Revista Brasileira de Ciência do Solo

Division - Soil Use and Management | Commission - Soil fertility and plant nutrition

Use of biochar as a component of substrates in horticulture and forestry: A review

Luiz Henrique Natalli[(1)*], Everton Hillig[(1)], Kátia Cylene Lombardi[(2)], Marcelo Godinho[(2)] and Remigio Paradelo Nuñez[(3)]

[(1)] Universidade Estadual do Centro-Oeste, Departamento de Engenharia Florestal, Irati, Paraná, Brasil.
[(2)] Universidade de Caxias do Sul, Energia e Bioprocessos, Caxias do Sul, Rio Grande do Sul, Brasil.
[(3)] Universidade de Santiago de Compostela, Departamento de Edafoloxía e Química Agrícola, CRETUS, Santiago de Compostela, Spain.

ABSTRACT: Plant production in nurseries, both in the forestry and horticultural sectors, has a large demand for substrates, making the use of natural resources such as peat high. The composition of substrates must not only have the necessary characteristics for good plant development, such as porosity, density, and water retention, but also look for sustainable and economical production. Biochar is a material derived from the processing of various organic residues which, due to its physical and chemical characteristics, presents great potential as a component of substrates for seedlings in nurseries. However, some issues still need to be resolved for this application, such as implementation costs, production process variables, feedstock origin and characterization, as well as the ideal proportions to be employed in formulations. To advance in these issues, we reviewed studies dealing with the different aspects of the use of biochar as a component of substrates. The literature suggests biochar can raise the quality of substrates, improve physical and chemical properties, contribute to waste management, and reduce production costs.

Keywords: residue, seedling, plant production, nursery.

*** Corresponding author:**
E-mail: natalli.luiz@gmail.com

Received: February 18, 2024

Approved: May 21, 2024

How to cite: Natalli LH, Hillig E, Lombardi KC, Godinho M, Nuñez RP. Use of biochar as a component of substrates in horticulture and forestry: A review. Rev Bras Cienc Solo. 2024;48:e0240027. https://doi.org/10.36783/18069657rbcs20240027

Editors: José Miguel Reichert and Wenceslau Geraldes Texeira.

INTRODUCTION

Human population has grown exponentially in recent decades, and with it, the consumption of food and goods, consequently increasing the demand for production and resources, as well as waste generation. This population growth strongly affects the forestry and agronomic sectors in which resource use and demand increase. Plant production sector in nurseries is where it all begins: to maintain the final quality of the plants, it is necessary to find renewable resources and materials that provide the desirable characteristics of the substrates, reducing the use of non-renewable materials. Due to the increasing production costs in nurseries, material availability, and environmental issues, evaluation studies of these factors have been performed since the 2000s. Replacement of part of these substrates by wastes is a better environmental and economical option, since they can cost up to 34 % less than commercial substrates (Carrión et al., 2006).

A suitable destination for several organic residues is the production of biochar, a carbon-rich material obtained from the thermochemical transformation of plant biomass in partial or total absence of oxygen at temperatures ranging from 300 to 1000 °C (Zhang et al., 2015; Sanchez-Reinoso et al., 2020). As it can be obtained from a wide variety of feedstocks, including agricultural and food industry waste, forest residues, and organic waste, biochar is often described as an important alternative for waste management (Amin et al., 2016; Herviyanti et al., 2019; Fernández et al., 2020; Yang et al., 2020; Silva et al., 2022). One of the presumptions of its origin is related to the “Amazonian Dark Earths” in the Amazon, which consists of patches of soil rich in organic carbon, with high fertility and high biological activity. “Dark Earths” are connected to the activities of pre-Columbian indigenous people, where the organic matter is in a recalcitrant state and, thus, reduces the emission of carbon, contributing to its sequestration (Mangrich et al., 2011).

Biochar has been attracting the interest of many researchers, as it is a very versatile product, with uses ranging from soil improvement, increasing crop productivity, better waste management, reducing environmental contamination by pathogenic microorganisms, heavy metals, pesticides, and pharmaceutical contaminants, still with properties of use as a water and gas filter to the mitigation of greenhouse gases, from its recalcitrant carbon, which remains in the soil for many years (Novak et al., 2016; Wang et al., 2016; Borchard et al., 2018; Laird et al., 2017; Cui et al., 2019; Lentz et al., 2019; Sigua et al., 2019; Yu et al., 2019). The use of this product, since they can cost up to 34 % less than commercial substrates, provides better waste management generated along different production chains and helps to reduce the use of fossil fuels, costs and also contributes to environmental issues, constituting a renewable material, making more sustainable production systems (Agegnehu et al., 2016; Calamai et al., 2019).

In this way, biochar is a way of better using existing resources, allowing the use of organic materials that are difficult to eliminate, such as waste from the wood, paper and paper industry, charcoal production for steel mills, and industrial biofuels (biodiesel and cellulosic production for ethanol production), as well as sewage sludge and agro-industry waste (rice husks, for example), biowastes from agriculture, food industry, and forestry (Shakya and Agarwal, 2017). With this technique, the productive sectors reduce their environmental liabilities, reducing production costs and avoiding environmental damage (Mangrich et al., 2011). Furthermore, biochar is a beneficial tool for the environment, helping to minimize impacts, as it reduces carbon emissions and other GHG (greenhouse gases), could help in climate change mitigation and technologies with sustainable development co-benefits (Tripathi et al., 2016; Aiph, 2017; Alvarez et al., 2018b; Smith et al., 2019), due, mainly, the nature carbon structure with the high stability (Nguyen et al., 2010; Lehmann et al., 2011), present in the biochar.

One of the biochar applications is its use in the composition of substrates. The good formation of seedlings for agriculture and forestry is related to the quality of the substrates.

Substrate composition has been widely studied to obtain growth media that offer uniform composition, low density, high cation exchange capacity, high water retention capacity, and good aeration and drainage. Those factors can be achieved from the use of biochar, which has the potential to provide ideal conditions for germination, growth, and development of seedlings (Lima et al., 2016; Barros et al., 2019; Basílio et al., 2020). The use of organic fertilizers becomes more important due to environmental degradation concerns. When incorporated into the substrate, biochar from different raw materials can enhance the properties and improve cultivation conditions and, consequently, the quality of the seedlings.

Herewith, it is known that biochar directly and/or indirectly influences the yield of crops. A poorly explored use of biochar is the formulation of nursery or soilless substrates in horticulture. These substrates are primarily composed of organic materials (mainly peat) and inorganic materials such as vermiculite or perlite, some of which should ideally be replaced to reduce the use of materials of fossil origin, and that may contribute to the mitigation of climate change and other environmental issues (Alvarez et al., 2018b; Gruda, 2019). Also, the use of organic waste as an alternative to peat can help protect the environment by providing an environmentally and economically benign way to dispose of organic waste (Zhang et al., 2013). Peat is the main substrate used in horticulture (Landis and Morgan, 2009) because of its homogeneous and ideal physical characteristics and high nutrient exchange capacity. Peat was the predominant bulky ingredient (75.1 %), followed by organic constituents other than peat and compost (10.8 %) and then compost (7.9 %). Given the environmental and ecological importance of peatlands and their conservation, there is an ever-increasing interest and trend to replace peat by using other organic materials such as compost (Schmilewski, 2009).

Although not all biochars can be good substitutes for peat (Steiner and Harttung, 2014), its use is a sustainable alternative in growing media (Carlile et al., 2015; Alvarez et al., 2017, 2018a), due to its high pH, high surface area, excellent water and nutrient retention properties (Vaughn et al., 2017), and richness in different forms of N, P, and K (Gul and Whalen, 2016; Laghari et al., 2016). From the economic and environmental perspective, using biochar (even in low proportions) would imply benefits for small and medium producers, represented in lower substrate costs (Gallo-Saravia and Barrera-Zapata, 2018). Biochar has shown the potential to be added in growing media, combined with other materials such as peat (Méndez et al., 2015; Prasad et al., 2018), compost (Nadeem et al., 2017; Huang et al., 2019), coir (Méndez et al., 2015) or vermicompost (Alvarez et al., 2017).

In this context, this review focuses on the potential use of biochar as a component of substrates for forestry and horticultural use, and more specifically, on its use in replacing other materials, the raw materials used for production, as well as positive and negative aspects of this use. Use for horticulture and forestry production are treated separately because the plant growth and the parameters required for the plant are different.

MATERIALS AND METHODS

Data collection

The literature, which reported the use of biochar in the composition of substrates for horticultural and forestry use, was mainly collected from online databases, such as google scholar, Web of Science, and Scopus platform.

To search for articles, the terms ‘biochar’, ‘substrates’, ‘horticultural use’, ‘forestry use’, ‘positive aspects’ and ‘negative aspects’, were used in the Google Scholar database. On the Web of Science platform, we searched for the terms ‘use of biochar in the composition of substrates’, and we found around 60 manuscripts from these searches.

The terms were then filtered for 'horticultural use' and 'forestry use'. Only biochar in substrates for horticultural and forestry use were considered in this review analysis to explore the main aspects of its use in substrates composition.

Biochar use in the composition of substrates for horticultural use

In this section, studies dealing with the use of biochar in the composition of substrates for ornamental and agronomic use are reviewed. Few studies were conducted in containers (Altland and Locke, 2013; Vaughn et al., 2013; Street et al., 2014; Zaccheo et al., 2014), even fewer regarded its utilization as growing substrate for ornamental potted plants (Tian et al., 2012; Zhang et al., 2014; Iacomino et al., 2023). The results and experimental conditions in those studies are summarized in table 1.

