

## Effects Of Biochar And Mycorrhizae In Dry Forest Ecosystems. A Literature Review

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### ABSTRACT

**Contextualization:** Tropical dry forests (TDF) are highly threatened ecosystems due to agricultural expansion, climate variability, and soil degradation. These pressures have led to a significant loss of biodiversity and crucial ecosystem functions.

**Knowledge gap:** Current agricultural needs drive innovation in the field. However, despite the growing interest in ecological restoration techniques, there is a lack of comprehensive synthesis on the combined potential of biochar and mycorrhizae as a strategy for the recovery of BST.

**Purpose:** This systematic review aims to analyze and synthesize current scientific evidence on the effects of biochar and mycorrhizae, both individually and in combination, in restoring and improving soil health in TDF ecosystems.

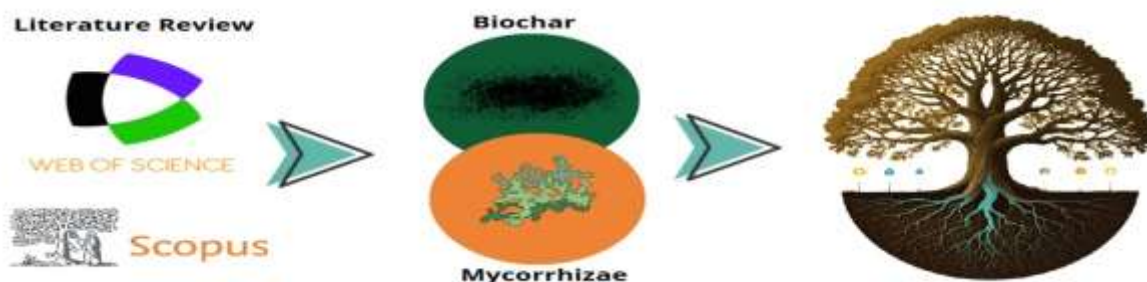
**Methodology:** A comprehensive bibliometric analysis was conducted using Web of Science and Scopus databases, complemented by the Litmaps tool. We examined 238 articles published between 1993 and 2024, selected through specific relevance and quality criteria.

**Results:** Biochar demonstrated significant improvements in water retention (up to 27%) and total organic carbon content (up to 23%) in TDF soils. Mycorrhizae, in turn, optimized nutrient uptake and increased plant resistance to stress. The combined application of biochar and mycorrhizae showed synergistic effects in some cases, although complex interactions were also observed that require further investigation.

**Conclusions:** The integration of biochar and mycorrhizae emerges as a promising strategy for TDF restoration, offering benefits in soil structure, water and nutrient retention, and ecosystem resilience. However, more research is needed to optimize their application in diverse ecological contexts and fully understand the long-term interactions between these components in TDF ecosystems.

**Keywords:** Ecological Restoration, Agricultural Sustainability, Agricultural Productivity, Intensive Agriculture.

### GRAPHIC SUMMARY



Fuente: Autores, adaptación de BioRender y Copilt.

## 1. INTRODUCCIÓN

In Colombia, agriculture has emerged as one of the fastest-growing economic activities. However, this expansion of agricultural land has led to significant changes in vegetation cover due to land conversion for agricultural use and landscape alteration, contributing to biodiversity loss in the affected areas. This is particularly serious in highly threatened ecosystems, such as the TDF. Siyum (2020) state that water scarcity, climate variability, poor soils, and human expansion are deteriorating tropical dry forests (TDF), intensifying these problems and affecting human well-being. According to B. V. Li & Jiang (2021), intensive agriculture has a negative impact on these forests, causing deforestation and biodiversity loss. Reyes Palomino & Cano Ccoa (2022), state that technified agriculture negatively impacts dry forests by causing deforestation and biodiversity loss. The use of agrochemicals contaminates soil and water, further damaging the ecosystem and exacerbating these problems.

Given the severity of these impacts, it is crucial to develop and implement agricultural practices that mitigate negative effects on the environment. According to Cruz-Cárdenas et al. (2021), beneficial microorganisms in agriculture, such as mycorrhizal fungi (MF), can play a vital role in reducing dependence on fertilizers and pesticides. These microorganisms improve soil health and promote more sustainable agricultural practices. One alternative agricultural practice is the inoculation of MFF, which can be extracted from tropical dry forests (TDF). TDWs are defined by Portillo-Quintero & Sánchez-Azofeifa (2010), as vegetation found in tropical regions with marked rainfall distribution, dominated by trees that lose their leaves due to drought and dry months during the year. On the other hand, HFM are essential for sustainable agriculture, as they improve nutrient absorption, strengthen plant resistance to biotic and abiotic stresses, and contribute to overall soil health. Their use reduces the need for chemical fertilizers and promotes more environmentally friendly agricultural practices. Biochar, another key component in sustainable agriculture, is a type of charcoal that improves soil health and fertility. As argued by Pentón Arias (2023), this material recycles nutrients and carbon, increases water retention, and reduces greenhouse gas emissions, making it essential for promoting effective agroecological practices.

Now, the mixture of biochar and mycorrhizae combines two soil amendments to improve plant growth. Biochar (BC), a type of charcoal that improves soil structure, increases water and nutrient retention, and provides a stable habitat for microorganisms. However, combining the two can have mixed effects, which are not always synergistic. While biochar can stimulate the presence of HFM spores in the soil, it can

also reduce the effective colonization of the roots of these fungi. This suggests that, although BC provides benefits to the soil, it can interfere with the ability of mycorrhizae to establish an effective relationship with plant roots. This has been reiterated by Vivanco Ube et al. (2024), who point out that mixing biochar with mycorrhizae can have benefits, such as an increase in the number of spores, but also has limitations. Biochar appears to inhibit mycorrhizal colonization in roots, which can reduce the positive effects of mycorrhizae on plant growth.

The objective of this systematic review is to evaluate and synthesize current findings on the effects of combining biochar and mycorrhizae on plant growth and soil health in BST. The aim is to identify and analyze relevant studies investigating how the interaction between these two practices can influence agricultural productivity, soil structure, and nutrient uptake efficiency, as well as to discuss the potential synergies and limitations associated with their combined use.

