nosso objetivo nesse estudo, foi avaliar as tendências e lacunas da produção científica sobre *Glomeromycota* no Cerrado, visando mostrar um panorama da produção científica nos últimos dez anos, mostrando tendências e lacunas das pesquisas com FMA no Cerrado. Para isso, utilizamos uma busca booleana de artigos na base de dados Web of Science com termos específicos. Recuperamos 63 artigos que nos mostraram que há uma tendência no aumento do número de publicações sobre FMA, entretanto a maioria dos estudos estão voltados para uma abordagem ecológica, taxonômica e agrícola do fungo, tendo uma grande lacuna de conhecimento biotecnológica e de uso desses fungos. Esperamos com esses dados, auxiliar pesquisas acerca de FMA, e impulsionar o conhecimento sobre o filo *Glomeromycota* no Cerrado.
Palavras-chave: Cerrado; cienciometria; fma; *Glomeromycota*.

ABSTRACT

Arbuscular mycorrhizal fungi (AMF) are obligate biotrophic fungi from the *Glomeromycota* phylum, closely related to plant biomass. However, little is known about these fungi since they live below ground, especially in threatened and important areas like the Cerrado. Our aim in this study was to evaluate the trends and gaps in the scientific production of *Glomeromycota* in the Cerrado, to show an overview of scientific production over the last ten years, showing trends and gaps in research on AMF in the Cerrado. We used a Boolean search for articles in the Web of Science database with specific terms to do this. We obtained 63 articles which showed us that there is a trend towards an increase in the number of publications on AMF, however, most of the studies are focused on an ecological, taxonomic, and agricultural approach to the fungus, leaving a large gap in biotechnological knowledge and the use of these fungi. We hope that these data will help with research into AMF and boost knowledge about the *Glomeromycota* phylum in the Cerrado.
Keywords: amf; Cerrado; *Glomeromycota*; scientometrics.

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Introduction

Arbuscular mycorrhizal fungi (AMF) from the *Glomeromycota* phylum have obligatory biotrophic interaction with most terrestrial plants. These fungi are strictly associated with nutrient cycling, the balance of the carbon cycle, and plant tolerance to stresses, as well as promoting the ecological balance of plant biodiversity, among other factors (Jesus et al. 2022; Cely et al. 2016; van der Heijden et al. 1998). However, there is little data on the regional and global distribution of AMF, as there is not enough information on the biogeography and biology of these organisms (Hart et al., 2018; Silva-Flores et al., 2021), especially when we talk about phytogeographic domains such as the Cerrado.

The Cerrado is Brazil second largest domain, connecting with several other biomes. It represents 30% of Brazil biodiversity and has a high rate of biodiversity endemism, representing significant importance for all Brazilian ecosystems (Carvalho et al. 2009; Santos et al. 2021). However, this domain has been suffering from several negative impacts, such as the intense reduction of vegetation cover, mainly associated with the expansion of the agricultural frontier into the Cerrado, with the main factors in the reduction of vegetation being deforestation and natural and unnatural fires (Santos et al., 2021; Silva & Barbosa, 2020). Despite this, this ecosystem is home to a high diversity of AMF species, and some of the phytophysiognomies present in it, such as the rupestrian grasslands, are highly promising in terms of species diversity, as reported in recent research on the group in this domain, which so far has 92 species recorded (Jobim et al., 2016).

Agricultural activities in the Cerrado cause various disturbances based on habitat fragmentation, impacting not only above ground organisms but also those that live below ground and, above all, those dependent on plant biomass, such as the fungi of the *Glomeromycota* phylum (Araujo et al., 2021; Gerz et al., 2019). In this sense, as the effects of global change and anthropogenic disturbance increase, AMF communities are being reduced, so global AMF diversity must be monitored and protected (French, 2017).

Therefore, studies that allow us to draw up a profile of scientific knowledge about the biodiversity of mycorrhizae are essential to advance local and global knowledge of these organisms, thus guaranteeing their conservation (Silva Flores et al., 2021). The present study aimed to evaluate the trends and gaps in the scientific production of *Glomeromycota* in the Cerrado, in scientometric terms, to list the temporal trends in scientific production, institutions that research AMF in the Cerrado, journals that publish on the subject, keywords, and what they show about scientific production on the subject. It is hoped that the results discussed here can spark new thinking about the biodiversity of AMF in the Cerrado and other areas and direct future studies to minimize the gaps in existing knowledge about this phylum.

Materials and Methods

Data search and processing

The search was conducted in the main collection of the Web of Science database (https://www.webofscience.com/wos/woscc/basic-search). A search was made using Boolean indexers for articles produced between 2012 and 2022, with a series of key index terms: "arbuscular mycorrhizal fung*" OR "mycorrhizal fung*" OR "*Glomeromycota*" AND "Cerrado" OR "Brazilian Savanna*". We used the asterisk to include all variations of terms in the algorithm during data collection. The search yielded 14,057 documents, and the bibliometric information was downloaded in BibTeX (.bib) format. We then carefully reviewed this data using a ".csv" file to remove all duplicate records or documents that did not fit our criteria (13,994) using the bibliometrix package for the R environment (Aria & Cuccurullo, 2017). After removing the documents that did not meet the criteria, a new database comprised 63 documents.