Feedstocks employed

Biochar can be produced from many different raw materials of residual origin, and its properties depend on the feedstock and pyrolysis conditions (Novotny et al., 2023). As shown in table 2, biochars tested as components of substrates include feedstocks from municipal solid waste to industrial waste, like sludges, biomass, food waste, wood, plant, and crop residues. The most commonly used organic feedstocks for pyrolysis include biomass from food waste, paper waste, straw waste, walnut shells or animal manure (Ippolito et al., 2020).

Formulation/Composition of substrates

For substrate formulation, biochar must be blended with other materials, which include poultry manure, coconut fiber, crop residues (agricultural and forest), and wood from different species (Table 1). Composition of substrates with biochar, percentage of use, and ideal formulation for better plant development depends on the specific feedstock and final use of the substrate. Biochar is typically blended with one to three components, such as commercial substrate and other organic materials, and the rates of biochar tested range from 2.5 to 75 % v/v. Also, feedstock types have greatly influenced the composition of biochar. As happens for other organic materials, its application at high rates can be negative to production, and the best results are often observed with low application rates. In this sense, Puentes-Escobar et al. (2022) tested different concentrations (0, 5, 10 and 20 %) of biochar as a substrate on growth seedlings and observed that the highest concentrations of biochar unbalanced the base conditions of the substrate. Silva et al. (2019) observed that the concentration of 5 % biochar showed viability to be used as a substrate conditioner, while concentrations above these values did not contribute to the growth of lettuce seedlings. As observed by Souza et al. (2021), the addition of biochar from coconut husk, in the proportion of 10 % of the substrate volume, was beneficial to the production of papaya seedlings. Silva (2018) observed the best results at the same rate (10 %) for the production of lettuce seedlings using biochar from the processing of coffee fruit. Xu (2015) observed that low concentrations (25 %) demonstrated greater efficiency and better results in the production of *Rosmarinus officinalis*. Lima et al. (2013) observed the best production of beet seedlings using 7.5 % biochar in the substrate composition, corroborating that using low rates provides better plant results. So, we can conclude the best rates for biochar use as a component of horticultural substrates would be low, according to the studies reviewed in this study, with values around 10 %, mainly since those were the conditions with the best results in these studies.

Some authors have studied some mechanisms responsible for the negative effects on germination and growth. Zhang et al. (2020) reported that phenolic compounds have been shown to influence plant growth negatively. Lian and Xing (2017) observed that, in the growth and development of plants, the presence of environmentally persistent free radicals (EPFRs) in biochar is related to the inhibition of plant germination and survival. Buss and Masek (2014) reported that the presence of Volatile Organic Compounds (VOCs) in biochar had an inhibitory effect on the germination and growth of plants. Visioli et al. (2016) demonstrated that electrical conductivity and Cu negatively affected germination and root elongation at a different biochar application rate. Brtnicky et al. (2021) also reported some biochar mechanisms that affect and cause negative risks to plant germination and growth, such as trace elements, high pH, high sorption capacity (CEC), combined feedstocks, contents of PAHs, PTEs and ash contents.

Substrate properties and plant growth

Studies in the literature have reported positive effects of biochar in plant growth of different species in horticultural production, as well as on the physical, chemical and biological properties of the substrates. In this sense, it is important to keep in mind that the production results depend on the feedstock, the conditions used in the process, and the application rates, presenting both positive and negative results.

Modification of substrate properties

Xu (2015) reported that the formulation of substrates using biochar, peat, and poultry manure in different proportions (% v: v) increased the air volume, decreased the shrinkage of the substrate, and helped to increase the pH or electrical conductivity and increased the organic matter content. Also observed by Silva et al. (2022), biochar from rice husks incorporated into the substrate improved the physical properties, such as increased specific surface area, which is related to nutrient absorption. Alvarez et al. (2019), using vermicompost and commercial biochar to compound substrates (4 and 12 %) to produce *Petunia* and *Pelargonium*, reported that only bulk density was affected by the addition of vermicompost and biochar, with an increase in values.

Regarding fertility and chemical properties, Souza et al. (2021) observed that biochar promotes changes in the physicochemical properties of the substrates, providing adequate seedling growth through the improvement of nutritional characteristics and adequate nutrient supply in the case of macronutrients such as K, Ca, Mg, S and P. Sasmita et al. (2017), with rice husk and wood biochar, Bahrun et al. (2017) and Herviyanti et al. (2019), with coconut waste biochar, and Bahrun et al. (2020), with cocoa pod husk, reported that the increase of biochar rates either alone or in combination with organic fertilizers increased available P, exchangeable base cations (N, K, Ca, Na and Mg) and pH, and reduced exchangeable Al and H in growing media of Cacao. Similar observations are reported by Alvarez et al. (2019), who observed biochar addition could be a significant source of potassium in growing media and may be considered in fertility programs for ornamental plants.

Plant growth and production

Due to its intrinsic characteristics, biochar improves the physical and chemical properties of substrates, thus enhancing plant growth and production when used as a conditioner. A high production of lettuce seedlings has been observed by Silva (2018), in Bioplant® commercial substrate based on biochar. According to Fascella et al. (2015), plants grown with biochar addition were positively influenced, as were their growth, development and production. Properties such as stem diameter, leaf area, number of flowers, root length and dry biomass showed high values when compared to substrates without biochar, which corresponds to the potential use of biochar for this purpose. Similar results were reported by Souza et al. (2021), who observed that biochar provided adequate seedling growth by improving biometric variables, like plant height, stem diameter, and number of leaves. Oliveira (2022) reported that biochar promoted a greater gain in root dry biomass for *Acrocomia aculeata* than treatments with NPK fertilization.

Table 1. Research on the use of biochar in the composition of substrates for horticultural use

Biochar			End-use	Results	Reference
Pyrolysis	Raw materials	Mixture/ blend			
600-800 °C	Peat	50 % biochar	Substrate ornamental plant	Vermicompost and biochar can help producers reduce the use of peat and chemical fertilizes	Alvarez et al. (2019)
600-800 °C	Pinus monticola wood	4, 8 and 12 %	Biochar and vermicompost used as a growing media replacement in horticulture	Plants showed similar or enhanced physiological response to those grown in the control using commercial peat-based substrate	Alvarez et al. (2018a)
600-800 °C	Commercial biochar	0, 4, 8 and 12 % biochar	Substitute of growing media in ornamental plants	Mixtures with low-medium vermicompost and biochar induced more growth and flower production than that of the control	Alvarez et al. (2017)
-	-	-	Biofertilizer (peat and wheat) to inoculate Trichoderma and evaluate its effects on the growth of plant	The use of Trichoderma as a biofertilizer component with peat and wheat is an economical and promising technique	Bader et al. (2020)
Carbonization 4-6h	Cocoa pod husk	10 g biochar kg^{-1}	Growth of Cocoa seedlings	Cocoa pod husk biochar can be recommended for improving cocoa production and soil-C sequestration	Bahrun et al. (2020)
450 °C	Pequi peel	0, 2.5, 5.0, 7,5 and 10 % v/v of biochar	Soil conditioner for common bean plants	Biochar acted as a corrective for soil acidity, but in higher doses, there was a decrease in bean plant production	Basílio et al. (2022)
450 °C	Corncobs	20, 30 and 40 Mg ha^{-1}	Influence on weed infestation and growth of *Arabica coffee*	A combined application of poultry manure and biochar appears essential for sustainable coffee seedling production	Billa et al. (2019)
-	Composts from melon, pepper, zucchini	-	Substrate for ornamental plants	A material with higher mineral compounds	Carrión et al. (2006)
-	Commercial biochar	20 g kg^{-1}	Growth and quality of cocoa seedlings	The combined application of biochar and biofertilizers on the substrates can enhance the growth and quality of cocoa seedlings	Chávez et al. (2020)
-	Commercial biochar	20 g kg^{-1}	Growth and quality of arabica coffee plants	Biochar tends to enhance both the growth and quality of coffee seedlings in the nursery	Chávez et al. (2022)
	Conifer wood	0, 15, 30, 45 and 60 % biochar	Biochar as a Peat reduced-growing substrate for ornamental plants	A substrate with 60 % conifers wood biochar and 40 % sphagnum peat is suitable for obtaining marketable plants with high ornamental value	Fascella et al. (2015)
-	Coniferous wood	0, 25, 50 and 75 % by volume	Coniferous wood biochar as a substrate component of two containerized Lavender species	Peat-based substrate amendment with 25 % coniferous wood biochar could be adopted as a sustainable production system for containerized lavenders, with no adverse effects on plant growth and ornamental quality	Fascella et al. (2020)
450 °C	Conifers wood	20, 40, 60, 80 and 100 % biochar v: v	Biochar as a Peat substitute for growing substrates for ornamental plants	Growing substrate containing 40 % brown peat and 60 % conifers wood biochar was the more suitable mixture, allowing a high quality of potted plants	Dispenza et al. (2016)
800 °C	Pruning wood and activated biochar	10, 15 and 100 % v: v	Biochar as a Peat substitute in growth media for ornamental plants	Biochar can serve as a partial peat substitute for ornamental as well for some horticulture species when applied at a relatively low application rate (10 %)	Iacomino et al. (2023)

