EFFECT OF MIXTURES OF BIOCHAR, ARBUSCULAR MYCORRHIZAL FUNGI, AND BIODIGESTATE AS PLANT GROWTH STIMULANTS

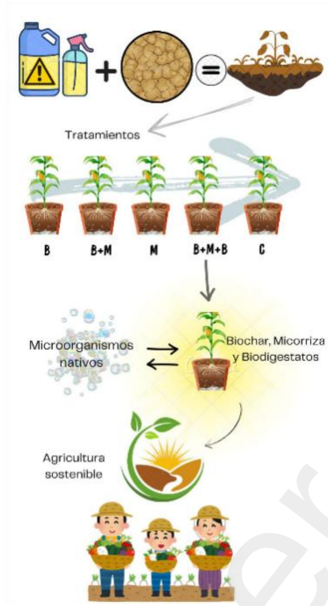
Yessica Lorena Perdomo Useche
Fundación Universitaria del área Andina, Cesar, Valledupar, Colombia
yperdomo11@areandina.edu.co
Hildelina Ochoa Bermúdez
Fundación Universitaria del área Andina, Cesar, Valledupar, Colombia
hochoa3@estudiantes.areandina.edu.co
0009-0005-7856-090X
Luis Alberto Quintero
Fundación Universitaria del área Andina, Cesar, Valledupar, Colombia
lquintero34@areandina.edu.co
César Marín
Universidad Santo Tomas, Valdivia, Chile
cmarind@santotomas.cl
0000-0002-2529-8929
Luis Alberto Quintero
Fundación Universitaria del área Andina, Cesar, Valledupar, Colombia
lquintero34@areandina.edu.co
0000-0002-3498-3469
Arístides José Noriega Hernández
Fundación Universitaria del área Andina, Cesar, Valledupar, Colombia
anoriega8@estudiantes.areandina.edu.co
0009-000-9674-8539
Tatiana Paola Aroca Gutiérrez
Fundación Universitaria del área Andina, Cesar, Valledupar, Colombia
taroca2@areandina.edu.co
0009-006-1151-8640
Antonio Rudas Muñoz
Fundación Universitaria del área Andina, Cesar, Valledupar, Colombia
anrudas@areandina.edu.co
0000-0002-8401-6071

Abstract

The excessive use of chemical fertilizers and extensive agricultural practices can lead to a decline in soil quality and functionality. Therefore, this study evaluated the combined effect of biochar, organic matter from biodigesters (OMB), and arbuscular mycorrhizal fungi (AMF) native to the tropical dry forest on soil fertility in maize (Zea mays L.) crops. The research was conducted using an experimental design with four treatments (A: 5% biochar in AFM inoculated soil, B: 5% OMB in AMF inoculated soil, C: 5% biochar and 5% OMB in AFM-inoculated soil, Bs-t: non-inoculated native soil) and a control (AFM-inoculated soil), each with 5 plants per experimental unit, and 3 experimental units per treatment, respectively. Fertility parameters (pH, cation exchange capacity, carbon and organic matter, phosphorus, and total nitrogen) and plant growth variables (height, number, and length of leaves) were measured. Additionally, surveys and semi-structured interviews were conducted with rural producers to identify their perceptions regarding the adoption of new technologies. It was found that the combined application of biochar, OMB, and AMF increases total organic carbon (28.6 g kg^{-1}), organic matter (49.4 g kg^{-1}), total phosphorus (436 mg kg^{-1}), and cation exchange capacity (30.4 cmol (+) kg^{-1}) in the soil. Maize seedlings under the treatment that included the complete mixture (C) recorded the highest values for height (34.3 cm), number of leaves (4.8), and leaf length (14.9 cm) compared to the control. Finally, farmers' perceptions reflected a favorable disposition toward adopting these practices, contingent on training and financial availability. It is concluded that the integration of biochar, OMB, and AMF constitutes an effective agroecological alternative for improving degraded soils and enhancing corn productivity in tropical

dry forest regions. However, processes of social appropriation of knowledge or environmental awareness are needed to enable farmers to transition to new technologies.

Keywords: Biochar, Mycorrhizal Fungi, Maize, Tropical dry forest**.**



Introduction

Population growth and the need to produce food have driven the mechanization of agriculture through the use of machinery and synthetic fertilizers (Agropinos, 2021). This model has degraded soil quality, increasing soil compaction, reducing nutrient levels, and decreasing soil biodiversity, in addition to disrupting the microbial communities necessary for plant growth (Allohverdi et al., 2021; Wang et al., 2022). Some crops of global importance, such as corn, have been particularly affected by these issues (Larsen et al., 2014). In Colombia, this situation is critical given maize's importance to food security and the rural economy: it accounts for 13% of agricultural production, supports more than 390,000 farming families—mostly smallholder farmers—and plays a central role in poverty reduction (Betancourt et al., 2024). However, soil degradation and climate change threaten its sustainability, requiring practices that increase productivity without compromising natural resources.

The tropical dry forest ecosystem is considered one of the most fragile in the region; according to Mongabay (2017), only 8% of the 9 million hectares it originally covered remain today, a decline primarily due to agricultural activities. This is why sustainable soil management alternatives are needed. Among these, biochar—a product of pyrolysis—improves soil structure by reducing bulk density, increasing porosity, and promoting water retention (Razzaghi et al., 2020). Arbuscular mycorrhizal fungi (AMF) are of great importance for the plant nutrition of 86% of terrestrial flora (Meng et al., 2023), and they also optimize water absorption and increase tolerance to biotic and abiotic stress (Marro et al., 2022; Birhane et al., 2023). Organic matter from biodigesters (OMB) provides available nutrients, and when combined with biochar, it reduces leaching and improves fertility (Brychkova et al., 2024). Previous studies have shown synergistic effects: biochar and AMF in rice increased nutrient availability and root branching (Wen et al., 2022), while the integration of biochar with OMB stimulated microbial activity and phosphorus uptake (Hammer et al., 2015). These results demonstrate the potential of the biochar–OMB–AMF combination for the rehabilitation of arid and semiarid soils.

The adoption of these technologies depends on the perceptions of farmers, who face resource constraints and resistance to change (Han & Niles, 2023). Although these practices are low-cost, efficient, and environmentally beneficial (CIMMYT & CIAT, 2019), their implementation requires overcoming sociocultural barriers, which calls for community participation in their validation (FAO, 2020).

Within this framework, the objective of the research was to evaluate the effect of the Biochar, OMB, and AMF mixture on maize growth in tropical dry forests, while also considering farmers' perceptions to facilitate the transition toward sustainable agricultural systems.

Materials and Methods

To evaluate the combined effect of biochar, organic matter from biodigesters (OMB), and arbuscular mycorrhizal fungi (AMF) on maize (Zea mays L.) growth and soil fertility under nursery conditions, a three-phase methodology was developed: initial assessment, experimental design, and a survey of smallholder farmers. The initial assessment included smallholder farmers' perceptions and the physicochemical characterization of the soil; the experimental phase was conducted using a design with experimental treatments and controls; and the survey of smallholder farmers incorporated mixed-methods approaches to understand farmers' social perceptions regarding the adoption of sustainable technologies. This strategy made it possible to validate the agronomic performance of the soil amendments and analyze their socio-territorial viability. The following section describes the technical procedures, tools used, and statistical criteria applied to ensure the validity and reliability of the results.