### Current situation

Dry tropical forest ecosystems (DTFs) play a crucial role in environmental balance and are characterized by complex ecological relationships between animals, plants, and microorganisms. These forests, together with mycorrhizal fungi (MFs), are essential for maintaining healthy and sustainable environments. According to Schröder et al. (2021), DRF ecosystems provide key environmental services (high biodiversity, protection against erosion, temperature regulation, facilitation of water infiltration). The interaction between MFFs and biochar in DRF ecosystems is a topic of growing interest in the scientific community. Mycorrhizae, symbiotic associations between fungi and plant roots, play a fundamental role in nutrient and water absorption, thus improving plant resistance to stress conditions. On the other hand, biochar, a carbon-rich product obtained from biomass pyrolysis, has been shown to have positive effects on soil structure and nutrient retention. Identifying the species that inhabit these forests is essential to understanding their ecological role. Research in Central America by Gillespie et al. (2000) and in Colombia by Romero-Duque et al. (2019) has identified that the predominant plant families in BSTs include Fabaceae, Bignoniaceae, Rubiaceae, and Euphorbiaceae. According to Ceccon et al. (2006), the regeneration of these forests depends on biotic and abiotic factors, such as seasonality and rainfall variability, as well as pressures from agricultural and livestock activities that can degrade their biodiversity.

Agriculture and livestock farming significantly alter the structure and functioning of forests, transforming fields and pastures into ecosystems with low diversity and simple vegetation

(Fuentes-Hernández et al., 2019). These practices increase temperature, reduce soil moisture, decrease its water storage capacity, increase erosion, and reduce productivity, thus hindering forest regeneration and recovery. In addition, many tropical soils face serious problems, such as low fertility, water stress, and high erosion (Cardoso et al., 2006). To support the regeneration of tropical dry forests, symbiosis with beneficial microorganisms such as mycorrhizal fungi (MF) can be useful.

Arbuscular mycorrhizae, present in all terrestrial ecosystems, are crucial in the tropics for improving plant nutrition and phosphorus uptake (Cardoso et al., 2017). According to Marinho et al. (2018), BSTs harbor the greatest richness and diversity of arbuscular mycorrhizal fungi (AMF) among tropical forests. This importance is also highlighted in the work of Devia Grimaldo et al. (2021), who emphasize the fundamental role of AMF in soil and plant health. Volcanic deposits offer an opportunity to observe the resilience of these fungi and their contribution to ecosystem restoration. Carrillo-Saucedo et al. (2022) emphasize that AMF are essential for soil health, as they improve nutrient exchange, increase plant resistance to pathogens, and contribute to the recovery of degraded soils, making them fundamental for ecological rehabilitation.

HMA can be integrated into agriculture to promote sustainable practices. According to Kalamulla et al. (2022), HMAs are key to sustainable agriculture, as they improve soil structure, nutrient uptake, and overall plant health, optimizing productivity. On the other hand, Varghese & Ray (2023) highlight that HMAs not only promote plant growth and stress resistance, but also optimize nutrient absorption and essential oil synthesis, as well as acting as biocontrol agents. Likewise Sierra-Escobar & Ortíz-Correa (2019), they emphasize that mycorrhizal symbiosis facilitates phosphorus absorption and contributes to the recovery of degraded soils, making AMF a crucial tool for ecosystem restoration and environmental rehabilitation.

One way to promote this symbiosis is through inoculation with HMF strains in soils, to integrate and develop plants with these fungi, whether they are native strains extracted from BSTs or commercial strains. Ordoñez-Castañeda et al. (2021) y Crespo-Flores et al. (2022) agree that inoculation with HMA is essential for improving plant development. Ordoñez-Castañeda et al. (2021) highlight its positive impact on plant growth, biomass, and nodulation, while Crespo-Flores et al. (2022) emphasize the optimization of nutrient absorption. Both studies advocate for further research on the effect of fertilization and inoculation on agricultural sustainability. In this sense, inoculation aids symbiosis

and plant development, since according to Falcón Oconor et al. (2021) mycorrhizae are essential for plant growth, as they facilitate root colonization and optimize nutrient absorption, promoting more robust root development and enhancing overall plant growth, regardless of the type of substrate used.

Inoculation with arbuscular mycorrhizal fungi (AMF) has been shown to be beneficial for both agricultural production and soil processes. This symbiosis plays a crucial role in production systems (Berruti et al., 2016). However, it is important to consider that different authors suggest different approaches to inoculation, whether with native or commercial species. Thus, Shao et al. (2023) indicate that indigenous AMF are more effective for aerial growth and plant leaf nutrition, while commercial AMF are better for root development. The choice between the two depends on the specific objectives of the crop.

Similarly, biochar acts as a soil amendment, as it helps improve soil quality and plant development González-Marquetti et al. (2020) y García Montero et al. (2021) agree that it is an effective tool for improving soil fertility, combating climate change by sequestering carbon, and enriching the soil, as well as improving interactions between plants and microorganisms, increasing resistance to pests when combined with compost. Milesi Delaye et al. (2020) highlight that its application in degraded horticultural and floricultural soils has significant potential to improve soil properties and contribute to climate change mitigation. Marín Armijos et al. (2020) highlights that biochar is a promising tool for improving soil quality and increasing productivity, particularly in corn crops, outperforming other treatments in plant height and stem thickness. Barrezueta Unda et al. (2021) also highlight the benefits of biochar, finding improvements in plant height, number of shoots, and weight, which underscores its potential in crop development.

On the other hand, Cargua Chávez et al. (2020) observes that the combination of biochar and biofertilizers is effective in improving seedling development and quality, significantly increasing dry mass and leaf area, as well as improving key growth indicators. Reyes Pallazhco et al. (2023) complement these findings by pointing out that its use in conjunction with microorganisms has a positive impact on plant development, improving height, stem diameter, and base, adapting to different soil textures. Pentón Fernández et al. (2021) affirm the importance of combining biochar with organic fertilizers, emphasizing that this mixture enhances the benefits of biochar, improving soil fertility and contributing to greater agricultural productivity and climate change mitigation.