Continue

Continuation

Biochar			End-use	Results	Reference
Pyrolysis	Raw materials	Mixture/ blend			
400-600 °C 500-600 °C	Forest wood, husks and paper fiber and bamboo	0, 5, 10, 15 and 20 % v: v	Peat additive/ partial Peat replacement in growing media	Wood biochar of beech, spruce, and pine and fertilized biochar of fruit trees were more promising for peat replacement for cabbage seedling production	Chrysargyris et al. (2019)
450 °C	Fruit husks	Biochar at 10 % M/M	Evaluation of horticultural seed germination in substrate with biochar	Plants planted in the orange biochar soil mixture showed a statistically similar behavior with the control treatment, however, the biochar of passion fruit and banana had a deleterious effect	Garcia (2018)
-	From charcoal kilns	0, 40, 80 and 120 Mg ha^{-1}	Effect on soil contents	Residual effect of biochar provided a significant increase in total nitrogen contents and an increase in C/N ratio	Guimarães (2017)
-	Coconut waste	0, 0.5, 1.0, 1.5 and 2.0 % of biochar	Improve chemical properties of ultisols and growth coffee	The application of 2 % of biochar increased total N and exchangeable cations (K, Ca and Mg)	Herviyanti et al. (2020)
-	Acacia wood	100 Mg dry height of biochar	Biochar to increased soil fertility	Changes in soil carbon/nitrogen ratios indicated biochar application increased nitrogen mineralization from native soil organic matter	Kätterer et al. (2019)
200-500 °C	Tree species wood	7.5 and 15 % of biochar	Growth of sugar beet seedlings with biochar	Biochar can conditioner substrate, even in the case of commercial substrates	Lima et al. (2013)
500 °C	Coffee husk	5, 10 and 20 % v/v for each type of biochar	Substrate on granadilla growth parameters	Biochar promoted further growth, but its effectiveness decreased at a concentration of 20 %	Puentes-Escobar et al. (2022)
-	Burned log of woods	0, 0.5, 1, 2, 3, 4 % biochar	Effect of biochar on soil and plant growth	Application of biochar was also able to increase the growth and biomass of coffee seedlings	Rahayu and Sari (2017)
350-400 °C	Rice husk and white albizia wood	0, 1, 2, 4 and 6 % v/v	Application on acid soil as growing medium for Cacao	The increase of biochar rate without organic fertilizer decreased the total dry weight of cacao and combination with organic fertilizer increased	Sasmita et al. (2017)
450 °C	Rice husk and green coconut shell	-	Biochar as a substrate to seedling production	Combination of coconut shell biochar showed better results to germination of seedlings	Silva et al. (2022)
-	Coffee fruit straw	0.0, 0.9, 1.8 and 2.7 % m/m biochar	Substrate component	Biochar addition to the commercial substrate, in the proportion of 10 % mass, showed viability in the conditioning and production of lettuce seedlings	Silva (2018)
-	Eucalyptus sawdust	5, 10, 15, 25, 50 and 75 % m/m	Substrate conditioner	Biochar addition to the commercial substrate, at a concentration of 5 % mass, showed feasibility to be used as a substrate conditioner	Silva et al. (2019)
500 °C	Corn silage, manure and vegetable waste	2:1 by volume	Productivity of Pelargonium graveolens	The best crop performances were found using biochar	Calamai et al. (2019)
450 °C	Rice husks	0, 0.15, 0,75 and 1.5 % w/v biochar	Seedling root growth	Biochar had positive effects on soybean seedling growth	Zhu et al. (2018)

Table 2. Main feedstocks employed for biochar production

Origin	Feedstock	Process	References
Municipal solid waste	Tree/residues pruning	Pyrolysis	Baronti et al. (2014)
	Sewage sludge	Pyrolysis	Figueiredo et al. (2017)
Agricultural waste	Crop residues	Pyrolysis	Dumroese et al. (2011) and Chávez et al. (2022)
	Sugar cane bagasse	Pyrolysis	Nie et al. (2018) and Matos et al. (2021)
	Sugar cane/Wheat straw	Pyrolysis	Quan et al. (2020)
	Rice husks	Pyrolysis	Zhu et al. (2018) and Silva et al. (2022)
	Coffee husks/straw	Pyrolysis	Silva (2018)
	Green coconut husk/shell	Pyrolysis	Souza et al. (2021) and Silva et al. (2022)
Animal waste	Poultry manure	Pyrolysis	Billa et al. (2019)
	Chicken manure	Pyrolysis	Boldrin et al. (2010)
Industrial waste	Industrial sludge	Pyrolysis	Novotny et al. (2023)
	Paper and cellulose	Pyrolysis	Méndez et al. (2015) and Novotny et al. (2023)
	Eucalyptus sawdust/wood	Pyrolysis	Rezende et al. (2016); Gwenzi et al. (2018); Silva et al. (2019); Santos et al. (2022)

Quality and plant yield of different species are also commonly improved by adding biochar, as observed by many researchers (Sasmita et al., 2017; Bahrun et al., 2020; Djenatou et al., 2020; and Puentes-Escobar et al., 2022) who reported that the use of biochar improved the growth quality of cocoa seedlings, improving their establishment, adaptation and production, similar to the effect of conventional mineral fertilization. Biochar also has potential to reduce nematode populations, weed infestation and vegetative growth, as reported by Rahayu and Sari (2017) and Billa et al. (2019). Besides, Zhu et al. (2018) observed that biochar can promote soybean root growth at the seedling stage, maintaining adequate root biomass, accelerating plant growth, and increasing seedling plant biomass. The same was reported by Chávez et al. (2022) in a study that coffee seedlings showed a higher response trend in growth and quality to the combined application with biochar in its composition. Also, Silva et al. (2022) report better seedling germination with the combination of biochar from green coconut husk fibers. Martins et al. (2023) observed that the germination of *Passiflora mucronata* seeds showed significant responses to the physiological quality of the plants. Callejo (2023) found that adding biochar did not favor the germination of forest plants. The same was reported by Reyes et al. (2015), in which biochar did not influence the germination of forest species. According to Phoungthong et al. (2018), heavy metals leaching from biochar into soil water solution inhibited seed germination.

In turn, some studies have reported no influence or even negative effects of biochar, in particular at high doses. Garcia (2018) observed that a blend of soil with orange biochar at 10 % (m/m) showed similar behavior to peat production in horticultural seedlings. In contrast, Herviyanti et al. (2019) observed that adding up to 2 % of biochar from young coconut waste has not significantly increased coffee growth. Gallo-Saravia and Barrera-Zapata (2018) observed that the replacement of commercial substrate by pine or rice husk biochar in proportions of 20 and 50 % for the cultivation of tomatoes promoted positive results in comparison with the results without biochar. However, substrates with biochar in larger proportions seem to negatively affect the crop, due to the nutrient deficiency in the culture medium. Martins et al. (2023) observed that eucalyptus biochar in smaller proportions showed the best results for plant growth. Silva et al. (2022) observed an increase in the number of germinated seeds with the mixture of green coconut fiber biochar. The type of feedstock and the parameters used in the process influence the final product. Therefore, it is necessary to characterize the feedstock before the process and determine the pyrolysis parameters according to the required end use to avoid negative effects.

Biochar use in the composition of substrates for forest use

The number of studies about biochar application for seedling production in the forestry sector is higher than in horticulture. Its use is very important in this sector, since it allows the reduction of costs and mainly the use of fertilizers and inorganic materials, presenting itself as a good practice in environmental terms, although it still needs further study, as mentioned previously. The optimization of the production process, such as the feedstock type, determines the best arrangement for its use. The studies reviewed here are summarized in table 3.

Feedstocks employed

Several types of feedstocks can be used for biochar production, especially woody materials (Table 2). *Eucalyptus* spp. wood is a raw material widely used for biochar production, as reported by Souchie et al. (2011) and Sólis et al. (2021). Fascella et al. (2015) found that coniferous wood biochar can be a good alternative to compound substrates. Other feedstocks, such as sewage sludge or rice husk, are also used in the composition of substrates for forest use (Monteiro et al., 2020).

Formulation/composition of substrates

Formulation and composition of the tested substrates are diverse, varying according to the types of feedstocks and species, as shown in table 4. The rates of biochar employed in this case vary from low values such as González-Zamora et al. (2020), who tested 2.5 % of biochar, or Soares et al. (2021), who tested 8.3 %, reaching maximum values of 50 %, as reported by Araújo (2016) and Lopes (2019), or 75 % (Solís et al., 2021). Saavedra and Miguel (2021) tested different percentages of biochar concentration (10, 20 and 30 %). For forest use, the concentration most recommended is 20-30 %, according to Monteiro et al. (2020), Rezende et al. (2016) and Siqueira (2022). Thus, in contrast to what has been observed in studies in horticulture in the previous section, medium doses of biochar present the best results for seedling production in the forest sector.

Substrate properties and plant growth

Modification of substrate properties

Physical properties of forestry substrates are improved with the addition of biochar, in particular porosity, water retention, and availability (Xu, 2015; Siqueira, 2022). Aeration is also enhanced, which results in better oxygenation of the root system and better evacuation of carbon dioxide gas (Morales-Maldonado and Casanova-Lugo, 2015; Delaye et al., 2020). Segura (2018) reported an increase of available water in mixtures of two types of biochar, which increased water retention by approximately 0.4 g of water/g of biochar when used at a 5 % ratio. The same was reported by Monteiro et al. (2020); as the proportion of biochar in the substrate composition increased, there was a decrease in density and, consequently, an increase in total porosity. Rezende et al. (2016) also observed lower substrate densities with adding biochar and porosity values close to the established optimal, which is between 70 and 80 % (Santos et al., 2022). For production of *Moringa oleífera*, all physical properties of the substrates, such as porosity, field capacity, water availability, were positively affected by biochar (Soares et al., 2019).