Phase 1: Initial Assessment (Population and Soil)

Farmers' Perceptions of Sustainable Agricultural Technologies

To assess the agricultural community's perceptions regarding the shift toward low-cost, high-yield, and pollution-free agricultural technologies, a mixed-methods (qualitative-quantitative) approach was employed, including structured surveys and interviews, which were approved—along with the informed consent forms—by the ethics committee of the Fundación Universitaria del Areandina. The surveys were designed with questions that allowed for the collection of general information on the level of knowledge, attitudes, and factors associated with the adoption of these technologies, while the interviews delved deeper into experiences and cultural and economic barriers. The sample was selected using purposive or stratified sampling to ensure representativeness, and the quantitative data were analyzed using statistical analysis in the RStudio statistical software (RStudio Team, 2023).

Characterization of the Study Site

To characterize the soil of the tropical dry forest, a composite sample was collected from five random subsamples in a protected area of the tropical dry forest located in the La Esperanza Nature Reserve (10°34'05.0"N 73°15'27.0" W, Valledupar, Cesar) at an elevation of 500 meters above sea level, which is characterized by the presence of plants such as Guazuma ulmifolia, Spidospema polyneuron, and Astronium graveolens, among others. The composite sample (1 kg) was analyzed at Laboratorios Nancy Flórez García S.A.S. to determine its physicochemical properties, including pH, cation exchange capacity (CEC), organic matter content, electrical conductivity, and nitrogen, phosphorus, and potassium content, as well as organic carbon. Soil samples were collected at random.

Phase 2: Implementation of the Experimental Design

Trap Cultures

In order to obtain the live inoculated soil that forms the basis of the treatments—in which the native HMA of the tropical dry forest will multiply—trap cultures were established using corn and grass seeds. These were planted in 500-gram pots, which contained 400 g of tropical dry forest (TDF) soil and 100 g of sterilized sand, following the method of Brundrett et al., 1996, with modifications. The seedlings grew for a month and a half; subsequently, water and mechanical stress were induced by cutting the plants and leaving them with two centimeters of growth for one month; finally, the soil was used for the experimental design, as it retained its active microbiome.

Experimental Design

Based on the physicochemical characterization of biochar and OMB (Tables 1 and 2), as well as the potential of AMF to influence soil fertility and plant growth, a pot experiment was designed to evaluate the effect of biochar, OMB, and AMF—both independently and as a mixture. Accordingly, five experimental treatments were established in pots, each with three replicates; each pot was filled with a total weight of 1,200 grams, with the following proportions in the treatments: Treatment 5 (Control) contains neither biochar nor OMB and is applied to living soil inoculated with AMF, using 1,200 grams of soil. Treatment A (4) incorporates 5% biochar and 0% OMB, respectively, in soil inoculated with AMF, weighing 1,140 grams. Treatment B (2) contains 0% biochar and 5% OMB in soil inoculated with AMF, weighing 1,140; treatment C (1) contains 5% biochar and 5% OM in soil inoculated with AMF, using 1,080 grams of soil. Finally, treatment Bs-T (3) contains neither biochar nor OMB and is conducted on native (uninoculated) soil.

Table 1: Physicochemical Characterization of Biochar

Property	Method - Technique	Result	Date of Analysis
Cation Exchange Capacity (meq/100 g)	NTC 5167 - Volumetry	15,01	24/6/2025
Total Organic Carbon (%)	NTC 5167 - Volumetry	92,16	24/6/2025
Ash Content (%)	NTC 5167 - Gravimetry	6,32	24/6/2025
Electrical Conductivity (dS/m)	NTC 5167 - Conductometry	0,52	24/6/2025
Bulk Density (g/cm³)	LBC 43 - Gravimetry	0,36	24/6/2025
True Density (g/cm³)	LBC 289 - Gravimetry	0,83	24/6/2025
pH	NTC 5167 - Potentiometry	10,12	24/6/2025

Fuente: Source: Authors.

Table 2: Physicochemical Characterization of OMB

Parameter	Expressed as	Method and/or Extractant/Technique/Standard	Result	Unit
pH	N.A	Saturation paste/Potentiometry/NTC 5167	7,08	pH
Organic Carbon	N.A	Oxidizing/Titrimetric/NTC 5167	3,22	g/l
Total Organic Nitrogen	N	Kjeldahl/Titrimetric/NTC 370	0,431	g/l
Carbon/Nitrogen	N.A	Mathematical calculation	7,47	-
Total Phosphorus	P_2O_5	MAR/Spectrophotometry/NTC 234	0,17	g/l
Total Alkaline-Soluble Oxidizable Organic Carbon	N.A	Oxidizing/Titrimetric/NTC 5167	2,25	g/l

Humic Acid Carbon	N.A	Oxidizing/Titrimetric/NTC 5167	1,95	g/l
Fulvic Acid Carbon	N.A	Oxidizing/Titrimetric/NTC 5167	0,30	g/l
Total Alkaline-Soluble Oxidizable Organic Carbon / Total Oxidizable Organic Carbon	N.A	Mathematical calculation	69,7	%
Total Alkaline-Soluble Oxidizable Organic Carbon / Total Humic Elemental Carbon	N.A	Mathematical calculation	86,8	%

Fuente: Source: Authors.

The study design was based on an initial study population of 75 cultivated corn plants, with 5 plants per experimental unit and 3 experimental units per treatment.

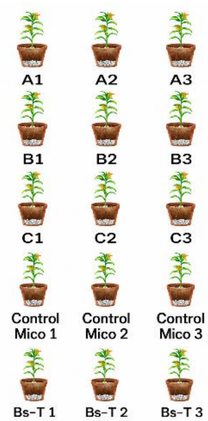
Table 3. Diseño experimental

Treatment	**% Biochar**	**% OMB**	**Soil type**	**Soil weight (g)**
Control	0%	0%	AMF-Inoculated	1200
A	5%	0%	AMF -Inoculated	1140
B	0%	5%	AMF -Inoculated	1140
C	5%	5%	AMF -Inoculated	1080
Bs-T	0%	0%	Native (uninoculated)	1200

Fuente: Source: Authors.

Once the 75 plants had germinated, 45 were selected—that is, 3 per pot—to avoid nutrient competition due to the size of the container. The results were observed in 15 pots to evaluate the effect of different combinations of biochar, OMB, and AMF on soil fertility and the growth of the corn plants. The treatments are as follows:

Fig. 1 Sketch of the experimental field



Fuente: Source: Authors.

Phase 3: Data Analysis

Determination of Soil Physicochemical Parameters

To evaluate the impact of the treatments on soil quality, various key physicochemical parameters were measured in the experimental plot, following national and international standards. Soil physicochemical properties were determined using standardized laboratory methods. Soil texture was evaluated using the Bouyoucos method, while cation exchange capacity (CEC) was determined by volumetric analysis. Total organic carbon and organic matter content were analyzed by spectrophotometry. Electrical conductivity and pH were measured using electrometric methods.