Statistical analysis

The following bibliometric parameters were analyzed using the bibliometrix package for the R environment: keywords, journals where the documents were published, year of publication, authors, author institution, country of affiliation, and year of availability. We then performed a Pearson correlation (r) ($P < 0.05$) between the total number of articles published for each year to determine the upward trend in the number of publications for each approach. We also checked the number of citations of these publications over time. Subsequently, a non-metric multidimensional scaling (nMDS) analysis was carried out using a correlation matrix with the 15 most used keywords per period (6.22% of a total of 241), using the PAST v.4.03 statistical environment to verify the temporal variation of the keywords, which makes it possible to visualize trends and gaps in research for a given period (Hammer et al., 2001). The other scientometric analyses were conducted using the biblioAnalysis function of the bibliometrix package for the R environment (Aria & Cuccurullo, 2017; R CORE TEAM, 2023).

Results

Overview of scientific production on arbuscular mycorrhizal fungi in the Cerrado

Based on the criteria established, a total of 63 publications were obtained. It was found that 2019 and 2022 had the highest number of publications, with nine and ten publications registered, respectively. On the other hand, 2013 was the year with the lowest number of publications, with only two publications registered. In the last ten years, studies on mycorrhizal fungi in the Brazilian Cerrado have not followed a clear growth pattern (r=0.301, P-value= <0.001), so publications tend to grow increasingly each year with an annual growth rate (AGR) of 7.18 percent, with a decrease only in the years 2020 and 2021 (Fig. 1).

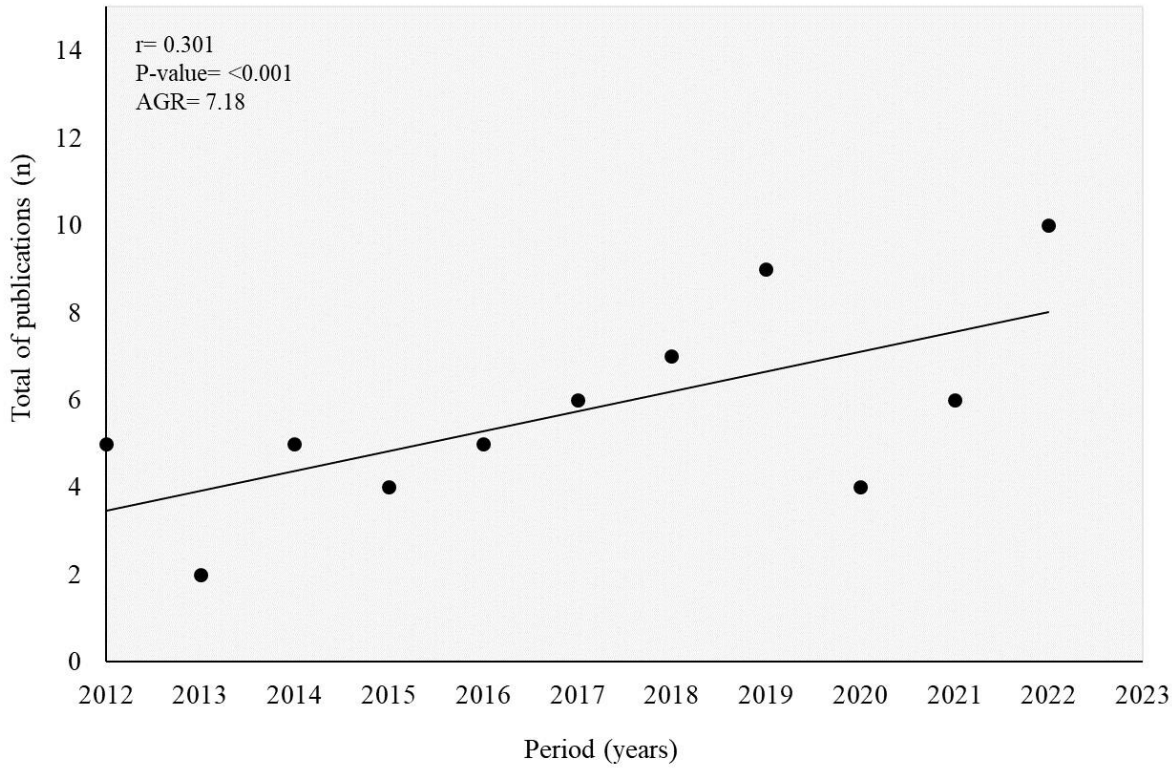

Figure 1. Temporal distribution of the number of articles on mycorrhizal fungi between 2012 and 2022, according to the criteria and data collection methods adopted in this research. Source: Authors.