Table 3. Consulted literature about using biochar in the composition of substrates for forest use

Biochar			End-use	Results	Reference
Pyrolysis	Raw materials	Mixture/blend			
300-500 °C	Sewage sludge	10, 20, 30, 40, 50 % v: v	Substrate for seedling production	Biochar produced by 300 °C could be used as a substrate for seedling production	Araújo (2016)
450 °C	Sawdust from native species	25, 50, 75, 100 % v: v	Production of *Eucalyptus urograndis*	Substrates with activated biochar and the nursery substrate presented superior results	Barros et al. (2019)
-	Cocoa husk	5 g/pound of substrate	Biochar effect on growth plants of *Ochroma pyramidale* (Balsa)	Application of biochar and biofertilizers together showed better results; after 40 days, a greater role and their interaction with biochar was evidenced	Gaón and Cedeño (2022)
464 °C	Wood	0.25, 5, 10 and 20 % v/v	Effect of biochar on the growth and survival of forest species	Biochar use as a soil amendment has a great potential for ecological restoration on degraded soils	González-Zamora et al. (2020)
-	Commercial biochar	-	Soil properties and tree growth in a tropical urban environment	Combined compost and biochar had the strongest effects on soils and growth of the urban species, and applications containing biochar resulted in the most significant soil improvements	Gosh et al. (2015)
500 °C	Eucalyptus wood	0, 5, 10, 20 and 35 % v/v	Production of *Anadenanthera macrocarpa* (Benth.) Brenan seedlings with biochar	Biochar application with N and P to the substrate shows potential for the production of quality seedlings	Lima et al. (2016)
200-500 °C	Wood of Cerrado native species	20 and 30 % of biochar and dystrophic red latosol	Biochar and organic compound for seedling production of *Magonia pubescens*	Substrates formed with a mixture of cattle manure and biochar are effective in improving the production of seedlings	Lima et al. (2015)
350 °C	Biosolid	25, 50 and 75 % biochar	Growth of forestry seedlings	Substrates with 50 and 75 % of biosolid provided higher quality seedlings, being those inoculated	Lopes (2019)
650-700 °C	Urban pruning residues	0, 10, 20 and 30 % biochar	Growth of *Prosopis limensis*	Concentration of organic carbon in the substrate increased after the incorporation of biochar as an amendment product	Saavedra and Miguel (2021)
300-600 °C	Sewage sludge	20, 25, 30, 35 and 40 % SS-biochar	Substrate for seedlings	Pyrolysis process enhanced the characteristics of sewage sludge as a component of substrates, with 20 % biochar	Monteiro et al. (2020)
	Filter cake	1, 2, 4, and 8 % v/v biochar	Soil quality and growth of Cerrado plants	Filter cake biochar promoted good growth and physiological responses and improved soil properties	Oliveira (2022)
750 °C	Leaves and fine branches	-	Effect on germination of different tree species	The use of biochar has effects that stimulate germination	Reyes et al. (2015)
450 °C	Fresh sawdust	25, 50 and 75 %	Substrate composition for production of teak seedlings	The use of 25 % activated biochar added to the commercial substrate is enough to improve seedling growth performance	Rezende et al. (2016)
-	Eucalyptus wood	0, 7.5, 15, 22,5 and 30 % biochar and biostimulant	Biostimulant in forming Schinus terebinthifolius seedlings	The proportions containing around 15 % biochar presented seedlings with the highest quality	Santos et al. (2022)

Continue

Continuation

Biochar			End-use	Results	Reference
Pyrolysis	Raw materials	Mixture/blend			
200-500 °C	Fire Wood	0, 0.5, 1, 2 and 4 kg biochar	Soil conditioner	Application of biochar to the planting hole time increased moderate to low development of the eucalyptus plants	Silva (2018)
-	Commercial biochar	20, 30 and 50 % biochar	Biochar in the composition of substrates	The use of biochar in the substrate composition is a viable and environmentally sustainable alternative to produce native forest seedlings	Siqueira (2022)
-	Eucalyptus charcoal mill	0, 7.5, 15, 22,5 and 30 %	Biostimulant in the production and quality of seedlings	The use of the biostimulant in the treatment of the seeds and biochar in the composition of the substrate did not provide an increase in the growth of the plants	Soares et al. (2021)
400-500 °C	Dry coconut shell/sewage sludge/orange bagasse sludge	1 and 2 % biochar	Composition of substrates	Biochar improved physical and chemical soil quality, promoting a better *Moringa oleifera* Lam. seedlings development.	Soares et al. (2019)
-	Eucalyptus wood	5, 12.5, 25 and 50 % biochar	Biochar as amendment to substrate of seedlings	Biochar is a good option as biological amendment to the substrate for the creation of healthy and more resistant seedlings of *Tachigali vulgaris*	Souchie et al. (2011)
-	Chicken manure	25, 50 and 75 %	Substrate component	Biochar improved cutting rooting concerning peat, which might mitigate that it contained growth stimulators	Xu (2015)

Table 4. Main composition and formulations used in substrates for forest seedlings

Biochar rate	Feedstocks	Species	References
%			
2.5	Urban solid waste Agricultural waste Industrial waste and Animal materials	*Prosopis limensis*	González-Zamora et al. (2020); Saavedra and Miguel (2021)
8.3		*Guazuma ulmifolia*	Soares et al. (2021)
10		*Crescentia alata*	González-Zamora et al. (2020)
15		*Cedrela odorata*	Souchie et al. (2011)
20		*Eucalyptus*	Monteiro et al. (2020)
25		*Tabebuia aurea*	González-Zamora et al. (2020)
30		*Pityrocarpa moniliformis*	Monteiro et al. (2020)
40		*Handroanthus impetiginosus*	Araújo (2016)
50		*Erythrina velutina*	Lopes (2019)
75		*Tectona grandis*	Solís et al. (2021)

Table 5. Main growth parameters improved with the addition of biochar

Plant growth parameters	Species	Biochar	References
Height and stem diameter			Agbna et al. (2017)
Height, neck diameter and dry mass	*Tachigali vulgaris*	*Eucalyptus* sp.	Souchie et al. (2011)
Stem diameter	*Tectona grandis*	Rice husk	Rezende et al. (2016)
Height, number of leaves and diameter	*C. odorata*	Agroforestry biomass residues	Sólis et al. (2021)
Steam, leaf and total dry matter biomass	*Cedrela odorata, Tabebuia rosea, Crescentia alata*	*Acacia pennatula* wood	González-Zamora et al. (2020)
Balance distribution of biomass	*Sapindus saponaria*	*Eucalyptus Charcoal* mill	Soares et al. (2021)
Root development	*Eucalyptus grandis; Senna multijuga; Schinus terebinthifolius*	Eucalyptus bark; Biosolids; Eucalyptus wood	Lopes (2019); Sartori (2021); Santos et al. (2022)
Physiological characteristics	Forest species	Residual biomass; Filter cake	Loyola-Savedra and Miguel (2021); Oliveira (2022)
Initial development	*Erythrina velutina*	Sewage sludge	Araújo (2016)

Regarding fertility and chemical properties, biochar acts to retain nutrients and provide a more balanced release of these nutrients to seedlings, which would also lead to lower loss of nutrients from the substrate by percolation or leaching (Maia et al., 2021). According to Soares et al. (2019), biochar improves chemical properties compared to the control, mainly pH, EC, CEC, sum of bases and base saturation, which improve seedlings production in all cases. Gosh et al. (2015) observed that combining soil/compost/biochar (3:2:1; 3:1:1; 3:1 proportions) increased N, P and K concentrations. Barros et al. (2019) also found a higher concentration of K in substrates with activated biochar. Lima et al. (2016) reported that the interaction between biochar and N benefited the quality and foliar concentration of Mg in *Anadenanthera macrocarpa* (Benth.) Brenan seedlings. When applying biochar and P, they showed greater quality and efficiency in the use of Ca and K nutrients. Siqueira (2022) reported higher concentrations of nutrients (P, K, Zn and Fe) in substrates with 50 % biochar. Lopes (2019) and Monteiro et al. (2020) observed that substrates composed of biochar had the highest pH values and available P.

Plant growth parameters and production

The studies carried out by the authors in table 5 show the main plant growth parameters, varying according to the characteristics of the biochar used. Regarding plant growth parameters, Agbna et al. (2017) found that biochar increases root growth, improves plant height, stem diameter, and fresh weight of its components and fruits, and increases crop yields. Souchie et al. (2011) observed that biochar from *Eucalyptus* sp. as substrate conditioner improved height, neck diameter, and dry mass of seedlings of *Tachigali vulgaris*. An increase in stem diameter and growth performance of teak seedlings (*Tectona grandis*) was observed by Rezende et al. (2016) by adding biochar in substrates. Due to greater root development, Sólis et al. (2021) observed positive effects of biochar on height, number of leaves, and diameter of *C. odorata*, which also improves nitrogen absorption. Seedlings of six forest species, including *Cedrela odorata L, Swietenia humilis* Zuuc, *Tabebuia rosea, Cordia alliodora*, *Guazuma ulmifolia* Lam and *Crescentia alata*, produced greater steam, leaf, total dry matter biomass, greater root biomass with biochar (González-Zamora et al., 2020). The balance in the biomass distribution in the seedling was studied by Soares et al. (2021), who observed that addition of biochar maintained a balance in the biomass distribution in the seedling.

Phenological characteristics also improved with biochar (Loyola-Savedra and Miguel, 2021). Substrates blended with different materials, such as coconut fiber, vermiculite, biosolid and biochar, provided good root development for the production of seedlings (Lopes, 2019; Sartori, 2021; Santos et al., 2022). According to Soares et al. (2019), different types of biochar positively affected the growth parameters of *M. oleifera* seedlings. Oliveira (2022) observed that biochar application and filter cake biochar contributed positively to the growth and physiology of forest species in the 'Cerrado' and can be indicated for planting. Positive effects were also observed by Araújo (2016), improving the quality and initial development of *Erythrina velutina* seedlings.