### 3. RESULTS AND DISCUSSION

This systematic review focused on evaluating the impact of biochar and mycorrhizae on BST ecosystems, with an emphasis on their effects on soil properties, plant development and growth, and ecological restoration. The bibliometric analysis conducted using the Web of Science and Scopus databases, supplemented by the Litmaps tool, yielded a final corpus of 238 relevant references published between 1993 and 2024, with a peak production of 37 articles in 2021.

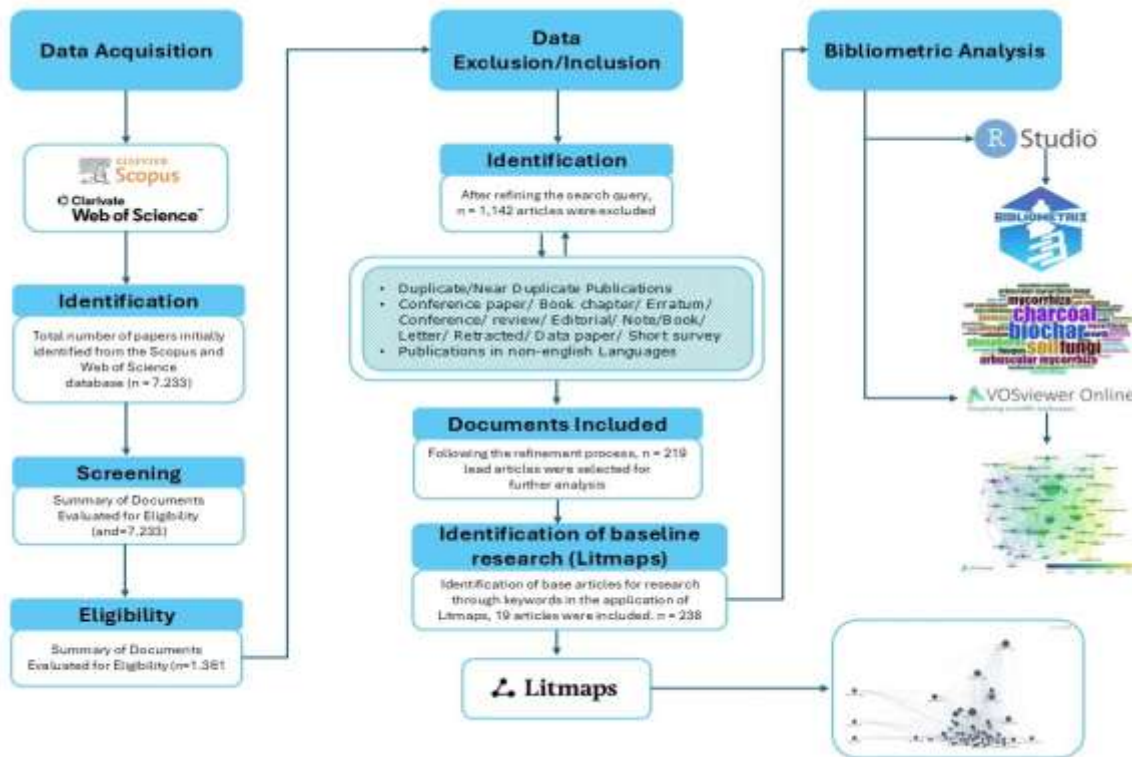
#### The results of this review can be categorized into three main areas:

**Effects of biochar on BST:** It was observed that the application of biochar to BST soils can significantly increase available water content (up to 28%) and field capacity by 20.3% regardless of soil type Edeh et al. (2020). These findings suggest significant potential for mitigating the effects of increasing aridity in these ecosystems.

**Impact of mycorrhizae on STB:** The studies analyzed indicate that mycorrhizal fungi (MF) play a crucial role in soil health and plant development in STB. It was found that inoculation with MFF, both native and commercial strains, can significantly improve nutrient uptake, especially phosphorus, and increase plant resistance to abiotic stress.

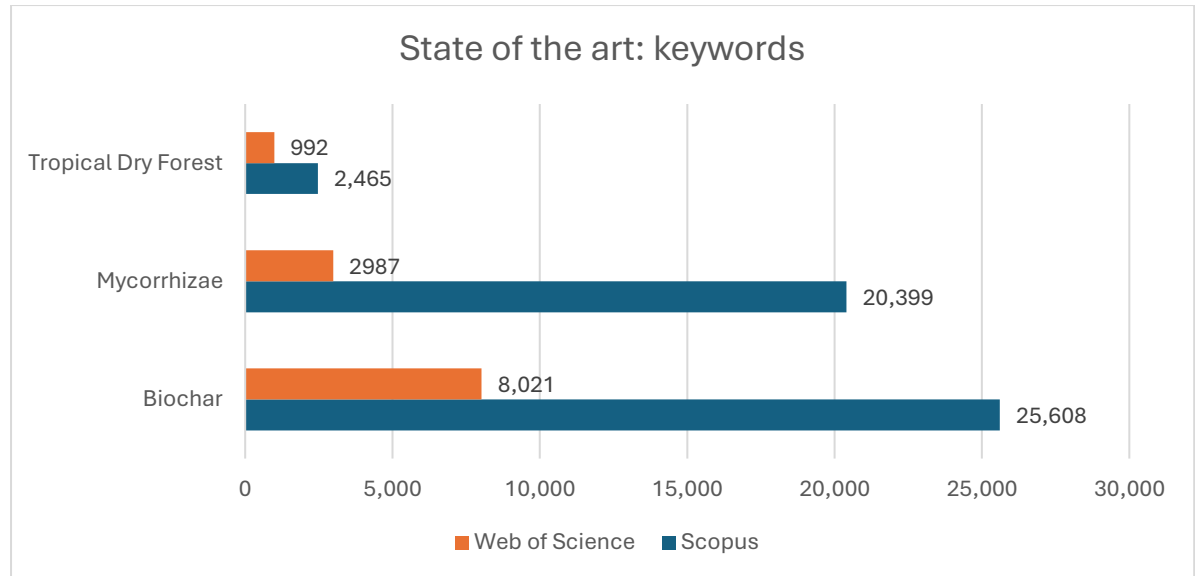
**Biochar-mycorrhiza interaction:** The review revealed a duality in the interaction between biochar and mycorrhizae. While biochar can stimulate the presence of mycorrhizal spores in the soil, it was also observed that it can inhibit effective colonization of roots by these fungi in some cases.