This number of articles is distributed in 45 journals, with ten journals concentrating 44.44% of the publications and having between two and four articles published in each. The international journal Rhizosphere (ISSN 2452-2198) and the Brazilian journals Revista Brasileira de Ciência do Solo (ISSN 1806-9657), and Ciência e Agrotecnologia (ISSN 1413-7054) have the highest number of publications (4), with different themes (Fig. 2).

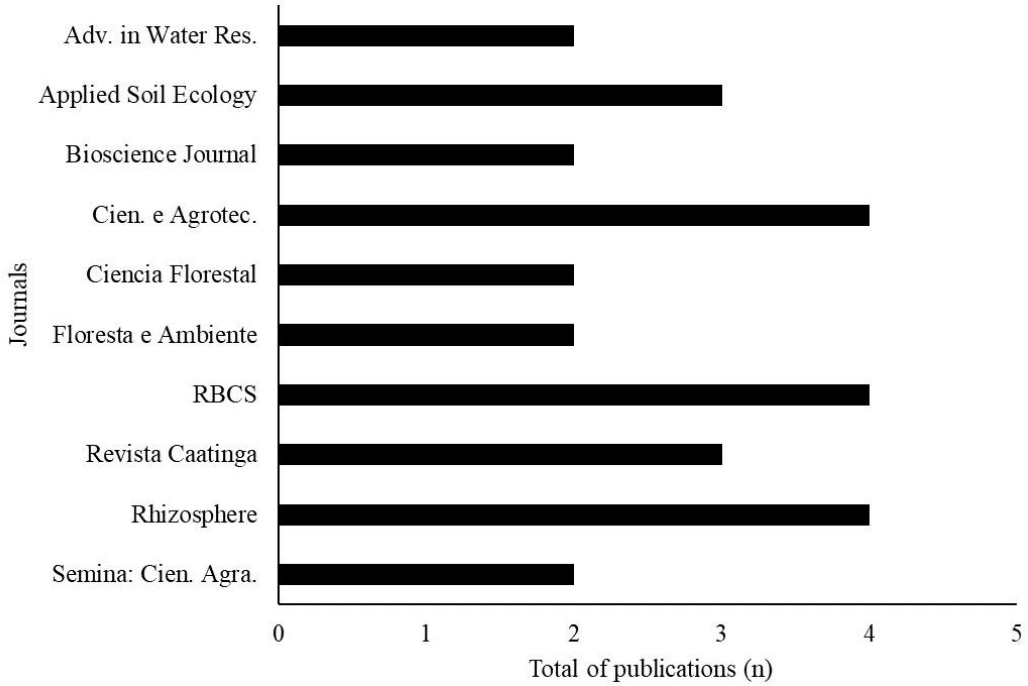

Figure 2. Total number of publications on mycorrhizal fungi between 2012 and 2022 for the ten scientific journals with the most publications, according to the criteria and data collection methods adopted in this research. Source: Authors.

The only paper with more than 100 citations (103 citations; 8.50 citations/year) was the study by Carvalho et al. (2012), published in the journal Applied Soil Ecology (ISSN 0929-1393). In addition, other studies had more citations between 2016 and 2019, with other publications registering less than 25 citations each (Fig. 3).

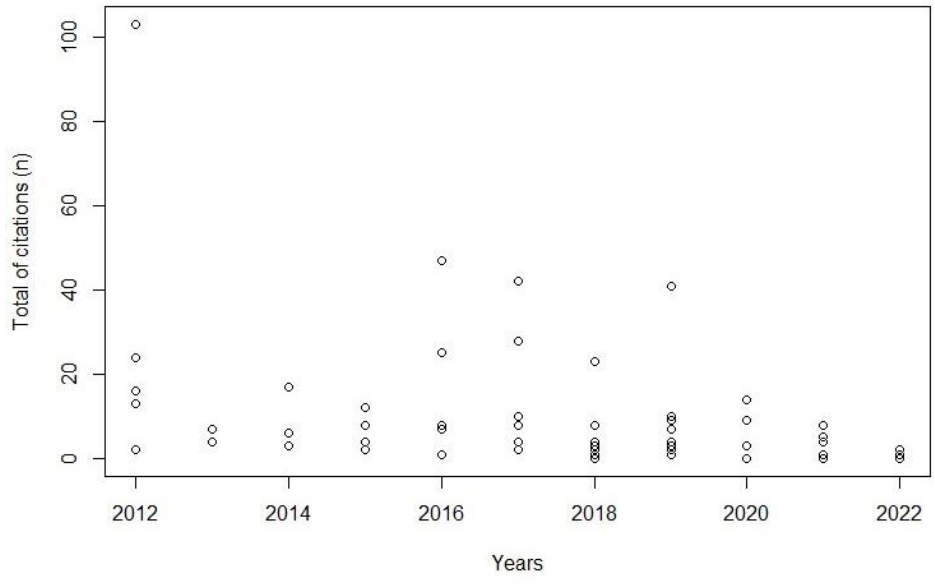

Figure 3. Total number of citations of articles published on mycorrhizal fungi between 2012 and 2022 for the ten scientific journals with the most publications according to the criteria and data collection methods adopted in this research. Source: Authors.