In turn, some studies have not found the influence of biochar in seedling growth parameters. Soares et al. (2021) observed that biochar did not increase the production characteristics of *Sapindus saponaria* seedlings. Souchie et al. (2011) reported that the production of *Tachigali vulgaris* seedlings with biochar did not affect the emergence of seedlings in the composition of substrates. By applying biochar from Cerrado wood to planting holes, Silva (2018) reported improvements in diameter, height, and canopy area in *Eucalyptus urograndis* seedlings. Lima et al. (2016) observed that pure biochar substrates were ineffective in improving seedlings' growth parameters. Rezende et al. (2016) observed that biochar without an activation procedure does not improve the quality parameters of seedlings when compared with a commercial substrate. Finally, negative effects have been observed, such as those reported by Sartori (2021), who indicated that doses over 15 % of biochar produced at pyrolysis temperatures of 450 and 600 °C are not recommended.

Regarding germination effects, most studies have demonstrated no adverse effects when rates of biochar <5 % are used in coniferous and deciduous trees (Gundale et al., 2016; Bu et al., 2020; Thomas, 2021). Germination percentage, seedling height, number of nodes, and seedling length root of *Prosopis limensis* were increased using biochar from organic residues, when compared to a substrate of the mix of river sand, chakra soil and the mix of both (Saavedra et al., 2022). Reyes et al. (2015) observed that biochar did not modify Acacia, Pinus and Quercus germination. According to Herrera et al. (2018), the type of biochar, depending on the feedstock used, influences the germination time of forest species. They also point out that low doses of biochar are recommended for the germination and growth of species. Carrari et al. (2018) suggested that a biochar level lower than 20 % did not affect germination. Jayakody et al. (2023), adding 250 g of biochar, showed a high seed germination rate for the species *P. conscens* and *F. limonia.* According to Vannini et al. (2022), the application of biochar produced from deciduous broadleaf trees did not affect seed germination or plant growth of European beech (*F. sylvatica*) and Turkey oak (*Q. cerris*), two of the most common tree species in Italian broadleaf forests.

Differences in biochar performance observed in these studies are likely due to its intrinsic characteristics, since biochar can be produced from different types of feedstocks, potentially with different characteristics, such as moisture, elemental composition, granulometry, porosity, mineral composition, heavy metals concentration, and these will influence its application and behavior. Also, its performance changes in relation to the conditions used in the production process, such as temperature or residence time. Although characteristics such as density, porosity, water retention are essential and indispensable for the quality of the substrates, their management regarding the availability of nutrients, quantity to be used, and intensity of irrigation or fertilization are different and must be treated separately. Studies demonstrate that process parameters directly influence the final characteristics of biochar, thus determining its appropriate use. Therefore, the study of biochar characteristics as a function of process parameters is a possible solution to finding the efficient use of biochar according to its final characteristics.

CONCLUSION

Use of biochar in the formulation of substrates for horticultural and forest use has been reported in many field experiences under different conditions, allowing us to produce some conclusions about this application and identify some limitations and opportunities for future studies. The effects of biochar on substrate properties include the improvement of their physical and chemical properties, density, water retention, porosity, VOC contents, and the retention and availability of nutrients to plants. Plant properties have also been observed to improve, including plant growth and yield, quality of seedlings, and phenological properties such as height, stem diameter or leaf area. In this sense, the use of biochar as a component of soilless substrates is an important alternative for reusing residues and represents an alternative to promote the growth and quality of seedlings in nurseries for horticulture and forest production, showing positive effects and benefits to plants, depending on the raw material and composition used, could replace partial some inorganic materials, like peat. However, it is still necessary to find the proper doses to avoid negative effects. In general, the application of lower doses showed the best results. Although, the feedstocks used and the parameters used in the production process need to be explored, as both factors influence the final characteristics and performance of the biochar after application. Finally, we should deepen our knowledge in points such as production costs, new technologies, characterization models, or process safety so that biochar can be used in the best possible way, encompassing its environmental aspects, accompanied by a perspective of change, making systems more sustainable.

DATA AVAILABILITY

The data will be provided upon request.

AUTHOR CONTRIBUTIONS

Conceptualization: Remigio Paradelo Nuñez (lead).

Data curation: Luiz Henrique Natalli (lead) and Remigio Paradelo Nuñez (supporting).

Formal analysis: Luiz Henrique Natalli (lead) and Remigio Paradelo Nuñez (supporting).

Investigation: Luiz Henrique Natalli (lead) and Remigio Paradelo Nuñez (supporting).

Methodology: Remigio Paradelo Nuñez (lead).

Supervision: Everton Hillig (equal), Kátia Cylene Lombardi (equal), Marcelo Godinho (lead) and Remigio Paradelo Nuñez (lead).

Validation: Everton Hillig (equal), Kátia Cylene Lombardi (equal), Luiz Henrique Natalli (lead), Marcelo Godinho (lead) and Remigio Paradelo Nuñez (lead).

Visualization: Everton Hillig (equal), Luiz Henrique Natalli (lead) and Marcelo Godinho (lead),

Writing – original draft: Everton Hillig (equal), Luiz Henrique Natalli (lead), Marcelo Godinho (equal) and Remigio Paradelo Nuñez (supporting).

Writing – review & editing: Everton Hillig (equal), Kátia Cylene Lombardi (equal), Luiz Henrique Natalli (lead), Marcelo Godinho (equal) and Remigio Paradelo Nuñez (supporting).

REFERENCES

Agbna GHDA, Ali AB, Bashir AK, Eltoum F, Hassan MM. Influence of biochar amendment on soil water characteristics and crop growth enhancement under salinity stress. Int J En Sci Works Kamb Publ Enterp. 2017;4:49-53.

Agegnehu G, Bass AMAM, Nelson PNPN, Bird MIMI. Benefits of biochar, compost and biochar-compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. Sci Total Environ. 2016;543:295-306. https://doi.org/10.1016/j.scitotenv.2015.11.054

Altland JE, Locke JC. Effect of biochar type on macronutrient retention and release from soilless substrate. HortScience. 2013;48:1397-402. https://doi.org/10.21273/HORTSCI.48.11.1397

Alvarez JM, Pasian C, Lal R, López R, Díaz M, Fernández M. Morpho-physiological plant quality when biochar and vermicompost are used as growing media replacement in urban horticulture. Urban For Urban Gree. 2018a;34:175-80. https://doi.org/10.1016/j.ufug.2018.06.021

Alvarez JM, Pasian C, Lal R, López R, Fernández M. Vermicompost and biochar substrates can reduce nutrients leachates on containerized ornamental plant production. Hortic Bras. 2019;37:47-53. https://doi.org/10.1590/S0102-053620190107

Alvarez JM, Pasian C, Lal R, Lopez R, Fernández MA. Biotic strategy to sequester carbon in the ornamental containerized bedding plant production. A review. Span J Agric Res. 2018b;16:E03r01. https://doi.org/10.5424/sjar/2018163-12871

Alvarez JM, Pasian C, Lal R, Lopez R, Fernandez M. Vermicompost and biochar as peat replacement for ornamental plant production. J App Hortic. 2017;19:205-14. https://doi.org/10.1590/S0102-053620190107

Amin FR, Huang Y, He Y, Zhang R, Liu G, Chen C. Biochar applications and modern techniques for characterization. Clean Techn Environ Policy. 2016;18:1457-73. https://doi.org/10.1007/s10098-016-1218-8

Araújo DD. Efeito do biochar de lodo de esgoto no crescimento inicial de mudas de *Erythrina Velutina Willd* [Dissertation]. Brasília, DF: Universidade De Brasília; 2016.

Bader AN, Salerno GL, Covacevich F, Consolo VF. Bioformulación de *Trichoderma harzianum* en sustrato sólido y efectos de su aplicación sobre plantas de pimiento. Rev Fac Agron. 2020;119:1-9. https://doi.org/10.24215/16699513e037

Bahrun A, Mardani, Rakian TC, Nuriad, Madiki A. Effect of different types of biochar on growth of cocoa seedlings (*Theobroma cacao* L.). Asian J Crop Sci. 2020;12:12-8. https://doi.org/10.3923/ajcs.2020.12.18

Baronti S, Vaccari FP, Miglietta F, Calzolari C, Lugato E, Orlandini S, Pini R, Zulian C, Genesio L. Impact of biochar application on plant water relations in *Vitis Vinifera* (L.). Eur J Agron. 2014;53:38-44, https://doi.org/10.1016/j.eja.2013.11.003

Barros DL, Rezende FA, Campos AT. Production of *Eucalyptus urograndis* plants cultivated with activated biochar. Rev Bras Cienc Agrar. 2019;14:e5649. https://doi.org/10.5039/agraria.v14i2a5649

Basílio JJN, Rodrigues LA, Silva MSA, Colen F, Oliveira LS. Biochar de casca de pequi como componente de substrato para produção de mudas de *Eucalyptus urophylla* S. T. Cad Cienc Agrar. 2020;12:1-10. https://doi.org/10.1590/0103-8478cr20200871

Billa S, Ngome A, Ngome T, Angwafo T. Influence of biochar and poultry manure on weed infestation and growth of arabica coffee (*coffeae arabica*) seedlings. Cur Res Agric Sci. 2019;6:9-19. https://doi.org/10.18488/journal.68.2019.61.9.19

Boldrin A, Hartling KR, Laugen M, Christensen TH. Environmental inventory modelling of the use of compost and peat in growth media preparation. Resour Conserv Recy. 2010;54,12:1250-60. https://doi.org/10.1016/j.resconrec.2010.04.003

Borchard N, Schirrmann M, Cayuela M, Kammann C, Wrage-Mönnig N, Estavillo JM, Fuertes-Mendizabal T, Sigua G, Spokas K, Ippolito JA, Novak J. Biochar, soil and land use interactions that reduce nitrate leaching and N_2O emissions: A metanalysis. Sci Total Environ. 2018;651:2354-64. https://doi.org/10.1016/j.scitotenv.2018.10.060

Brtnicky M, Datta R, Holatko J, Bielska L, Gusiatin ZM, Kucerik J, Hammerschmiedt T, Danish S, Radziemska M, Mravcova L, Fahad S, Kintl A, Sudoma M, Ahmed N, Pecina V. A critical review of the possible adverse effects of biochar in the soil environment. Sci Total Environ. 2021;796:148756. https://doi.org/10.1016/j.scitotenv.2021.148756

Bu X, Xue J, Wu Y, Ma W. Effect of biochar on seed germination and seedling growth of *Robinia pseudoacacia* L. in karst calcareous soils. Commun Soil Sci Plan. 2020;51:352-63. https://doi.org/10.1080/00103624.2019.1709484

Buss W, Masek O. Mobile organic compounds in biochar – a potential source of contamination – phytotoxic effects on cress seed (Lepidium sativum) germination. J Environ Manage. 2014;137:111-9. https://doi.org/10.1016/j.jenvman.2014.01.045

Calamai A, Palchetti E, Masoni A, Marini L, Chiaramonti D, Dibari C, Brilli L. The influence of biochar and solid digestate on rose-scented geranium (*Pelargonium graveolens* L'Hér.) productivity and essential oil quality. Agronomy. 2019;9:260. https://doi.org/10.3390/agronomy9050260

Callejo TP. Análisis de la eficácia de la aplicación de biochar em el crecimiento de planta florestal [trabajo de fin de grado]. Léon, Espanha: Universidad de León; 2023.