These findings provide a solid basis for understanding the potential of combining biochar and mycorrhizae as a strategy for BST restoration and conservation, but they also underscore the need for further research to optimize their application in different ecological contexts.



**Figure 2.** Graph of the methodology for searching and processing information (Chen et al., 2024) Search results for contextualization of the topic of interest using keywords in the Scopus and Web Of Science databases. Source: authors—adapted from (Chen et al., 2024).

This study was conducted using the information search and processing methodology Chen et al. (2024), based on a review of the Web of Science (WoS) and Scopus databases as data sources. Key terms such as “Biochar,” “Mycorrhizae,” and “Tropical Dry Forest” were used, resulting in a total of 60,472 references (Figure 2). This search revealed research by year, by country, and by journal.



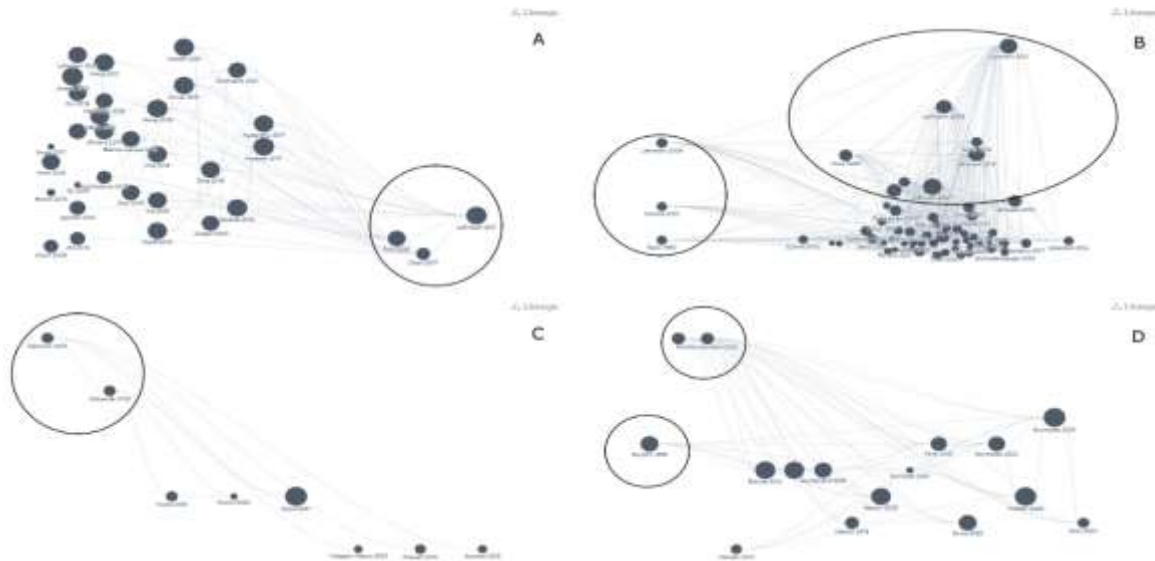
**Figure 3.** Search results for contextualization of the topic of interest using keywords in the Scopus and Web of Science databases. Source: authors.

The search criteria and procedure were carried out in five main steps:

1. **Obtaining the scientific information base:** A strategic search equation was applied that included the terms (biochar AND mycorrhizae AND “tropical dry forest”) OR (biochar AND “tropical dry forest”) OR (biochar AND mycorrhizae) OR (mycorrhizae AND “tropical dry forest”) AND (biochar OR mycorrhizae OR “tropical dry forest”), which yielded a total of 7,233 references.
2. **Filtering of results:** The results were filtered to collect only those articles in which the search equation was found in the title, abstract, and keywords, yielding a total of 279 references.
3. **Selection by document type:** The results were filtered by document type, limiting the search to articles and reviews, leaving a total of 252 references.
4. **Limitation by language:** Finally, the search was restricted to publications in English, resulting in a total of 238 references.
5. **Exclusion of documents:** The articles collected were manually reviewed to exclude duplicate and irrelevant documents for bibliometric analysis, resulting in a total of 219 references.