In addition to the study by Carvalho et al. (2012), the most cited studies were those by Abrahão et al. (2019), Castro et al. (2016), Pontes et al. (2017), and Teixeira et al. (2017). Among these studies, two studied the agricultural use of AMFs, two studied diversity in rupestrian grasslands, and one studied different phytophysiognomies (Table 1). An interesting and relevant observation to consider is the fact that the research with the greatest impact on the study of the biology and ecology of AMFs in the Cerrado, i.e., the research with the highest number of citations, was led by women, which reinforces the role of Brazilian women mycologists and researchers in advancing AMF research in Central Brazil.

Table 1. Most cited articles on mycorrhizal fungi in the Cerrado, listed by their total number of citations in the period assessed (2012 to 2022). DOI: digital object identifier; TC: total citations; TC/year: average of total citations per year.

Reference	Title	Journal	DOI	TC	TC/year
Carvalho *et al.* (2012)	The mosaic of habitats in the high altitude Brazilian rupestrian fields is a hotspot for arbuscular mycorrhizal fungi	Applied Soil Ecology	10.1016/j.apsoil.2011.10.001	103	8.58
Castro *et al*. (2016)	Microbial diversity in Cerrado biome (neotropical savanna) soils	Plos One	10.1371/journal.pone.0148785	47	5.88
Pontes *et al*. (2017)	Diversity of arbuscular mycorrhizal fungi in the Brazilian Cerrado and in soybean under conservation and conventional tillage	Applied Soil Ecology	10.1016/j.apsoil.2017.04.023	42	6
Abrahão *et al*. (2019)	Soil types select for plants with matching nutrient acquisition and use traits in hyperdiverse and severely nutrient impoverished campos rupestres and Cerrado in central Brazil	Journal of Ecology	10.1111/1365-2745.13111	41	8.20
Teixeira *et al*. (2017)	Arbuscular mycorrhizal fungal communities in an iron mining area and its surroundings: inoculum potential, density and diversity of spores related to soil properties	Ciência e Agrotecnologia	10.1590/1413-70542017415014617	28	4

Source: Authors.

Collaborative networks in research with arbuscular mycorrhizal fungi in the Cerrado

Five countries besides Brazil are among those that cite and collaborate the most with research on arbuscular mycorrhizal fungi in the Cerrado, namely the United States (USA), Switzerland, Portugal, Chile, and Mexico (Fig. 4A). Mexico, Portugal, and Switzerland have the lowest number of studies; however, Switzerland

has the highest average number of article citations (14), followed by the United States (11.50), Portugal (10), and Brazil (9.54).

Brazil undoubtedly publishes the most on arbuscular mycorrhizal fungi in the Cerrado and collaborates directly with the United States, Australia, Portugal, the United Kingdom, Germany, and Israel (Fig. 4B).