Total nitrogen was determined by digestion and titration using a modification of the Kjeldahl method. Total phosphorus and potassium contents were obtained through acid digestion followed by analysis via inductively coupled plasma optical emission spectrometry (ICP-OES).

Statistical Analysis

A comparison test was conducted using analysis of variance (ANOVA) and multiple comparison tests employing Fisher's LSD method with a 95% confidence level to identify specific treatments that had distinct effects on plant growth parameters such as plant height, number of leaves, and leaf length, as well as a descriptive analysis of the results obtained from the surveys and interviews.

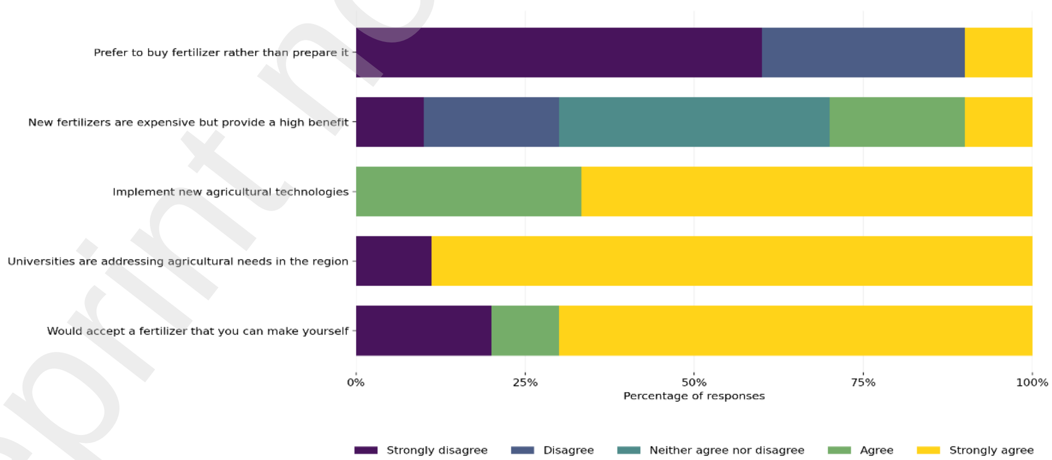
Results and Discussion

Phase 1. Initial Assessment (Population and Soil)

Farmers' Perceptions of Sustainable Agricultural Technologies

Analysis of the survey administered to rural communities in the municipality of Valledupar, Colombia, revealed general perceptions regarding the implementation of new agricultural technologies, specifically the use of the biochar-AMF mixture as a sustainable strategy for crop fertilization. The results show that participants—most of whom are directly involved in agricultural activities—exhibit a high willingness to adopt change, provided that the new practices are backed by verifiable benefits, technical training, and affordability.

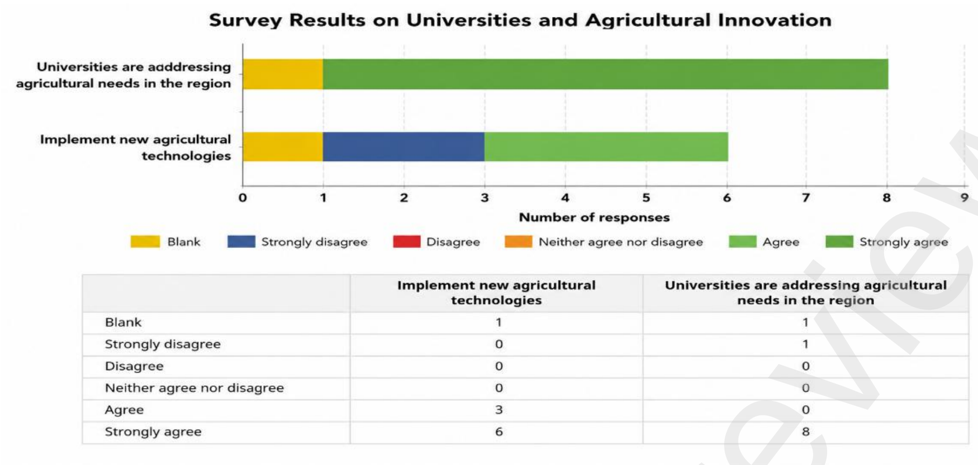
Fig. 2 Community perceptions regarding the use of fertilizers



Source: Authors.

With regard to environmental awareness, the community was found to be conscious of the importance of conserving natural resources and opposed to unregulated extractive practices, which fosters receptiveness to sustainable technologies. Furthermore, there is nearly unanimous support for the role of universities in finding agricultural solutions adapted to the local context.

Fig. 3 Community perception of university involvement

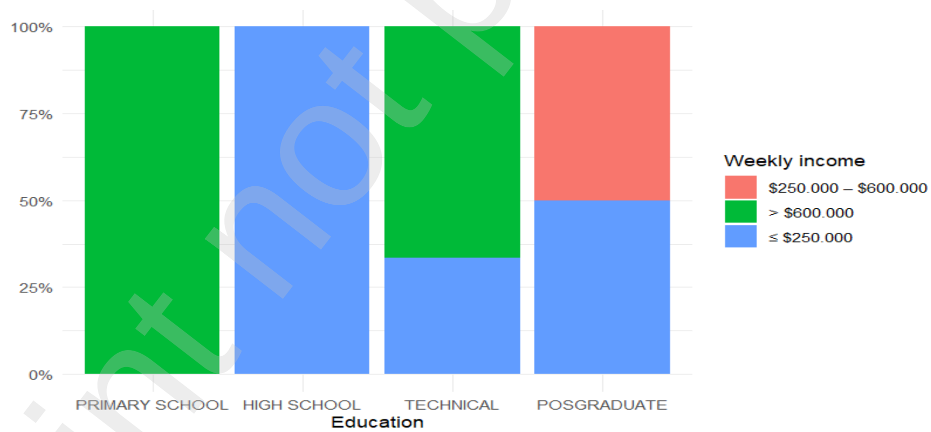


	Implement new agricultural technologies	Universities are addressing agricultural needs in the region
Blank	1	1
Strongly disagree	0	1
Disagree	0	0
Neither agree nor disagree	0	0
Agree	3	0
Strongly agree	6	8

Source: Authors.

Economically, despite the vulnerability and income constraints that hinder the adoption of technologies, there is interest in strategies that strengthen self-reliance, such as producing their own fertilizers. This approach seeks to improve long-term productivity without compromising the environment. The surveyed community expressed a favorable attitude toward agricultural innovation, provided that it is tailored to their economic realities and promoted through participatory training processes that recognize their traditional knowledge. The survey included 10 participants (50% men and 50% women) between the ages of 18 and 65, which provides diversity, although the sample size limits the generalizability of the findings.