Carlile WR, Cattivello C, Zaccheo P. Organic growing media: Constituents and properties. Vadose Zone J. 2015;14:1-13. https://doi.org/10.2136/vzj2014.09.0125

Carrari E, Ampoorter E, Bussotti F, Coppi A, Nogales AG, Pollastrini M, Verheyen K, Selvi F. Effects of charcoal hearth soil on forest regeneration: Evidence from a two-year experiment on tree seedlings. Forest Ecol Manag. 2018;427:37-44. https://doi.org/10.1016/j.foreco.2018.05.038

Carrión C, Abad M, Puchades R. Desarrollo de nuevos sustratos de cultivo para la producción de planta ornamental en maceta a partir de compost de residuos de cultivos hortícolas [thesis]. València, Espanha: Universitat Politècnica de València; 2006.

Chávez JEC, Arangundi CME, García GAC. Efectividad de biochar y biofertilizantes en el crecimiento y calidad de plântulas de cacao. Rev ESPAMCienc. 2020;11:95-100. https://doi.org/10.51260/revista_espamciencia.v11i2.224

Chávez JEC, Tamayo AKL, Sanango HG, García GAC, Sacón AFC. Crecimiento y calidad de plants de café arábica con la aplicación de biochar y biofertilizantes en vivero. Chil J Agric Anim Sci. 2022;38:3-14. https://doi.org/10.29393/CHJAAS38-1CCJA50001

Chrysargyris A, Prasad M, Kavanagh A, Tzortzakis N. Biochar type and ratio as a peat additive/ partial peat replacement in growing media for Cabbage seedling production. Agronomy. 2019;9:693. https://doi.org/10.3390/agronomy9110693

Cui L, Yin C, Chen T, Quan J, Ippolito JA, Gan H, Xiao B, Pan M, Lui B, Yan J, Ding C, Hussain Q, Umer M. Remediation of organic halogen-contaminated wetland soil using biochar. Sci Total Environ. 2019;696:134087. https://doi.org/10.1016/j.scitotenv.2019.134087

Delaye LA, Ullé JÁ, Andruilo AE. Aplicación de biochar en un suelo degradado bajo producción de batata. Efecto sobre propiedades edáficas. Cienc Suelo. 2020;38:162-73.

Dispenza V, Pasquale C, Fascella G, Mammano M, Alonzo G. Use of biochar as peat substitute for growing substrates of *Euphorbia* x *lomi* potted plants. Span J Agric Res. 2016;14:e0908. https://doi.org/10.5424/sjar/2016144-9082

Djenatou P, Ndooh JPN, Kosma P, Magaptche ELN. Evaluation of the inoculation effect of arbuscular mycorrhizal fungi on the growth of cocoa seedlings (*Theobroma cacao* L.) in the nursery. Int J Sci. 2020;9:6-13 https://doi.org/10.18483/ijSci.2352

Dumroese RK, Heiskanen J, Englund K, Tervahauta A. Pelleted biochar: Chemical and physical properties show potential use as a substrate in container nurseries. Biomass Bioenerg. 2011;35:2018-27. https://doi.org/10.1016/j.biombioe.2011.01.053

Fascella G, D'angiolillo F, Mammano MM, Ferlito F. Utilizzo del biochar come sostituto de la torba nei substrati di coltivazione per piante ornamentali in vaso. Acta Italus Hortus. 2015;18:23-5.

Fascella G, Mammano MM, D'Angiolillo F, Pannico A. Coniferous wood biochar as substrate component of two containerized Lavender species: Effects on morpho-physiological traits and

nutrients partitioning. Sci Hort. 2020;267:109356.
https://doi.org/10.1016/j.scienta.2020.109356

Fernández GP, Schmidt HP, Rodríguez MCM, Martín GJM, Maure OB, Zulueta JB. Empleo de fertilizantes orgánicos basados en biochar, producidos a partir de residuos agropecuários. In: Fernández GP, Schmidt HP, Rodríguez MCM, Martín GJM, Brea O, Brunet J, editors. Manejo agroecológico de los sistemas agropecuarios. Usos del suelo con abonos y biochar. Matanzas, Cuba: EEPF Indio Hatuey; 2020. p. 54-75.

Figueiredo C, Lopes H, Coser T, Vale A, Busato J, Aguiar N, Novotny E, Canellas L. Influence of pyrolysis temperature on chemical and physical properties of biochar from sewage sludge. Arch Agron Soil Sci. 2017;64:881-9. https://doi.org/10.1080/03650340.2017.1407870

Gallo-Saravia M, Lugo-Sierra L, Barrera-Zapata R. Evaluación de biochar como alternativa de sustrato en cultivos de tomate. Sci Techn. 2018;23:300-7.
https://doi.org/10.22517/23447214.17691

Gaón DMM, Cedeño PAS. Efecto de biofertilizantes y biochar sobre el crecimiento inicial y calidad de plântulas de balsa (*Ochroma pyramidale*) [trabajo de integración curricular]. Calceta, Ecuador: Escuela Superior Politécnica Agropecuaria De Manabí Manuel Félix López; 2022.

Garcia JDR. Evaluación de germinación de semillas horto frutícolas en sustrato de biocarbón a base de cascara de frutales [thesis]. Villavicencio Meta: Universidad de los Llanos; 2018.

González Zamora JM, Cruz REL, Cruz TUG. Efecto del biochar sobre el crecimiento y sobrevivencia de seis espécies forestales con potencial uso para la restauración de suelos degradados [trabajo de fin de grado]. Managua, Nicarágua: Universidad Nacional Autónoma de Nicarágua; 2020.

Gosh S, Ow LF, Wilson, B. Influence of biochar and compost on soil properties and tree growth in a tropical urban environment. Int J Environ Sci Technol. 2015;12:1303-10.
https://doi.org/10.1007/s13762-014-0508-0

Gruda NS. Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems. Agronomy. 2019;9:298. https://doi.org/10.3390/agronomy9060298

Guimarães RS. Efeito do biocarvão e pó de serra na disponibilidade dos nutrientes, crescimento e na produção de milho (*Zea mays*. L) em Latossolo Amarelo distrófico na Amazônia Central [dissertation]. Manaus, Amazonas: INstituto Nacional de Pesquisa da Amazônia - INPA; 2017.

Gul S, Whalen JK. Biochemical cycling of nitrogen and phosphorus in biochar-amended soils. Soil Biol Biochem. 2016;103:1-15. https://doi.org/10.1016/j.soilbio.2016.08.001

Gundale MJ, Nilsson M-C, Pluchon N, Wardle DA. The effect of biochar management on soil and plant community properties in a boreal forest. GCB Bioenergy. 2016;8:777-89.
https://doi.org/10.1111/gcbb.12274

Gwenzi W, Nyambishi TJ, Chaukura N, Mapope N. Synthesis and nutrient release patterns of a biochar-based N-P-K slow-release fertilizer. Int J Env Sci Technol. 2018;15:405-14.
https://doi.org/10.1007/s13762-017-1399-7

Herrera EL, Feijoo CY, Alfaro R, Solís JL, Gómez MM, Keiski RL, Cruz GJF. Producción de biocarbón a partir de biomassa residual y su uso en la germinación y crecimiento en vivero de *Capparis scabrida* (Sapote). Sci Agropec. 2018;9:569-77.
https://doi.org/10.17268/sci.agropecu.2018.04.13

Herviyanti H, Maulana A, Prima S, Aprisal A, Crisna S, Lita, A. Effect of biochar from young coconut waste to improve chemical properties of Ultisols and growth coffee [*coffeae arabica* L.] plant seeds. Earth Environ Sci. 2019;497:012038.
https://doi.org/10.1088/1755-1315/497/1/012038

Huang L, Niu G, Feagley SE, Gu M. Evaluation of a hardwood biochar and two composts mixes as replacements for a peat-based commercial substrate. Ind Crops Prod. 2019;129:549-60.
https://doi.org/10.1016/j.indcrop.2018.12.044

Iacomino G, Cozzolino A, Idbella M, Amoroso G, Bertoli T, Bonanomi G, Motti R. Potential of biochar as a peat substitute in growth media for *Lavandula angustifolia*, *Salvia rosmarinus* and *Fragaria* x *ananassa*. Plants. 2023;12:3689. https://doi.org/10.3390/plants12213689

International Association of Horticultural Producers - Aiph. The international statistics flowers and plants yearbook. Hannover, Alemanha: Universität Hannover, Institut Für Gartenbau Ökonomie; 2017.