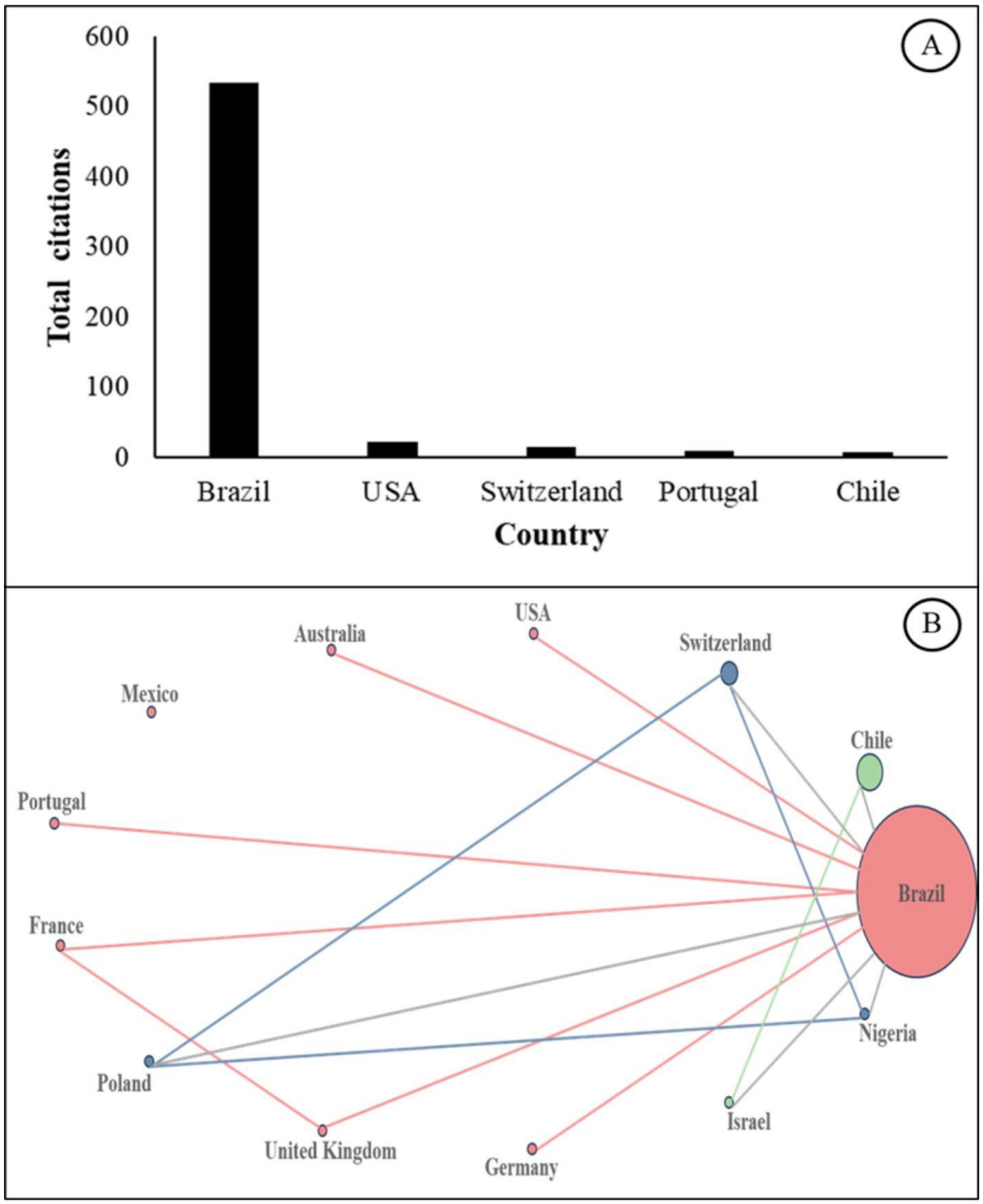

Figure 4. Global quotations of studies on arbuscular fungi in the Cerrado published between 2012 and 2022 (A) and Network of collaboration between countries in research on arbuscular mycorrhizae in the Cerrado. Source: Authors.

Among the universities in Brazil, the ones that do the most research on arbuscular mycorrhizae in the Cerrado are the Federal University of Lavras, the University of São Paulo, and the Federal University of Goiás, which collaborate strongly with each other and with other universities, forming the largest collaborative network on arbuscular mycorrhizae research in the Cerrado in Brazil (Fig. 5).