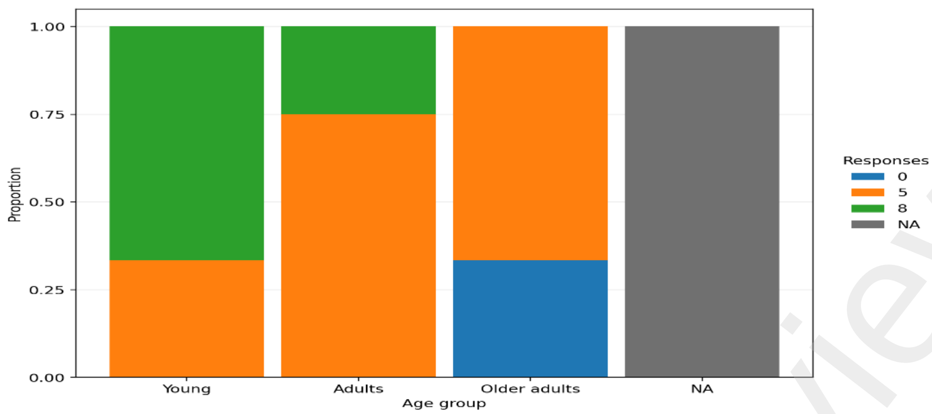
Fig. 4 Weekly Income by Education Level



Source: Authors.

An exploratory analysis of the relationship between educational attainment and weekly income indicated a trend toward higher income with higher educational attainment, as shown in Figure 15; however, internal variability and sample size reduce the statistical robustness of the model.

Fig. 5 Acceptance of Agricultural Technologies by Age Group



Source: Authors.

There was a high willingness to accept home-produced fertilizers, with no significant differences between genders ($\chi^2 = 3.14$; $p = 0.21$). Regarding organic farming, 60% believed it requires greater effort, with few extreme responses. The adoption of new technologies was more widely accepted among young people and adults, while older adults tended to give negative responses, suggesting generational differences. Overall, the results indicate favorable perceptions toward sustainable practices, although factors such as age and educational level influence the willingness to adopt them.

Phase 2: Implementation of the Experimental Design

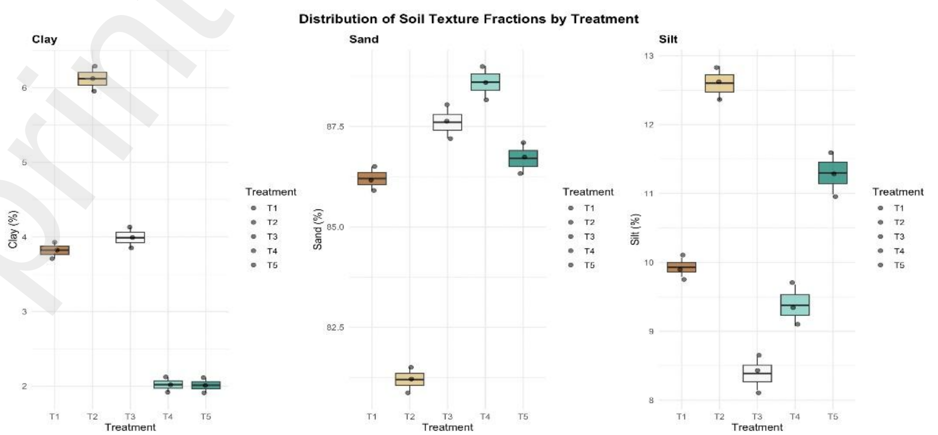
Physicochemical Analysis of Soils

Based on the application of the different treatments to inoculated soils in the tropical dry forest (TDF), results were obtained that allow for an evaluation of their impact on various physicochemical properties of the soil.

1. Soil Composition and Texture

The different treatments applied reflect variations in soil texture (see Figure 2). The soil of the tropical dry forest (TDF) has predominantly sandy characteristics, with low percentages of clay and silt, which limits its capacity to retain water and nutrients. It is observed that the treatment with biochar and mycorrhizae (Treatment 4) has 2.02% clay and 88.6% sand, while the treatment with mycorrhizae and biochar combined with a biodigester (Treatment 1) has 3.82% clay and 86.2% sand. This suggests that the application of biochar improves moisture retention and nutrient exchange capacity.

Fig. 6 Textural Analysis of the Treatments



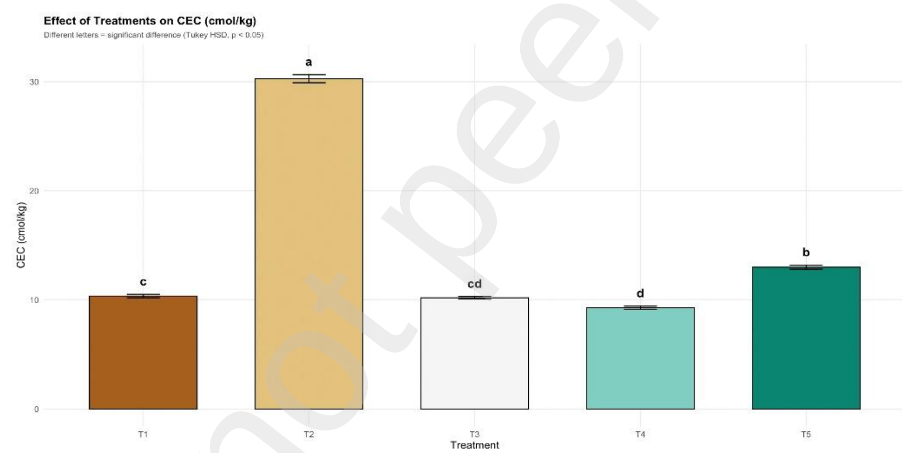
Source: Authors.

Treatments 1 and 4, which included biochar and mycorrhizae as shown in Figure 2, slightly altered soil texture, reducing the sandy fraction and increasing the clay content. Although the changes are not statistically significant, they suggest an improvement in the soil's ability to retain water and nutrients. Several studies have shown that incorporating biochar into the soil helps improve its structure, optimize nutrient retention, promote microbial activity, and enhance nutrient uptake by plants (Haddad et al. (2023) Similarly, Majumder et al. (2019) note that the application of biochar promotes soil aggregation, improves water-holding capacity and pH, and stimulates microbial activity, thereby contributing to an overall improvement in soil quality. These effects are particularly relevant in sandy soils of the tropical dry forest, where even minimal physical improvements can have substantial impacts on agricultural productivity.

2. Cation Exchange Capacity (CEC)

Figure 2 shows that the treatment with OMB and mycorrhizae (T2) exhibited a notable and significantly higher increase in CEC (30.40 cmol(+)/kg), followed by mycorrhizae alone (T5) at 13.00 cmol(+)/kg, while treatments T1, T3, and T4 showed no significant differences: biochar and mycorrhizae (T4) yielded 9.29 cmol(+)/kg, whereas the control (T1) showed 10.6 cmol(+)/kg. Cation exchange capacity (CEC) reflects soil fertility by determining its ability to retain essential cations such as calcium, magnesium, and potassium; therefore, these results demonstrate that mycorrhizae are critical for improving CEC, and their combination with biochar enhances this effect, although without exceeding the values obtained with the individual treatments.

Fig. 7 Cation exchange capacity.