Ippolito J, Cui L, Kammann C, Wrage-Monnig N, Estavillo J, Fuertes-Mendizabal T, Cayuela M, Sigua G, Novak J, Spokas K, Borchard N. Feedstock choice, pyrolysis temperature and type influence biochar characteristics: A comprehensive meta-data analysis review. Biochar. 2020;2:421-38. https://doi.org/10.1007/s42773-020-00067-x

Jayakody N, Madhushan A, Pelawatta A, Yapa N. Effect of biofertilizers and organic amendments on germination and seedling growth of common dry zone forest species in Sri Lanka: Sustainable reforestation practices in Sri Lanka. Turk J Agric - Food Sci Technol. 2023;11:287-91. https://doi.org/10.24925/turjaf.v11i2.287-291.5639

Kätterer T, Roobroeck D, Andrén O, Kimutai G, Karltun E, Kirchmann H, Nyberg G, Vanlauwe B, Nowina KR. Biochar addition persistently increased soil fertility and yields in maize-soybean rotations over 10 years in sub-humid regions of Kenya. Field Crops Res. 2019;235:18-26. https://doi.org/10.1016/j.fcr.2019.02.015

Laghari M, Hu Z, Mirjat MS, Xiao B, Tagar AA, Hu M. Fast pyrolysis biochar from sawdust improves the quality of desert soils and enhances plant growth. J Sci Food Agric. 2016;96:199-206. https://doi.org/10.1002/jsfa.7082

Laird DA, Novak JM, Collins HP, Ippolito JA, Karlen DL, Lentz RD, Sistani KR, Spokas K, van Pelt RS. Multi-year and multilocation soil quality and crop biomass yield responses to hardwood fast pyrolysis biochar. Geoderma. 2017;289:46-53 https://doi.org/10.1016/j.geoderma.2016.11.025

Landis TD, Morgan N. Growing media alternatives for forest and native plant nurseries. In: Haase DL, Pinto JR, Wilkinson KM, editors. National proceedings: Forest and conservation nursery associations. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station; 2009. p. 26-31. Available from: http://www.fs.fed.us/rm/pubs/ rmrs_p058.html.

Lehmann J, Rilig MC, Thies J, Masiello CA, Hockaday WC, Crowley D. Biochar effects on soil biota - a review. Soil Biol Biochem. 2011;43:1812-36. https://doi.org/10.1016/j.soilbio.2011.04.022

Lentz RD, Ippolito JA, Lehrsch GA. Biochar, manure, and sawdust alter long-term water retention dynamics in degraded soil. Soil Sci Soc Am J. 2019;83:1491-501. https://doi.org/10.2136/sssaj2019.04.0115

Lian F, Xing B. Black carbon (Biochar) in water/soil environments: Molecular structure, sorption, stability, and potential risk. Environ Sci Technol. 2017;51:13517-32. https://doi.org/10.1021/acs.est.7b02528

Lima SL, Marimon Jr BH, Melo-Santos KS, Reis SM, Petter FA, Vilar CC, Marimon BS. Biochar no manejo de nitrogênio e fósforo para a produção de mudas de angico. Pesq Agropec Bras. 2016;51:120-31. https://doi.org/10.1590/S0100-204X2016000200004

Lima SL, Tamiozzo S, Palomino EC, Petter FA, Marimon Jr BH. Interactions of biochar and organic compound for seedlings production of *Magonia pubescens* A. St.- Hill. Rev Árvore. 2015;39:655-61. https://doi.org/10.1590/0100-67622015000400007

Lima SL, Tamiozzo S, Petter FA, Marimon BS, Marimon Jr BH. Desenvolvimento de mudas de beterraba em substratos comerciais tratados com biochar. Agrotrópica. 2013;25:181-6. https://doi.org/10.21757/0103-3816.2013v25n3p181-186

Lopes, DA. Biocarvão de biossólido na composição de substratos para a produção de mudas florestais. Dissertação [dissertation]. Seropédica, RJ: Universidade Federal Rural do Rio de Janeiro; 2019.

Maia CMBF, Guiotoku M, Peixoto RTG, Vargas LMP. Biochar e o eucalipto. In: O eucalipto e a Embrapa: Quatro décadas de pesquisa e desenvolvimento. Brasília, DF: Embrapa; 2021. p. 589-610.

Mangrich AS, Maia CMBF, Novotny EH. Biochar: As terras pretas de índios e o sequestro de carbono. CiênciaHoje. 2011;47:48-52.

Martins MNC, Lima PAM, Almeida TFR, Souza TS, Passos RR, Lopes SO, Alexandre RS, Lopes JC. Qualidade fisiológica de sementes de Passiflora mucronata semeadas em substrato composto com biochar, com e sem a presença de bioestimulante. Contrib Cienc Soc. 2023;16:19051-64. https://doi.org/10.55905/revconv.16n.10-020

Matos TTS, Fornari MR, Mangrich AS, Schultz J, Batista EMCC, Ribeiro ROC, Romão LPC, Yamamoto CI, Grasel FS, Bayer C, Dieckow J, Bittencourt JA. Low temperature production of biochars from different biomasses: effect of static and rotary lab reactors and application as soil conditioners. J Environ Chem Eng. 2021;9:105472. https://doi.org/10.1016/j.jece.2021.105472

Méndez A, Paz-Ferreiro J, Gil E, Gascó G. The effect of paper sludge and biochar addition on brown peat and coir based growing media properties. Sci Hortic. 2015;193:225-30. https://doi.org/10.1016/j.scienta.2015.07.032

Monteiro AB, Pereira IS, Banberg AL, Söcker CM, Timm LC. Substrates for seedlings with sewage sludge and biochar. Rev Ceres. 2020;67:491-500. https://doi.org/10.1590/0034-737X202067060009

Morales-Maldonado ER, Casanova-Lugo F. Mesclas de sustratos orgánicos e inorgánicos, tamaño de partícula y proporción. Agron Mesoamer. 2015;26:365-72. https://doi.org/10.15517/am.v26i2.19331

Nadeem SM, Imran M, Naveed M, Khan MY, Ahmad M, Zahir ZA, Crowley DE. Synergistic use of biochar, compost and plant growth-promoting rhizobacteria for enhancing cucumber growth under water deficit conditions. J Sci Food Agric. 2017;97:5139-45. https://doi.org/10.1002/jsfa.8393

Nguyen B, Lehmann J, Hockaday WC, Joseph S, Masiello CA. Temperature sensitivity of black carbon decomposition and oxidation. Environ Sci Technol. 2010;44:3324-31. https://doi.org/10.1021/es903016y

Nie C, Yang X, Niazi NK, Xu X, Wen Y, Rinklebe J, Ok YS, Xu S, Wang H. Impact of sugarcane bagasse derived biochar on heavy metal availability and microbial activity: A field study. Chemosphere. 2018;200:274282. https://doi.org/10.1016/j.chemosphere.2018.02.134

Novak JM, Ippolito JA, Lentz RD, Spokas KA, Bolster CH, Sistani K, Trippe KM, Johnson MG. Soil health, crop productivity, microbial transport, and mine spoil response to biochars. Bioenerg Res. 2016;9:454-64. https://doi.org/10.1007/s12155-016-9720-8

Novotny M, Marković M, Raček J, Šipka M, Chorazy T, Tošić I, Hlavínek P. The use of biochar made from biomass and biosolids as a substrate for green infrastructure: A review. Sustain Chem Pharm. 2023;32:100999. https://doi.org/10.1016/j.scp.2023.100999

Oliveira JC. Qualidade do solo e crescimento inicial de plantas do Cerrado após adubação com resíduos de cana-de-açúcar e biochar de torta de filtro [thesis]. Belo Horizonte: Universidade Federal de Minas Gerais, Instituto de Ciências Agrárias; 2022.

Phoungthong K, Zhang H, Shao LM, He PJ. Leaching characteristics and phytotoxic effects of sewage sludge biochar. J Mater Cycles Waste Manag. 2018;20:2089-99. https://doi.org/10.1007/s10163-018-0763-0

Prasad M, Tzortzakis N, McDaniel N. Chemical characterization of biochar and assessment of the nutrient dynamics by means of preliminary plant growth tests. J Environ Manage. 2018;216:89-95. https://doi.org/10.1016/j.jenvman.2017.04.020

Puentes-Escobar TC, Rodriguez-Carlosama A, López CA. Effect of biochar use as a substrate on granadilla (*Passiflora Ligularis* Juss.) Growth parameters. Agron Colom. 2022;40:22-8. https://doi.org/10.15446/agron.colomb.v40n1.98112

Quan G, Fan Q, Zimmerman AR, Sun J, Cui L, Wang H, Gao B, Yan J. Effects of laboratory biotic aging on the characteristics of biochar and its water-soluble organic products. J Hazard Mater. 2020;15:121071. https://doi.org/10.1016/j.jhazmat.2019.121071

Rahayu DS and Sari NP. Development of *Pratylenchus coffeae* in biochar applied soil, coffee roots and its effect on plant growth. Pelita Perkebunan. 2017;33:24-32.

Reyes O, Kaal J, Arán D, Gago R, Bernal J, García-Duro J, Basante M. The effects of ash and black carbon (biochar) on germination of different tree species. Fire Ecol. 2015;11:119-33. https://doi.org/10.4996/fireecology.1101119

Rezende FA, Santos VAHF, Maia CMBF, Morales MM. Biochar in substrate composition for production of teak seedlings. Pesq Agropec Bras. 2016;51:1449-56. https://doi.org/10.1590/S0100-204X2016000900043

Saavedra IRL, Miguel JJO. Biochar de biomasa residual por pirólisis lenta para la germinación y crecimiento de la semilla del *Prosopis limensis* en el distrito de cieneguilla [thesis]. Lima, Peru: Facultad de Ingeniería y Arquitectura, Escuela Profesional de Ingenieria Ambiental; 2021.