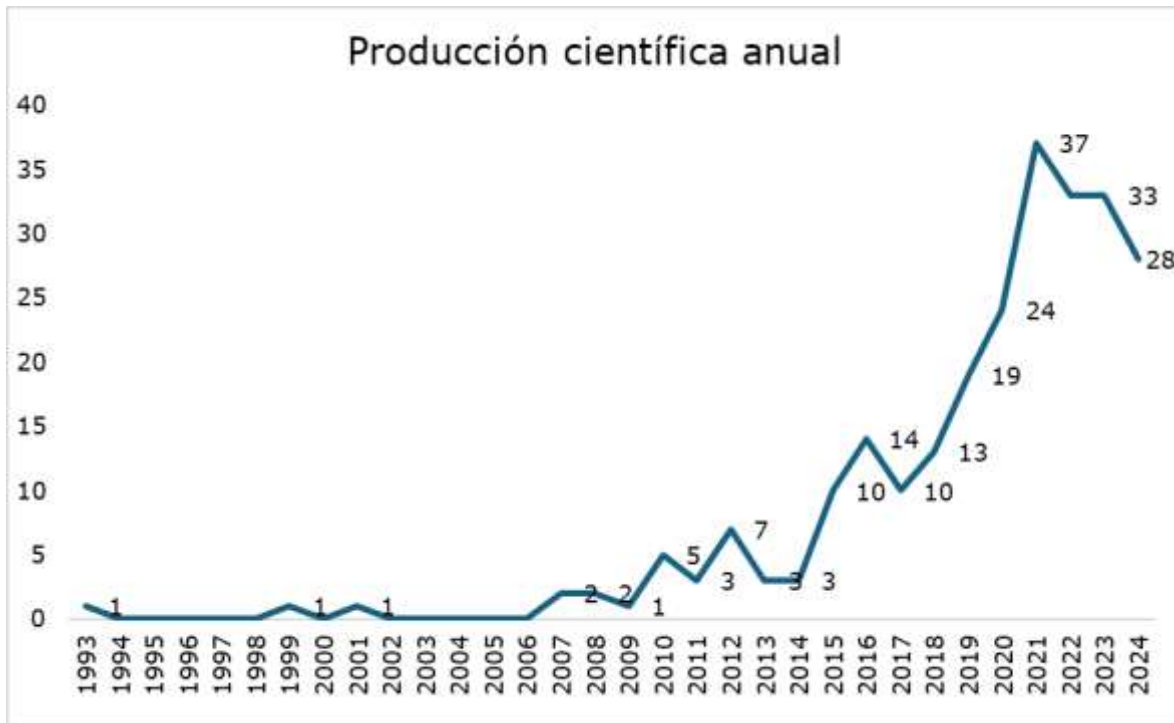
Subsequently, the literature retrieved from the two selected databases was subjected to further analysis using Litmaps, based on research conducted by Wang et al. (2024), who used this tool as an innovative strategy that, through the application of advanced algorithms, reveals hidden connections between academic documents based on their digital identifiers (DOI). According to Kaur et al. (2022), Litmaps operates on the premise that academic works are interrelated through common themes, concepts, and contexts. By semantically analyzing texts, Litmaps creates conceptual maps that visualize the structure and relationships between different documents.

In our study, we used Litmaps to explore the literature on the research topic of interest, working from the keywords (tropical dry forest and agriculture; biochar and native mycorrhizae and restoration; biochar and native mycorrhizae; Biochar). Litmaps identified new articles that had not been found in the initial searches in Scopus and Web of Science. These results, visualized in Figure 2, demonstrate Litmaps' ability to discover unexpected connections and broaden the scope of our literature review. Nineteen references were identified for bibliometric analysis, with a total of 238 references.



**Figure 4.** Graph of results in Litmaps. Identification of base articles for research through keywords in the Litmaps application. A. Biochar; B. Biochar and Native Mycorrhizae; C. Biochar and Native and Restoration; D. Tropical Dry Forest And Agriculture. In addition, these articles are fundamental to research on the topic of interest. **Source:** Litmaps.

The search criteria and procedure were carried out to obtain the main results of the review, where articles were found with an initial production in 1993 and a final production of 28 articles in 2024. Likewise, a maximum production of 37 articles was recorded in 2021.



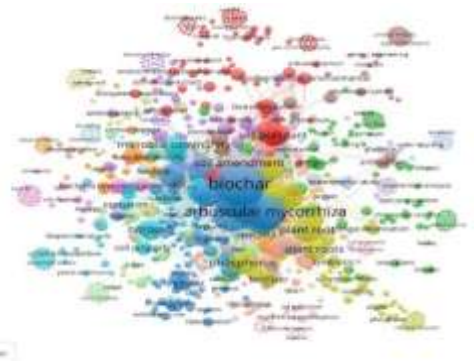
**Figure 5.** Graph of search results for annual scientific production between 1993 and 2024. Source: Authors

biochar, charcoal, soil, fungi, mycorrhiza, arbuscular mycorrhiza, phosphorus, biomass, fungus, and growth.

The search identified a total of 1,881 keywords used in the review articles analyzed. Among these, the following ten words were the most recurrent:

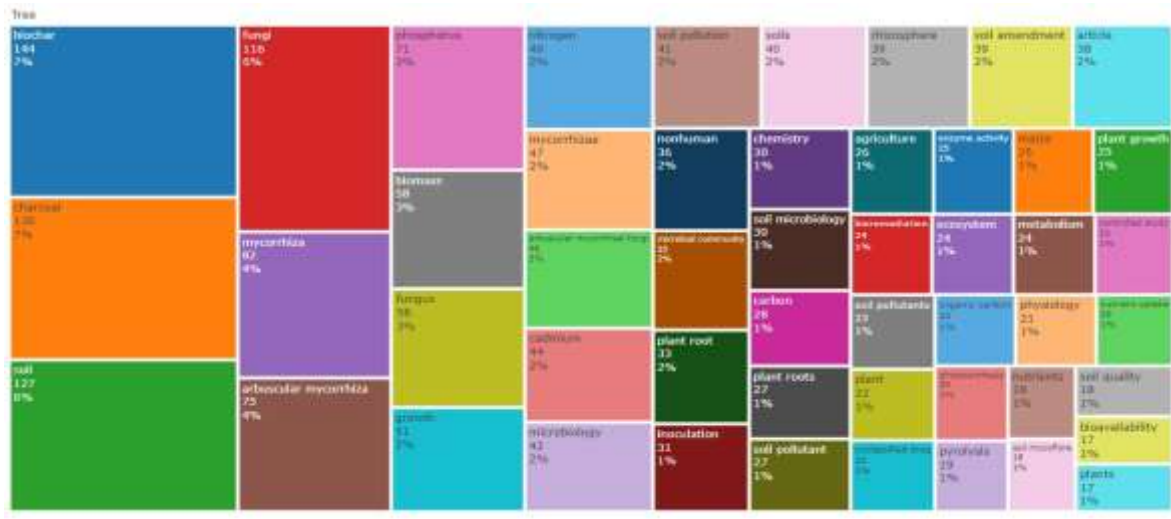
This finding highlights the relevance of these terms in the scientific literature related to the review topic. The frequent use of words such as “biochar” and

“mycorrhiza” suggests a significant focus on the interaction between these elements and their impact on soil and biology in BST ecosystems.



**Figure 6.** Word cloud graph. 6.a and 6.b Identification of the most recurrent keywords in the articles selected for review and where the relevance of the keywords

biochar and mycorrhiza is framed. **Source:** Authors—Adapted from Biblioshiny and VOSviewer.