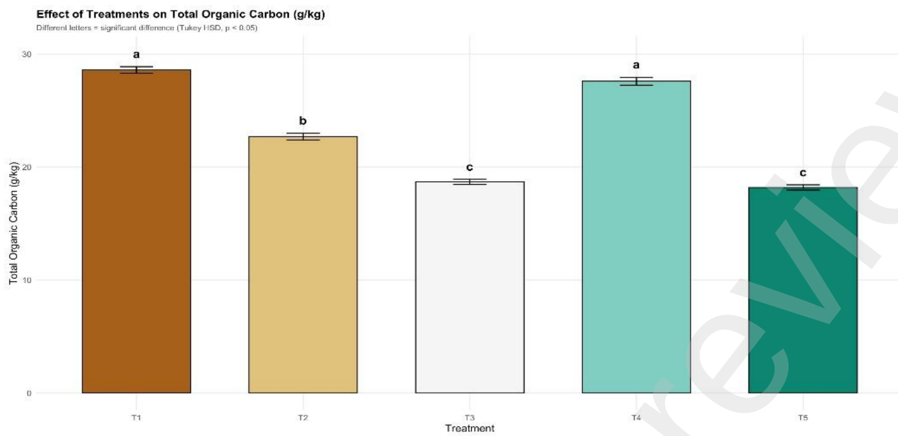
Source: Authors.

In the experiment, the treatments with mycorrhizae—especially those without biochar—showed the highest CIC values, although biochar also had positive effects when combined with them. This difference is attributed to the biological activity stimulated by mycorrhizae. According to Karthik et al. (2020), biochar helps raise soil pH, as well as its organic carbon content and cation exchange capacity. For their part, Nadeem et al. (2014) note that the mycelia of various mycorrhizal fungi exhibit a remarkable capacity for both cation exchange and metal absorption. Thus, the synergy between biochar and mycorrhizae enhances soil fertility in a sustainable manner.

3. Organic Carbon and Organic Matter

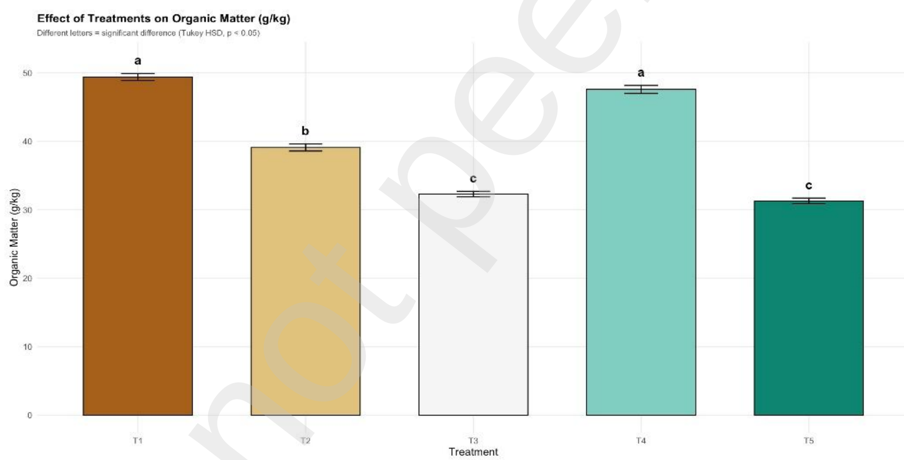
Figure 3 shows that the treatment with biochar, mycorrhizae, and (T1) achieved the highest values: total organic carbon of 28.6 g/kg and organic matter of 49.4 g/kg. The treatment with biochar and mycorrhizae (T4) also showed significant increases, with 27.6 g/kg of organic carbon and 47.6 g/kg of organic matter, indicating that these are the most representative treatments and that there are no significant differences between them. Compared to the control (BST) and mycorrhizae alone, the biochar treatments demonstrated greater carbon sequestration and better soil quality. This demonstrates that one of the main benefits of biochar is to increase organic carbon and improve the stability of organic matter in the soil, thereby enhancing its contribution to fertility.

Fig. 4 Total Organic Carbon



Source: Authors.

Fig. 5 Organic Matter Content



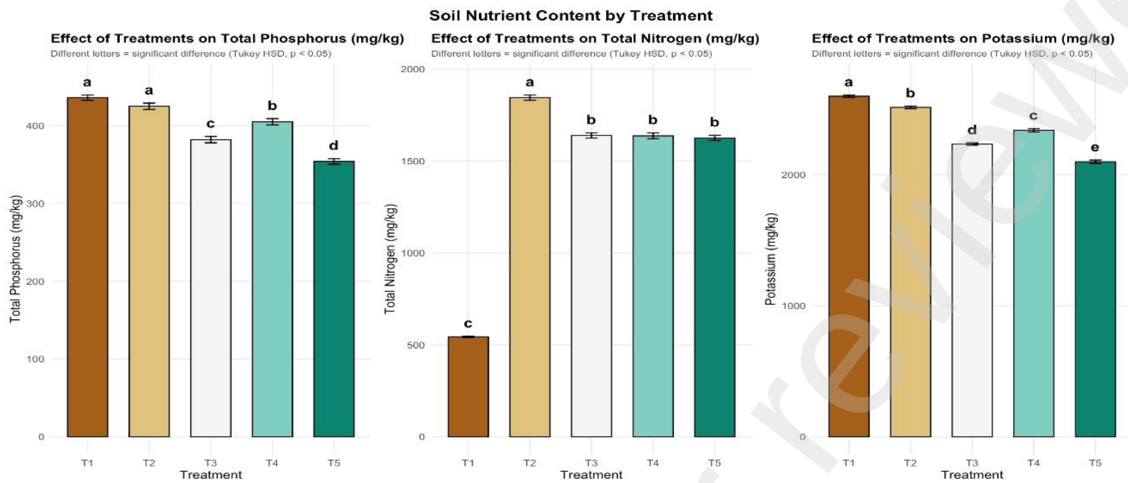
Source: Authors.

The combined treatment of biochar, mycorrhizae, and OMB recorded the highest values for total organic carbon (TOC) and organic matter (OM), demonstrating a cumulative effect between organic and symbiotic inputs. This result is consistent with the findings of Majumder et al. (2019), who concluded that "biochar, when applied both alone and in combination with chemical fertilization, improved the soil's organic carbon sequestration potential (COS) by 32%–35%." Similarly, Karthik et al. (2020) note that biochar increases soil carbon content, acting as an effective mechanism for both improving fertility and mitigating climate change.

4. Phosphorus and Total Nitrogen

A significant increase in potassium levels was observed in the treatments with biochar and mycorrhizae. Potassium is considered an essential nutrient for plant development, but its availability in tropical soils is often limited due to its fixation in forms that cannot be utilized by plants. As shown in Figure 6, Treatment 1 has the highest phosphorus content at 436 mg/kg, followed by Treatment 2 at 425 mg/kg; that is, there is no significant difference between them. This suggests that biochar facilitates the gradual release of this nutrient. Total phosphorus is higher in the treatments with biochar and mycorrhizae (436 mg/kg in Treatment 1 and 405 mg/kg in Treatment 4), indicating greater availability to plants and a possible effect on phosphorus uptake due to inoculation.

Fig. 6 Soil nutrient availability



Source: Authors.