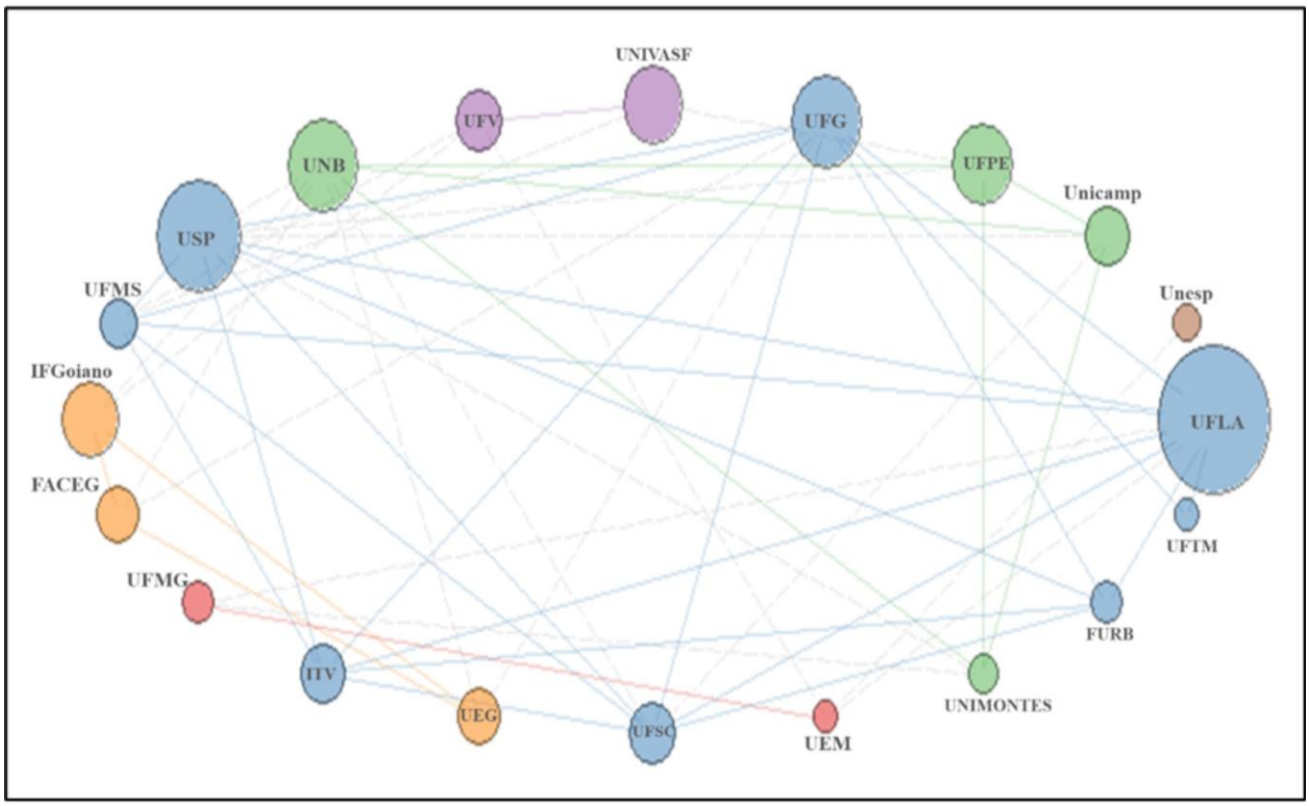

Figure 5. Collaborative network between higher education institutions in Brazil on AMF studies. Federal University of Lavras (UFLA), São Paulo State University (Unesp), State University of Campinas (Unicamp), Federal University of Pernambuco (UFPE), Federal University of Goiás (UFG), Federal University of the São Francisco Valley (UNIVASF), Federal University of Viçosa (UFV), University of Brasília (UNB), University of São Paulo (USP), Federal University of Mato Grosso do Sul (UFMS), Federal Institute of Goiás (FIGoiano), Evangelical College of Goianésia (FACEG), Federal University of Minas Gerais (UFMG), Vale Institute of Technology (ITV), State University of Goiás (UEG), Federal University of Santa Catarina (UFSC), State University of Maringá (UEM), State University of Montes Claros (UNIMONTES), Regional University of Blumenau (FURB), Federal University of the Triângulo Mineiro (UFTM). Source: Authors.

Trends and gaps in research with arbuscular mycorrhizal fungi in Brazil

The non-metric multidimensional scaling (nMDS) analysis showed that most of the studies obtained can be divided into three large groups: studies involving glomalin in Cerrado soils, studies of mycorrhizal colonization in plants, and studies focused on the diversity of mycorrhizal fungi. The other studies can be classified as generalist, covering a mixture of topics about the group, such as symbiosis and diversity of *Glomeromycota* (Fig. 6A). The use of these main keywords does not seem to remain stable over time, with these words being used in different years.

It was found that the same keywords were used in both the title and the abstract, which is why only one representation of the co-occurrence analysis was used, as shown in Figure 6B. The analysis showed that the co-occurrence of words could be divided into two groups, the first being more general words, the most frequently co-occurring of which are "cerrado", "mychorrizal", "arbuscular", and "brazilian", these words also co-occur with other words, which occur less frequently such as "fungal", "systems", "growth", "species" and "community". The second group can be considered as words focused on studies of soil types, diversity, and colonization of mycorrhizae, with the words "fungi" and "soil" appearing most frequently.