**Figure 7.** Word tree graph. Recognition of the most recurrent keywords and their impact or relevance in the articles selected for review. **Source:** Authors—Adapted from Biblioshiny.



**Figure 8.** Geographic distribution of scientific production. The figure presents a choropleth map illustrating the global distribution of scientific production in the subject area of this literature review. The intensity of the color in each country reflects the volume of publications, with darker shades indicating greater scientific productivity.

Analysis of the map reveals a marked concentration of research in certain regions. The United States and China stand out as the main centers of scientific production, exhibiting the most intense coloring. These countries are closely followed by Pakistan and Iran, which also show significant research activity in this field. In addition, the map suggests possible patterns of international collaboration and areas of opportunity for future studies in less represented regions.

### **Tropical Dry Forest - Strategic Ecosystem**

Tropical dry forests are vital ecosystems that provide numerous ecological, economic, and social benefits. They cover approximately 42% of all tropical forests on the planet and play a crucial role in biodiversity conservation, carbon sequestration, and the provision of other ecosystem services (Murphy & Lugo, 1986). These forests are characterized by seasonal droughts, which influence their unique flora, fauna, and fungi. They support a diverse range of species, many of which are endemic and adapted to the specific climatic conditions of these regions. The importance of tropical dry forests extends beyond their biological diversity; they also serve as critical resources for local communities, providing timber, firewood, and non-timber forest products essential for livelihoods (Portillo Quintero et al., 2015).

Agricultural expansion, urbanization, and logging are the main drivers of deforestation, leading to substantial habitat loss and fragmentation of tropical dry forests (Fremout et al., 2020; González-M et al., 2018; Toms et al., 2012). In some regions, less than 2% of the original forest remains (Toms et al., 2012). Furthermore, climate change exacerbates these challenges by altering precipitation patterns and increasing the frequency of extreme weather events, which can disrupt the delicate balance of these ecosystems (Siyum, 2020). The combined effects of these pressures have resulted in a decline in biodiversity and the degradation of ecosystem services that are crucial to both environmental health and human well-being.

The ecological dynamics of tropical dry forests are complex and influenced by various factors. For example, the phenology of plant species in these forests is closely linked to seasonal rainfall patterns (Borchert, 1996). This relationship highlights the vulnerability of these ecosystems to climate

variability. In addition, studies have shown that disturbances such as grazing and fires can significantly affect species composition and forest structure (Chaturvedi et al., 2012). Understanding these dynamics is essential for developing effective conservation strategies that can mitigate the impacts of human activities and climate change.

There is growing recognition that initiatives to restore tropical dry forests are vital to improving resilience to environmental stressors (Griscom & Ashton (2011). Identifying the species that inhabit these forests is essential to understanding their ecological role. Combining ecological knowledge with conventional science improves ecological management and control. This integration helps to design effective management strategies and policies, as seen in community forestry projects in the US (Chamley et al., 2007).

### **Analysis of the impact of Biochar and Mycorrhizae on BST.**

The application of biochar in BST ecosystems has received significant attention due to its potential to improve soil properties and support ecosystem restoration efforts. Recent studies have shown that biochar amendments can have a positive impact on soil water retention, organic carbon content, and microbial communities in these water-scarce environments (Amoakwah et al., 2022; Lima et al., 2020). In a study conducted in Brazil's Caatinga biome, Lima et al. (2020), found that biochar application increased soil water content by up to 27% and total organic carbon by 23% in a Regosol, although no significant effects on soil respiration were observed. Oliveira et al. (2017), also highlight the potential of biochar to improve water availability for vegetation in tropical dry forests, especially in the face of increasing aridity due to climate change. Amoakwah et al. (2022) reported that biochar amendment significantly altered microbial community structures and improved biological and enzymatic activities in weathered tropical sandy loam soil. Idbella et al. (2024 & H. Xu et al. (2021), also observed positive effects of biochar on the physical and biological properties of soil in tropical soils. They also noted that biochar is a viable strategy for addressing the challenges of food security and climate change in agroecosystems.

Recent research has highlighted the role of biochar in enhancing soil microbial dynamics and enzymatic activity in tropical dry forest soils. Amoakwah et al. (2022), demonstrated that biochar amendments significantly reshaped microbial community structures and increased microbial biomass carbon, nitrogen, and phosphorus, as well as the activities of key enzymes such as  $\beta$ -glucosidase, acid phosphatase, and urease. Similarly, Lima et al. (2020), reported that biochar application improved soil

water retention and organic carbon content in a Caatinga dry forest soil, contributing to more favorable conditions for microbial functioning. Together, these findings suggest that improvements in soil biological properties driven by biochar may have important implications for nutrient cycling and plant growth in tropical dry forest ecosystems, potentially enhancing ecosystem resilience and productivity.

The raw material for biochar production in tropical dry forest regions has been explored, with a focus on the use of locally available waste materials. Baghel et al. (2025), investigated the use of *Prosopis juliflora* seed waste as a raw material for biochar for environmental remediation purposes. Although their study focused on the removal of methylene blue, the potential for using biomass from invasive species for biochar production in tropical dry forest regions is noteworthy. This approach could provide the dual benefit of managing invasive species while producing a valuable soil amendment, in line with sustainable resource management practices in these ecosystems (Palai et al., 2024).

While much of the research on biochar in tropical dry forests has focused on agricultural and restoration applications, Chen et al. (2024), explored its potential in the ecological engineering of subtropical landfills. Their findings suggest that biochar can improve vegetation establishment and enhance soil quality in degraded environments, which may have implications for the restoration of severely disturbed areas within tropical dry forest landscapes. Biochar's ability to support plant growth under conditions of nutrient scarcity and limited water makes it a promising tool for ecological restoration efforts in tropical dry forests, particularly in areas affected by land-use change or environmental degradation (Kabir et al., 2023).