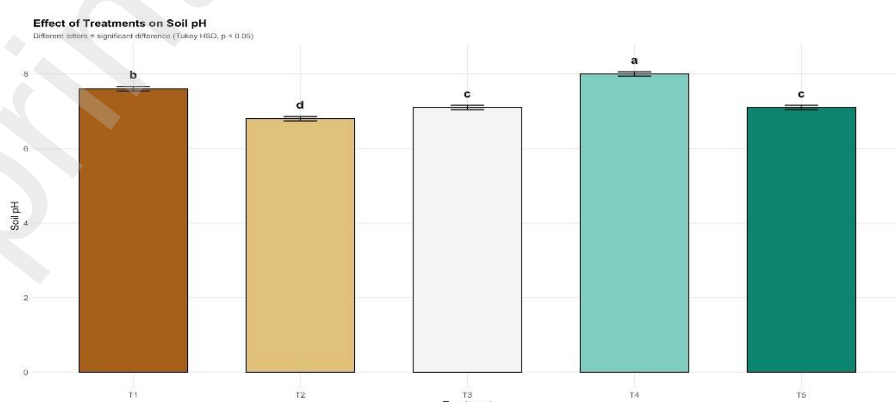
With regard to total nitrogen, the highest values were recorded in Treatment 2 (Biochar + OMB + mycorrhizae) at 1,845 mg/kg, followed by Treatment 4 (Biochar + mycorrhizae) at 1,637 mg/kg, and Treatment 5 (mycorrhizae) at 1,626 mg/kg. These results demonstrate that live mycorrhizal inoculum plays an essential role in nitrogen dynamics, while biochar acts as a complementary soil amendment that enhances

Regarding total phosphorus, the highest levels were found in treatments with biochar and mycorrhizae, confirming that biochar reduces phosphorus fixation in the soil and promotes its utilization. At the same time, increases in nitrogen were associated with treatments that incorporated HMA, suggesting a positive interaction with nitrogen-fixing microbial communities. These results are consistent with those reported by Zaman et al. (2025), who indicate that biochar promotes mycorrhizal colonization and optimizes nitrogen and phosphorus uptake by plants.

5. Soil pH

Figure 6 shows that the treatment with biochar and mycorrhizae (Treatment 4) raises the soil pH, suggesting moderate neutralization and demonstrating that pH is a determining factor in soil nutrient availability.

Fig. 7 Soil Nutrient Availability



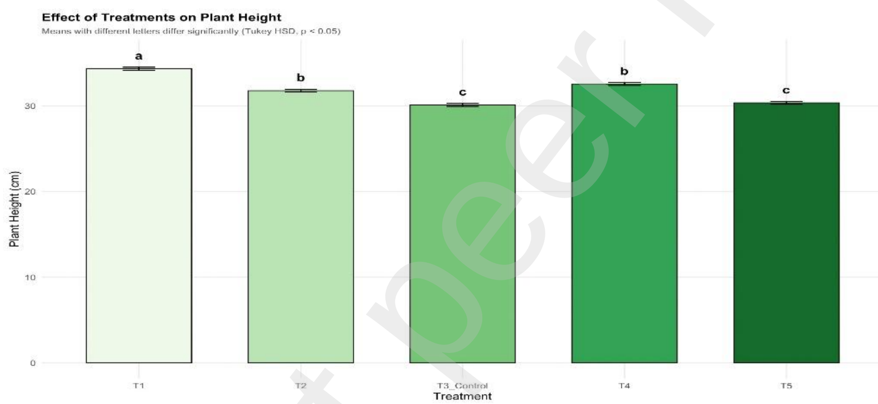
Source: Authors.

Treatment 4 reached the highest pH (8.0), which was significantly higher than that of the other treatments, confirming the alkalizing effect of biochar compared to the control. This behavior is attributable to its alkaline salts, carbonates, and ash, which reduce soil acidity. According to Karthik et al. (2020), biochar helps raise soil pH, thereby neutralizing soils with acidic or slightly acidic conditions—a significant benefit in tropical ecosystems such as the Tropical Dry Forest. However, it is necessary to monitor the increase in pH to prevent micronutrient deficiencies (Fe, Mn). When combined with mycorrhizae, biochar enhances phosphorus availability and reduces aluminum toxicity.

Growth Analysis of Corn Seedlings

The analysis revealed significant differences in height, number of leaves, and leaf length among treatments. The combined Biochar-AMF-OMB treatment achieved the highest values for all variables, establishing itself as the most effective. In terms of height, it recorded an average of 34.34 cm, higher than the control (30.13 cm) and the other treatments; however, in terms of height, the combination of mycorrhizae with the other factors did not produce an additional synergistic effect. These results suggest a positive synergistic effect among the three bio-inputs,

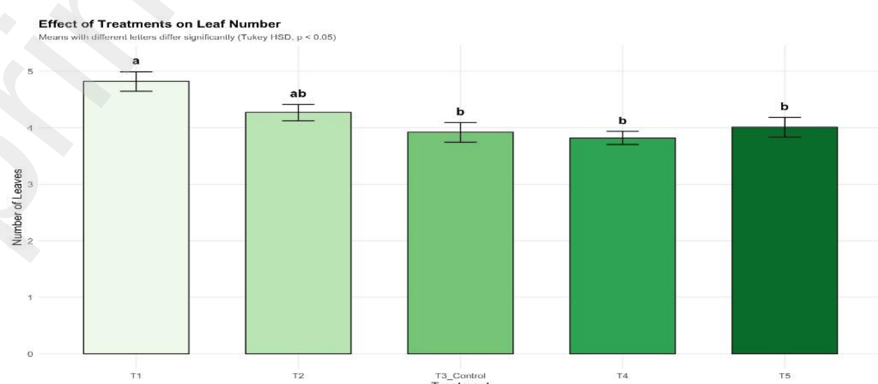
Fig. 8 Plant height



Source: Authors.

Regarding the number of leaves, treatment C again had the highest mean (4.82 leaves), followed by Biod-AMF (4.27), while Bic-AMF showed the lowest value (3.82), though it did not differ significantly from the control. Although the differences in this variable were more modest, the results point to a trend toward greater foliar development associated with the integrated application of bio-inputs. Additionally, it should be noted that this is soil that has been impacted and is undergoing passive restoration.

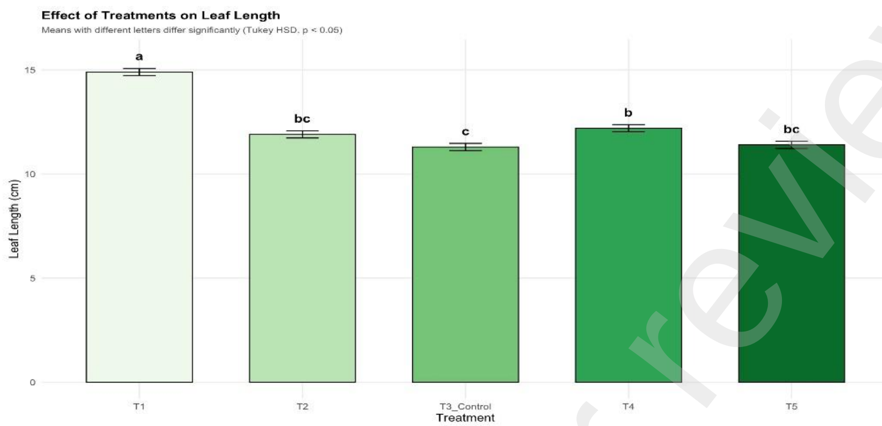
Fig. 9 Number of leaves per plant



Source: Authors.