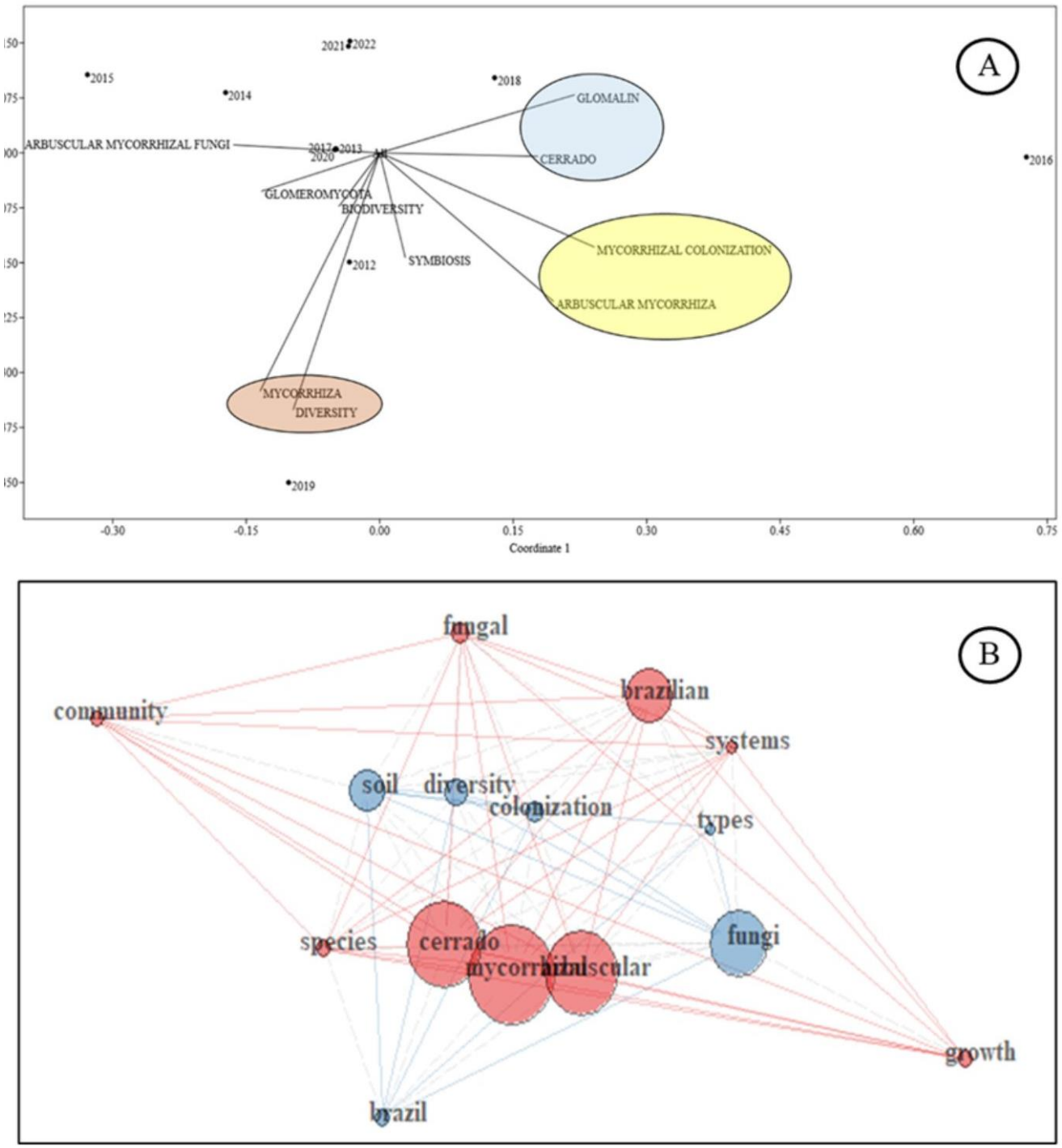

Figure 6. Temporal variation of keywords among studies on arbuscular mycorrhizal fungi in the Cerrado based on non-metric multidimensional scaling (nMDS) between the frequencies of use of the ten most used keywords (A) and analysis of co-occurrence of keywords in the title and abstract. Source: Authors.

Discussion

Most studies on mycorrhizae are conducted in the northern hemisphere, thus leaving an extensive knowledge gap in various areas of the world, especially in arid ecosystems such as the Cerrado (Martínez-García, 2011; Silva Flores et al., 2021). In the Cerrado, the intensification of agricultural activities generates a landscape structure detrimental to biodiversity conservation (Carvalho et al. 2009). In addition, studies show that the physicochemical properties and biota of the soil have changed over time in the Cerrado in response to intensive agricultural practices (Aker et al. 2022; Santos et al. 2021).

Some researchers have been taking the below ground biota into account and developing research to improve sustainable agriculture and soil conservation in the Cerrado (Araujo et al., 2021; Castro et al., 2016; Lucas et al., 2022; Souza et al., 2019). Our data showed that scientific production of mycorrhizal fungi in the Cerrado has increased in the last ten years; however, in 2020 and 2021, there was a significant decrease (Fig. 1). This drop in production may be related to the effects of isolation during the COVID-19 pandemic in this period; however, in 2022, production intensified again, which can be explained by the resumption of activities due to immunization campaigns and the end of social isolation.

The 63 publications obtained between 2012 and 2022 were published in 45 different journals; Rhizosphere, Revista Brasileira de Ciência do Solo, and Ciência e Agrotecnologia were the journals that published the most, with four publications each. Despite the decrease in scientific production in 2020 and 2021, 2022 and 2019 were the years with the highest number of studies, respectively.

In 2022, several studies were found, focusing on the influence of soil, vegetation, and seasonality on AMF communities in the Cerrado (Aker et al., 2022; Calaça & Bustamante, 2022; Guilherme et al., 2022), diversity and interactions of AMF in agricultural systems and pastures (Barbosa et al. 2022; Lucas et al. 2022; Silva et al. 2022a), and effects of AMF on the growth and development of seedlings (Jesus et al., 2022; Paiva Neto et al., 2022; Silva et al., 2022b). In the same year, a study was published on the effects of fire on AMF communities in the Cerrado, providing information of significant importance since Cerrado plants evolved with fire and the Cerrado suffers intensely from arson, but little is known about the effect of fire on the biota below ground (Moura et al., 2022).

In 2019, the second year with the highest number of publications, most of the papers were focused on mycorrhizal fungi diversity, as shown by the nMDS (Fig. 5A), with them focusing on specific mycorrhizal fungi interactions with Cerrado plants (Moura et al. 2019; Detmann et al. 2019), diversity, distribution, and interaction of mycorrhizal fungi in natural Cerrado habitats (Abrahão et al., 2019; Leite et al., 2019; Vieira et al., 2019), and diversity, distribution, and interaction of AMF in agricultural systems (Carneiro et al., 2019; Moraes et al., 2019; Souza et al., 2019).

Many studies aimed at developing seedlings of Cerrado plants have worked with *Dipteryx alata* Vogel (*Fabaceae*), and studies on this species were only found in 2022. Popularly known as Baru, *D. alata* is a species native to the Cerrado, with high socio-economic interest and great socio-environmental importance (Lima et al., 2022). However, this species has been threatened with extinction due to the intensification of deforestation in the Cerrado and is of interest for conservation due to its importance (Magalhães, 2014).