### **Mycorrhizae in Tropical Dry Forest**

Arbuscular mycorrhizal fungi (AMF) play an essential role in the ecology and restoration of tropical dry forests, especially in the context of climate change and land use transformation. These fungi improve plant nutrition, soil structure, and ecosystem resilience:

**Nutrient loss mitigation:** HMAs significantly reduce nitrogen and phosphorus losses in the soil, which is crucial for maintaining soil fertility in dry ecosystems (Qiu et al., 2022).

**Improved Stress Resistance:** AMF increases plant tolerance to drought and improves photosynthesis, which is vital in dry environments where water is limited (Tang et al., 2023; Tao et al., 2022).

**Soil Structure and Diversity:** In dry tropical forests, AMF contribute to soil aggregation and microbial

diversity, improving soil structure and its ability to retain water and nutrients (Delavaux et al., 2017; Rodriguez-Echeverria et al., 2017).

**Resilience to Land Use Change:** HMA spore communities show resilience to land use changes, such as the conversion of forests to grasslands, maintaining their composition and structure (Carrillo-Saucedo et al., 2018).

**Adaptation to Global Change Factors:** AMF help plants adapt to global change factors such as increased CO<sub>2</sub> and nitrogen addition, improving their performance under these conditions (Tang et al., 2023).

**Interaction with Pathogens:** HMAs can reduce the impact of necrotrophic diseases on plants, which can be beneficial under climate change conditions where diseases may be more prevalent (M. Liu et al., 2024).

In the Brazilian Caatinga, a BST biome, it has been discovered that precipitation and temperature shape the biogeography of HMA communities (Sousa et al., 2022). This relationship between environmental factors and mycorrhizal distribution is fundamental to understanding ecosystem dynamics and planning restoration efforts. Furthermore, research in the Mexican BST has demonstrated a high compatibility between HMA communities and seedlings from different land use types, suggesting the potential of mycorrhizae to facilitate ecosystem recovery after disturbance (Gavito et al., 2008; Huante et al., 2012).

The application of mycorrhizal fungi in restoration projects has shown promising results in tropical dry forest ecosystems. Sierra-Escobar & Ortiz-Correa (2023) proposed using mycorrhizal symbiotic effectiveness as a decision-making tool for tropical dry forest restoration, emphasizing the importance of selecting appropriate fungal partners for target plant species. In Venezuela, a study of a restored STF on Margarita Island revealed diverse AMF communities associated with the recovery process, highlighting the potential of these fungi in ecosystem rehabilitation (Fajardo et al., 2015). In addition, research in Mexico has demonstrated the role of AMF in the early stages of restoration of seasonally dry tropical forests, indicating their potential to improve plant establishment and growth in degraded areas (Huante et al., 2012).

Arbuscular mycorrhizal fungi (AMF) play a crucial role in the nutrient cycle and carbon storage in the soil of various ecosystems, including tropical dry forests. Glomalin, a soil glycoprotein associated with these fungi, has been studied for its potential contribution to soil carbon storage. However, recent research has questioned some of the initial claims

about glomalin and its role in soil (Holátko et al., 2021). On the other hand, mycorrhizal fungi could contribute to carbon storage in the soil of tree rhizospheres and forest understory spaces in tropical dry forests (Singh et al., 2021). This finding underscores the importance of mycorrhizal associations in carbon sequestration and climate change mitigation. In addition, research on the efficiency of nitrogen, phosphorus, and cation use in tropical dry forest regeneration has revealed complex interactions between plant nutrition and mycorrhizal symbiosis (Waring et al., 2015). These studies highlight the potential of mycorrhizal fungi to improve nutrient uptake and soil fertility in degraded tropical dry forest ecosystems.

The impact of land use change and seasonal variations on mycorrhizal communities in tropical dry forests has been the focus of recent research. In Brazil, a study of the semi-arid Caatinga forest found seasonal differences in HMA communities associated with woody species, emphasizing the need to consider temporal dynamics in conservation and restoration efforts (Teixeira-Rios et al., 2018). In addition, research in Mexico has examined the short-term consequences of slash-and-burn practices on HMA communities in tropical dry forests, revealing the resilience of these fungal symbionts to disturbances (Aguilar-Fernández et al., 2009). These findings underscore the importance of understanding the ecological impacts of land-use change on mycorrhizal communities and their potential role in ecosystem recovery. This importance is also highlighted in the work of Devia Grimaldo et al. (2021), who emphasize the fundamental role of HMAs in soil and plant health.

### **Mycorrhizae and Biochar: Synergistic Approaches for BST Restoration.**

The combined application of mycorrhizal fungi and biochar has emerged as a promising strategy for restoring degraded ecosystems in the BSTs and improving agricultural productivity in these regions. Recent studies have demonstrated the potential of this integrated approach to improve soil health, plant growth, and ecosystem resilience to environmental stressors (Abbaspour et al., 2020; Ghanbari et al., 2019; Jabborova et al., 2022; Sahin et al., 2023).

Biochar, a carbon-rich material produced through the pyrolysis of organic matter, has been shown to improve the physical, chemical, and biological properties of soil when applied to degraded soils (M. Liu et al., 2020; Pandian et al., 2016; Zhang et al., 2019). In BST ecosystems, biochar application can improve water retention, increase nutrient availability, and promote the growth of beneficial soil microorganisms, including mycorrhizal fungi (J. Li et al., 2023; Solaiman et al., 2019; Zhu et al., 2022). Several studies have reported that biochar amendment can significantly increase arbuscular mycorrhizal

fungi (AMF) colonization rates and improve the symbiotic relationship between plants and mycorrhizae (Hammer et al., 2015; Mickan et al., 2016; Yang et al., 2022).

Synergistic effects of biochar and mycorrhizal inoculation have been observed in several plant species and soil types relevant to BST ecosystems. For example, Qiao et al. (2015) found that the combined application of biochar and mycorrhizal fungi improved phosphorus availability and uptake in corn plants grown in cadmium-contaminated soils. Similarly, Jabborova et al. (2021) reported improved growth, nutrient uptake, and drought tolerance in soybean plants treated with both biochar and mycorrhizal fungi under water-limited conditions. These findings suggest that the integration of biochar and mycorrhizal fungi may be particularly beneficial in addressing the challenges of nutrient deficiency and water scarcity often found in BST regions (Rivera-García et al., 2024; Siles et al., 2022; Wen et al., 2024).