Regarding leaf length, the AMF-Bio-OMB treatment again stood out with an average of 14.9 cm, in contrast to the control (11.3 cm) and treatments such as Bic-AMF (12.2 cm) and Biod- (11.9 cm). Significant differences were identified among multiple combinations, highlighting the ability of the complete treatment to induce superior leaf growth.

Fig. 10 Plant length



Source: Authors.

Overall, the results show that the simultaneous application of biochar, AMF, and OMB improves plant height, leaf number, and leaf size, promoting comprehensive development from early stages. This is attributed to the synergistic interaction of the bio-inputs, which optimizes physiological and nutritional conditions. According to Ramazanoglu et al. (2025), treatments with mycorrhizae and with the combination of mycorrhizae and biochar promoted plant growth and enzymatic activity. However, the exclusive use of mycorrhizae promoted better nutrient absorption. The mixture of mycorrhizae with 3.0% biochar was the most effective, while biochar applied alone did not show significant differences.

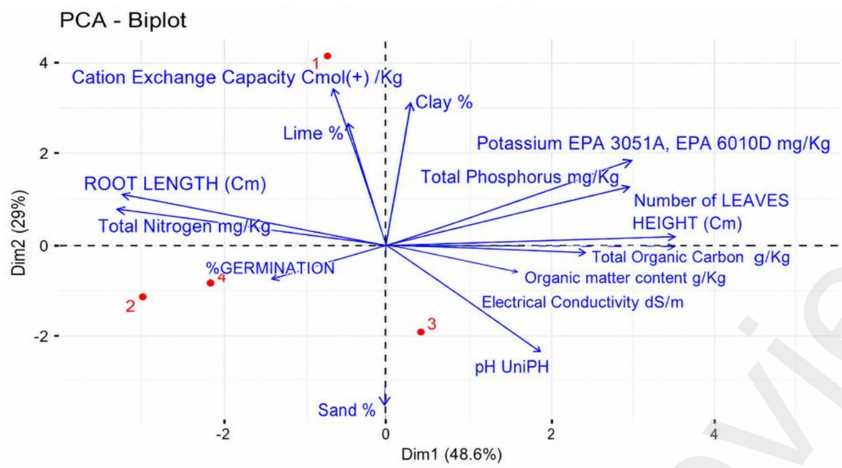
Analysis of Soil Physicochemical Parameters

Treatment with arbuscular mycorrhizal fungi (AMF), applied alone, showed a moderate effect on improving cation exchange capacity and increasing nitrogen content, a result attributable to the symbiosis established between roots and AMF, which promotes nutrient uptake. However, its impact on carbon and organic matter was limited, indicating a reduced contribution to the accumulation of stable soil fractions.

In contrast, the Biochar + AFM combination significantly increased total carbon and phosphorus content, in addition to raising the soil pH to 8.0—it was the only treatment to produce this effect. Such alkalization may be beneficial in acidic tropical soils by improving the availability of basic nutrients such as calcium and magnesium. Biochar, thanks to its porous structure, promotes nutrient retention and acts as a habitat for microorganisms, reinforcing the symbiotic action of mycorrhizae.

Meanwhile, the OMB + AMF treatment stood out for achieving the highest cation exchange capacity (30.4 cmol(+)/kg) and the highest level of total nitrogen (1845 mg/kg). Finally, the Biochar + AMF + OMB combination was the most comprehensive, showing higher values for carbon, phosphorus, and organic matter, as shown in Figure 11.

Fig. 11 Principal component análisis



Source: Authors.

A comparison with untreated soil (BST)—which has low edaphic quality (soils with low fertility, scarce nutrients, and physical or chemical conditions that limit vegetation growth)—demonstrates the effectiveness of the bio-inputs evaluated. Overall, biochar, AMF, and OMB—applied individually or in combination—improved fertility and laid the groundwork for soil sustainability. The exclusive use of AMF promoted biological activity and nitrogen fixation, although its effects were limited. In contrast, treatments with Biochar and OMB offered more comprehensive improvements. The combined treatment (Biochar + AMF + OMB) stood out by generating a synergistic effect that optimized organic matter, carbon, phosphorus, and pH, establishing itself as a key strategy for restoring degraded soils.

Conclusions

The results of this study confirm that the combined application of biochar, OMB, and AMF in tropical dry forest soils significantly improves soil properties and the vigor of corn seedlings. The combined treatment increased total organic carbon to 28.6 g kg^{-1}, organic matter to 49.4 g kg^{-1}, total phosphorus to 436 mg kg^{-1}, and CIC to 30.4 cmol(+) kg^{-1}, while stabilizing the pH at 8.0.

In terms of plant development, the seedlings reached greater height (34.34 cm), had a higher number of leaves (4.82), and exhibited greater leaf length (14.9 cm), demonstrating a synergistic effect on soil nutrition and structure.

Finally, the social assessment with farmers revealed a high willingness to adopt these agroecological technologies, provided they are guaranteed technical training, field demonstrations, and affordable access to inputs. This positive perception is key to the scalability of these practices, as it demonstrates that scientific validation must be accompanied by processes of knowledge transfer and the strengthening of productive autonomy in rural communities.

It is suggested that participatory studies with rural communities be expanded, incorporating action-research methodologies that strengthen local ownership of knowledge and promote agroecological transition processes tailored to the local context.

Bibliography

Agropinos. (2021). Importancia del cultivo de maíz en Colombia. https://www.agropinos.com/blog/importancia-del-cultivo-de-maiz-en-colombia

Allohverdi, T., Mohanty, A., Roy, P., & Misra, M. (2021). A review on current status of biochar uses in agriculture. Molecules, 26, 5584. https://doi.org/10.3390/molecules26185584

Betancourt, J. A., Florez Yepes, G. Y., & Garcés Gómez, Y. A. (2024). Agricultural productivity and multidimensional poverty reduction in Colombia: An analysis of coffee, plantain, and corn crops. Earth, 5(4), 623–639. https://doi.org/10.3390/earth5040032

Birhane, E., Bongers, F., Damtew, A., Tesfay, A., Norgrove, L., & Kuyper, T. W. (2023). Arbuscular mycorrhizal fungi improve nutrient status of Commiphora myrrha seedlings under drought. Journal of Arid Environments, 209, 104877. https://doi.org/10.1016/j.jaridenv.2022.104877

Brychkova, G., McGrath, A., Larkin, T., Goff, J., McKeown, P. C., & Spillane, C. (2024). Use of anaerobic digestate to substitute inorganic fertilisers for more sustainable nitrogen cycling. Journal of Cleaner Production, 446, 141016. https://doi.org/10.1016/j.jclepro.2024.141016