Recent studies conducted to enhance the production of *D. alata* seedlings have shown that the interaction of the plant with arbuscular mycorrhizal fungi such as *Glomus clarum* (T.H. Nicolson & N.C. Schenck) and *Rhizophagus clarum* (T.H. Nicolson & N.C. Schenck) C. Walker & A. Schüßler, causes these fungi to increase the availability of phosphorus and nitrogen, important macronutrients for plant development, as well as increasing plant biomass, especially leaves and roots (Silva et al., 2022a). These responses are also satisfactory under drought conditions, as the fungi cause the plants to accumulate more water in the plant tissues, increase chlorophyll production, and show greater activity of the rubisco enzyme, factors that have a direct impact on the plant photosynthetic rate, and consequently on its development (Jesus et al., 2022).

In addition to studying specific interactions with Cerrado vegetation, studying the composition of AMF within the Cerrado phytophysiognomic mosaic is a strategy for gathering relevant information for the conservation of the domain and is important for discovering new species. Recent studies have evaluated the taxonomic composition and potential functions of soil microbial communities in four different physiognomies (Dense cerrado, Cerrado *stricto sensu*, Campo sujo, and Riparian forest) during the dry and rainy seasons (Calaça & Bustamante, 2022; Castro et al., 2016). It was observed that *Glomeromycota* spores usually decrease in the rainy

season and that spore density decreases in some phytophysiognomies even with high floristic similarity, especially in the transition from the dry to the rainy season.

Considering the phytophysiognomies, some are of great importance for conservation, such as the rupestrian grasslands, which are one of the most threatened on the planet, as they have poor soils and several highly selective factors in the composition of the microbiota and the composition of the vegetation. Among the studies analyzed, the two most cited on the occurrence of AMF in rupestrian grasslands and recent data have shown that this phytophysiognomy has a high potential for AMF diversity (Jobim et al. 2016). Studies have shown that the diversity of AMF is related to the heterogeneity of habitats and that soil texture is more related to the structure of these fungal communities than to the chemical attributes of the soil. In addition, the strategies for acquiring and using nutrients by plants in rupestrian fields differ concerning other phytophysiognomies (Abrahão et al., 2019; Carvalho et al., 2012).

Scientific trends on arbuscular mycorrhizal fungi in the Cerrado have shown a significant increase in recent years, driven by Brazilian researchers, with some international collaborations, mainly from the United States, Switzerland, and Portugal. This may be intrinsically related to the agronomic and even conservation interest in the Cerrado by these countries, especially Brazil.

In addition, several public research institutions in Brazil are involved, with major research interests in the Cerrado, mainly in the Southeast, such as the University of Lavras, which focuses its studies on agricultural and sustainable uses, the University of São Paulo, which is one of the largest research centers in Brazil, and the Midwest, such as the Federal University of Goiás, which focuses its research on the Cerrado, mainly on conservation of the domain. This shows that important universities train specialists in different regions to work with these fungi in the Cerrado.

The publications obtained on AMF in the Cerrado in the period analyzed show a predominance of the words "cerrado", "mychorrizal", "arbuscular", and "brazilian", which strongly co-occur both in the title and the abstract. This fact can lead to difficulty indexing and searching for articles related to the topic since there is no variation of words to be found during searches. It can even be a limiting factor in collaborating with other authors.

However, the non-metric multidimensional scaling analysis showed that most studies can be divided into three large groups: soil quality, mycorrhizal colonization in plants, and the diversity and distribution of mycorrhizal fungi. This shows that few studies use terms focused on biotechnology or other terms that demonstrate the application of mycorrhizae. This is a gap in research on mycorrhizae in the Cerrado, where most studies take a taxonomic, ecological and agricultural approach.

Final Considerations

The results presented in this study showed an increase in the number of publications on arbuscular mycorrhizal fungi in the Cerrado until 2019, then, there was a decrease due to the pandemic, but it rebounded in 2022. These studies are taking place in Brazil since it is a Brazilian domain. Besides being the country that publishes the most on arbuscular mycorrhizal fungi in the Cerrado, it also has some international collaborations. Most studies focus on an ecological, taxonomic, and agricultural approach to the fungus. However, studies of these fungi are still considerably low, and there are still gaps in the knowledge of AMF in the Cerrado, especially concerning the applicability of these fungi and their biotechnological potential.

Some knowledge about the ecology of these fungi, mainly related to their richness and distribution in the Cerrado phytophysiognomic mosaic, is moving towards solid construction, but there are still many gaps to be filled. However, more studies on AMF communities in the Cerrado are needed to understand how the structure and function of these organism communities vary with the impacts of intensive agricultural activity in the

Cerrado, and little is known about the impact on the balance of plant communities. We hope that the results presented here will reinforce the need for future research and funding to understand the potential of these organisms and guarantee their conservation, as well as ensure that public policies are put in place to conserve the soil and biodiversity of the Cerrado.

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