In addition, the application of biochar and mycorrhizae has been shown to have the potential to mitigate the negative impacts of intensive agriculture on BST ecosystems. Some studies have shown that this combined approach can enhance soil carbon sequestration, improve soil structure, and promote the restoration of native plant communities (Ghadirnezhad Shiade et al., 2023; Herawati et al., 2021; Khanna et al., 2022). Furthermore, the use of biochar and mycorrhizal inoculation has been found to reduce the leaching of agrochemicals and heavy metals, thereby minimizing the environmental impact of agricultural activities on surrounding ecosystems (Cheng et al., 2020; Zhang et al., 2021; Zhao et al., 2021). These findings highlight the potential of integrating biochar and mycorrhiza technologies into sustainable soil management practices for conservation and restoration efforts in the BST in Colombia and other regions facing similar challenges (Mukhopadhyay et al., 2021; Rocha Martins et al., 2022; Sobhani et al., 2022).

Biochar can serve as a suitable habitat for mycorrhizal fungi, promoting their colonization and enhancing their beneficial effects on plant growth (Ennis et al., 2012; Wei et al., 2021a). Some studies have shown that adding biochar to dry tropical forest soils can increase the abundance and diversity of AMF, leading to improved nutrient cycling and ecosystem functioning (Camenzind et al., 2018; Elzobair et al., 2016). Furthermore, the presence of mycorrhizae may facilitate the decomposition of biochar, potentially increasing its long-term benefits for soil fertility and carbon sequestration (Atkinson et al., 2010; Zenero et al., 2021). This synergistic relationship between biochar and mycorrhizae offers promising opportunities for the restoration and conservation of

BST ecosystems in Colombia and other regions facing similar environmental challenges.

The application of biochar and mycorrhizae in tropical dry forest ecosystems can have significant implications for agricultural productivity and sustainability. In these ecosystems, where soil fertility is often limited by low organic matter content and nutrient availability, the combined use of biochar and mycorrhizae can help address these constraints (Rékási et al., 2019; Wei et al., 2021b). Biochar has been shown to improve soil physical properties, such as water holding capacity and soil structure, which are particularly important in the context of tropical dry forests with seasonal water shortages (Atkinson et al., 2010; Ennis et al., 2012). In addition, the presence of mycorrhizal fungi can improve nutrient uptake by plants, particularly phosphorus, which is often a limiting nutrient in tropical soils (Alvarez-Manjarrez et al., 2021; Fern et al., 2011). The combined application of biochar and mycorrhizae has the potential to reduce the need for synthetic fertilizers and irrigation, contributing to more sustainable agricultural practices in BST regions (Elzobair et al., 2016; Zenero et al., 2021).

However, several authors highlight the beneficial qualities of combining biochar and mycorrhizae. W. Xu et al. (2021) report positive effects of biochar on soil microbial communities, promoting the growth of microbial biomass and the abundance of HFM, which improves the soil's carbon capture capacity. On the other hand, Sun et al. (2022) point out that the joint inoculation of HFM and biochar in corn crops promotes nutrient absorption, leading to an increase in physiological properties and stimulating plant growth. Additionally, C. Liu et al. (2017), demonstrated that the efficient mixing of biochar, mycorrhizae, and fertilizers can result in a positive interaction for the growth of plants such as alfalfa, improving nutrient absorption and reducing the concentration of heavy metals such as cadmium.

While the potential benefits of biochar and mycorrhizae in tropical dry forest ecosystems are promising, it is important to consider the specific nature of the context of their effects and possible limitations. The effectiveness of biochar and mycorrhizae can vary depending on factors such as soil type, climatic conditions, and plant species composition (Camenzind et al., 2018; Rékási et al., 2019). Furthermore, the long-term impacts of biochar application on soil microbial communities and ecosystem processes in tropical dry forests require further research (Elzobair et al., 2016; Ennis et al., 2012). Likewise, the sourcing and production of biochar, as well as the selection of appropriate mycorrhizal inoculants, must be carefully considered to ensure its sustainable and effective use in tropical

dry forest restoration and conservation efforts (Atkinson et al., 2010; Wei et al., 2021b). Future research should focus on optimizing the combined application of biochar and mycorrhizae for specific tropical dry forest ecosystems, taking into account local environmental conditions and management practices to maximize their potential benefits for ecosystem restoration and sustainable agriculture in Colombia and other tropical regions.

#### 4. CONCLUSIONS

This review highlights the significant potential of biochar and mycorrhizal amendments to improve soil quality in BST ecosystems. Biochar application has demonstrated multiple benefits, including increased water retention, improved soil structure, and enhanced carbon sequestration. HFMs optimize nutrient uptake and promote plant resistance to stress conditions. This synergy not only reduces dependence on chemical fertilizers but also promotes greater crop sustainability. Together, these amendments are emerging as essential tools for the remediation of degraded soils in BSTs, offering a comprehensive solution for the recovery and maintenance of these vulnerable ecosystems.

The application of biochar in BST ecosystems shows significant potential for improving the physicochemical properties of the soil, particularly in terms of water retention and organic carbon content. The studies analyzed report increases of up to 27% in soil water content and 23% in total organic carbon following biochar application, which is especially relevant in the context of increasing aridity associated with climate change.

The interaction of the two amendments has varied effects, since in some cases biochar can reduce root colonization, but when integrated together, various studies have shown that the mixture contributes to improving soil properties and plant development. In this sense, it generates a restoration in BSTs, giving these ecosystems resilience due to the improvement it can produce in these soils, which has a positive effect on their conservation, as they play an important role in climate regulation.

#### AUTHORSHIP CONTRIBUTION

First author: methodology, research, data analysis, conceptualization, writing, revision, and editing. Second author: research, conceptualization, data analysis, writing. Third author: data analysis, revision, and editing. Fourth author: thesis supervision, research project leader within the framework of the research, logistics, revision, and editing. Fifth author: research, conceptualization, revision, and editing.

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