Brundrett, M., Bougher, N., Dell, B., Grove, T., & Malajczuk, N. (1996). Working with mycorrhizas in forestry and agriculture. Australian Centre for International Agricultural Research (ACIAR). https://doi.org/10.1071/9780643060738

Castro Rebolledo, M. I., Mestre Carrillo, G. I., & Núñez Avellaneda, L. A. (2018). Cambio climático y fertilización: efectos en la biota de un arroyo andino. En A. Correa (Ed.), Agrociencias y cambio climático (1.ª ed., p. 7). Universidad de La Salle. https://doi.org/10.1016/j.apsoil.2014.11.016

CIMMYT, & CIAT. (2019). Maíz para Colombia: Visión 2030. Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT) y Centro Internacional de Agricultura Tropical (CIAT). https://fenalce.co/wp-content/uploads/2021/10/Maiz-para-Colombia.pdf

Comisión Económica para América Latina y el Caribe (CEPAL). (2018). Segundo informe anual sobre el progreso y los desafíos regionales de la Agenda 2030 para el Desarrollo Sostenible en América Latina y el Caribe. Naciones Unidas.

Guzmán, H., Perdomo, Y., Mosquera, H., Peréz, U., & Varón, M. (2022). Characterization of vegetation and the arbuscular mycorrhizal fungi community in soils impacted by gold mining in Colombia. Ciencia y Tecnología Agropecuaria, 23(3). https://doi.org/10.21930/rcta.vol23_num3_art:2394

Hammer, E., Forstreuter, M., Rillig, M. C., & Kohler, J. (2015). Biochar increases arbuscular mycorrhizal plant growth enhancement and ameliorates salinity stress. Applied Soil Ecology, 96, 114–121. https://doi.org/10.1016/j.apsoil.2015.07.014

Han, G., & Niles, M. T. (2023). An adoption spectrum for sustainable agriculture practices: A new framework applied to cover crop adoption. Agricultural Systems, 212, 103771. https://doi.org/10.1016/j.agsy.2023.103771

Hernández Jiménez, A., Vera Macías, L., Naveda Basurto, C. A., Guzmán Cedeño, A. M., Vivar Arrieta, M. R., Zambrano Teódulo, M. G., Freddy Ormanza, K., León Aguilar, R. V., & López Alava, G. A. (2017). Variaciones en algunas propiedades del suelo por el cambio de uso de la tierra, en las partes media y baja de la microcuenca Membrillo, Manabí, Ecuador. Cultivos Tropicales, 38(1), 50–56.

I. I. A., & A. E. S. (2021). Effect of biochar rates on A-mycorrhizal fungi performance and maize plant growth, phosphorus uptake, and soil P availability under calcareous soil conditions. Communications in Soil Science and Plant Analysis, 52(8), 815–831. https://doi.org/10.1080/00103624.2020.1869766

Li, Q., & Imran. (2025). Using biochar, compost, and dry-based organic amendments in combination with mycorrhizae for mitigating heavy metal contamination in soil. International Journal of Phytoremediation, 1–12. https://doi.org/10.1080/15226514.2025.2502458

Larsen, E., Grossman, J., Edgell, J., Hoyt, G., Osmond, D., & Hu, S. (2014). Soil biological properties, soil losses and corn yield in long-term organic and conventional farming systems. Soil and Tillage Research, 139, 37–45. https://doi.org/10.1016/j.still.2014.02.002

Marro, N., Grilli, G., Soteras, F., Caccia, M., Longo, S., Cofré, N., ... & Urcelay, C. (2022). The effects of arbuscular mycorrhizal fungal species and taxonomic groups on stressed and unstressed plants: A global meta-analysis. New Phytologist, 235(1), 320–332. https://doi.org/10.1111/nph.18102

Meng, Y., Davison, J., Clarke, J. T., Zobel, M., Gerz, M., Moora, M., ... & Bueno, C. G. (2023). Environmental modulation of plant mycorrhizal traits in the global flora. Ecology Letters, 26(11), 1862–1876. https://doi.org/10.1111/ele.14309

Mohammad, M. J., & Al-Smadi, B. (2022). Influence of mycorrhizal fungi and biochar on nitrogen use efficiency correlated with yield and yield components of wheat. Jordan Journal of Agricultural Sciences, 18(4), 1–15. https://doi.org/10.14719/pst.1486

Organización de las Naciones Unidas. (2015). Objetivos de desarrollo sostenible. https://www.un.org/sustainabledevelopment/es/

Pavithra, D., & Yapa, N. (2018). La inoculación de hongos micorrízicos arbusculares mejora la tolerancia de las plantas al estrés hídrico. Groundwater for Sustainable Development, 7, 490–494. https://doi.org/10.1016/j.gsd.2018.03.005

RStudio Team. (2023). RStudio: Integrated development environment for R [Computer software]. Posit Software, PBC. http://www.posit.co/

Ramazanoglu, E., Yanardag, İ. H., Sakin, E., & et al. (2025). Efectos de los hongos micorrízicos arbusculares (HMA) y el biocarbón en plantas de algodón: Un estudio exhaustivo. Journal of Soil Science and Plant Nutrition, 25, 3527–3544. https://doi.org/10.1007/s42729-025-02350-x

Razzaghi, F., Obour, P. B., & Arthur, E. (2020). Does biochar improve soil water retention? A systematic review and meta-analysis. Geoderma, 361, 114055. https://doi.org/10.1016/j.geoderma.2019.114055

Silva, P., Aguilar, A., Calaça, F., & Duchicela, J. (2021). Mycorrhizal science outreach: Scope of action and available resources in the face of global change. Plants, People, Planet, 1–17. https://doi.org/10.1002/ppp3.10213

Wang, M., Wu, Y., Zhao, J., Liu, Y., Chen, Z., Tang, Z., Tian, W., Xi, Y., & Zhang, J. (2022). La fertilización a largo plazo reduce la actividad de la fosfatasa alcalina al afectar la comunidad bacteriana que alberga phoD en el sistema de rotación arroz-trigo de invierno. Science of the Total Environment, 821, 153406. https://doi.org/10.1016/j.scitotenv.2022.153406

Wang, F. (2017). Occurrence of arbuscular mycorrhizal fungi in mining-impacted sites and their contribution to ecological restoration: Mechanisms and applications. Critical Reviews in Environmental Science and Technology, 47(20), 1901–1957. https://doi.org/10.1080/10643389.2017.1400853

Wen, Z., Chen, Y., Liu, Z., & Meng, J. (2022). Biochar and arbuscular mycorrhizal fungi stimulate rice root growth strategy and soil nutrient availability. European Journal of Soil Biology, 113, 103448. https://doi.org/10.1016/j.ejsobi.2022.103448

Yadav, V., Jain, S., Mishra, P., Khare, P., Shukla, A. K., Karak, T., & Singh, A. K. (2019). Mejora de la mineralización de nutrientes y la actividad microbiana en suelos franco arenosos mediante biocarbón envejecido en campo a corto plazo. Applied Soil Ecology, 138, 144–155. https://doi.org/10.1016/j.apsoil.2019.01.012