Saavedra IRL, Miguel JJO, Castañeda-Olivera CA, Galvan JJO, Alfaro EGB. Biochar from residual lignocellulosic biomass for the cultivation of *Prosopis limensis*. Chem Eng Trans. 2022;92:223-8. https://doi.org/10.3303/CET2292038

Sanchez-Reinoso AD, Avila-Pedraza EA, Restrepo-Diaz H. Use of biochar in agriculture. Acta Biol. 2020;25:327338. https://doi.org/10.15446/abc.v25n2.79466

Santos FP, Lima APL, Lima SF, Silva AAP, Contardi LM, Vendruscolo EP. Biochar and biostimulant in forming *Schinus terebinthifolius* seedlings. Rev Bras Eng Agr Ambient. 2022;26:520-6. https://doi.org/10.1590/18071929/agriambi.v26n7p520-526

Sartori AF. Potencial de uso de biocarvão como substrato e na dinâmica do carbono do solo na cultura do eucalipto [thesis]. Vitória, ES: Universidade Federal do Espírito Santo; 2021.

Sasmita KD, Anas I, Anwar S, Yahya S, Djajakirana G. Application of biochar and organic fertilizer on acid soil as growing medium for cacao (*Theobroma cacao* L.) seedlings. Int J Sci Basic Appl Res (IJSBAR). 2017;36:261-73.

Schmilewski G. Growing medium constituents used in the EU. Acta Hortic. 2019;819:33-46. https://doi.org/10.17660/ActaHortic.2009.819.3

Segura CD. Control de calidad de biocarbón para la producción de terra preta [trabajo de fin de grado]. Cartago: Escuela de Química, Instituto Tecnológico de Costa Rica; 2018.

Shakya A, Agarwal T. Poultry litter biochar: An approach towards poultry litter management - a review. Intern J Curr Microbiol Appl Sci. 2017;6:2657–68 https://doi.org/10.20546/ijcmas.2017.610.314

Sigua GC, Novak JM, Watts DW, Ippolito JA, Ducey TF, Johnson MG, Spokas KA. Phytostabilization of Zn and Cd in mine soil using corn in combination with manure-based biochar and compost. Environments. 2019;6:69. https://doi.org/10.3390/environments6060069

Silva JL, Bueno AB, Souza DM, Modolo RCE, Kappler G, Moraes CAM. Uso de biocarvão como substrato na produção de mudas a partir de duas biomassas diferentes. Rev Tecnol Soc. 2022;18:237-248. https://doi.org/10.3895/rts.v18n53.15768

Silva LFV. Biocarvão da palha do fruto do cafeeiro na remediação do solo e na complementação de substratos [TCC]. Monte Carmelo, MG: Universidade Federal de Uberlândia; 2018.

Silva LFV, Melo EI, Gonçalves PAS. Biochar de serragem de eucalipto como condicionador de substratos para produção de mudas de alface. Rev Agri-Environm Sci. 2019;5:e019005. https://doi.org/10.36725/agries.v5i0.1614

Siqueira ES. Uso de biochar na composição de substratos para produção de mudas de espécies florestais [dissertation]. Macaíba, RN: Universidade Federal do Rio Grande do Norte; 2022.

Sólis AR, Valverde YB, Moya R. Agronomic effects of *Tectona grandis* biochar from wood residues on the growth of young *Cedrela odorata* plants in a nursery. Agronomy. 2021;11:2079. https://doi.org/10.3390/agronomy11102079

Smith P, Adams J, Beerling DJ, Beringer T, Calvin KV, Fuss S, Griscom B, Hagemann N, Kammann C, Kraxner F, Minx JC, Popp A, Renforth P, Vicente JLV, Keesstra S. Impacts of land-based greenhouse gas removal options on ecosystem services and the United Nations Sustainable Development Goals. Annu Rev Environ Resour. 2019;44:255-86. https://doi.org/10.1146/annurev-environ-101718-033129

Soares DCO, Lima SF, Lima APL, Paula JAF. Uso do biochar e de bioestimulante na produção e qualidade de mudas de *Sapindus Saponaria* L. Cienc Florest. 2021;31:106-22. https://doi.org/10.5902/1980509828677

Soares TFSN, Lima I, Silva, Almeida AQ, Gonzaga MI, Fialho CAS, Gomes ILR, Massaranduba WM. Substrates formulated with biochar for seedlings production of *Moringa Oleifera* Lam. J Agric Sci. 2019;11:92570891. https://doi.org/10.5539/jas.v11n4p515

Solís AR, Valverde YB, Moya R. Agronomic effects of *Tectona grandis* biochar from wood residues on the growth of young *Cedrela odorata* plants in a nursery. Agronomy. 2021;11:2079. https://doi.org/10.3390/agronomy11102079

Souchie FF, Marimon Jr BH, Petter FA, Madari BE, Marimon BS, Lenza E. Carvão pirogênico como condicionante para substrato de mudas de *Tachigali Vulgaris* L.G. Silva & H.C. Lima. Cienc Florest. 2011;21:811-21. https://doi.org/10.5902/198050984526

Souza FEC, Natale W, Mesquita RO, Braga MM, Lima JBP, Costa RS. Use of biochar in the composition of organic substrates for the production of Papaya Seedlings. Rev Bras Cienc Agrar. 2021;16:e9103. https://doi.org/10.5039/agraria.v16i4a9103

Steiner C, Harttung T. Biochar as a growing media additive and peat substitute. Solid Earth. 2014;5:995-9. https://doi.org/10.5194/se-5-995-2014

Street TA, Doyle RB, Close DC. Biochar media addition impacts apple rootstock growth and nutrition. Hortscience. 2014;49:1188-93. https://doi.org/10.21273/HORTSCI.49.9.1188

Thomas SC. Biochar effects on germination and radicle extension in temperate tree seedlings under field conditions. Can J For Res. 2021;51:10-7. https://doi.org/10.1139/cjfr-2019-0386

Tian Y, Sun X, Li S, Wang H, Wang L, Cao J, Zhang L. Biochar made from green waste as peat substitute in growth media for *Calathea rotundifola cv. Fasciata*. Sci Hortic. 2012;143:15-8. https://doi.org/10.1016/j.scienta.2012.05.018

Tripathi M, Sahu JN, Ganesan P. Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. Renew Sustain Energy Rev. 2016;55:467-81. https://doi.org/10.1016/j.rser.2015.10.122.

Vannini A, Carbognani M, Chiari G, Forte TGW, Lumiero F, Malcevschi A, Rodolfi M, Ganino T, Petraglia A. Effects of wood-derived biochar on germination, physiology, and growth of European beech (*Fagus sylvatica* L.) and Turkey oak (*Quercus cerris* L.). Plants. 2022;11:3254. https://doi.org/10.3390/plants11233254

Vaughn SF, Kenar JA, Thompson AR, Peterson SC. Comparison of biochars derived from wood pellets and pelletized wheat straw as replacements for peat in potting substrates. Ind Crops Prod. 2013;51:437-43. https://doi.org/10.1111/j.1747-0765.2006.00065.x

Vaughn SF, Kenar JA, Tisserat B, Jackson MA, Joshee N, Vaidya BN, Peterson SC. Chemical and physical properties of Paulownia elongata biochar modified with oxidants for horticultural applications. Ind Crops Prod. 2017;97:260-7. https://doi.org/10.1016/j.indcrop.2016.12.017

Visioli G, Conti FD, Menta C, Bandiera M, Malcevschi A, Jones DL, Vamerali T. Assessing biochar ecotoxicology for soil amendment by root phytotoxicity bioassays. Environ Monit Assess. 2016;188:166. https://doi.org/10.1007/s10661-016-5173-y

Wang J, Xiong Z, Kuzyakov Y. Biochar stability in soil: meta-analysis of decomposition and priming effects. Glob Change Biol Bioenergy. 2016;8:512-23. https://doi.org/10.1111/gcbb.12266

Xu LL. Desarrollo de nuevos sustratos a base de compost y biochar para la propagación y producción de *Rosmarinus Officinalis* L. en vivero profesional [trabajo de fin de grado]. Valencia: Universitat Politècnica De València – Escola Tècnica Superior D'enginyeria Agronòmica i Del Medi Natural; 2015.

Yang H, Ye S, Zeng Z, Zeng G, Tan X, Xiao R, Wang J, Song B, Du L, Qin M, Yang Y, Xu F. Utilization of biochar for resource recovery from water: a review. Chem Eng J. 2020;397:125502. https://doi.org/10.1016/j.cej.2020.125502

Yu H, Zou W, Chen J, Chen H, Yu Z, Huang J, Tang H, Wei X, Gao B. Biochar amendment improves crop production in problem soils: A review. J Environ Manage. 2019;232:8-21. https://doi.org/10.1016/j.jenvman.2018.10.117

Zaccheo P, Crippa L, Cattivello C. Liming power of different particle fractions of biochar. Acta Hort. 2014;1034:363-8. https://doi.org/10.17660/ActaHortic.2014.1034.4

Zhang H, Voroney RP, Price GW. Effects of temperature and processing conditions on biochar chemical properties and their influence on soil C and N transformations. Soil Biol Biochem. 2015;83:19-28. https://doi.org/10.1016/j.soilbio.2015.01.006

Zhang K, Wang Y, Mao J, Chen B. Effects of biochar nanoparticles on seed germination and seedling growing. Environ Pollut. 2020;256:113409. https://doi.org/10.1016/j.envpol.2019.113409

Zhang L, Sun X, Tian Y, Gong X. Composted Green Waste as a substitute for peat in growth media: effects on growth and nutrition of Calathea insignis. PloS ONE. 2013;8:e78121. https://doi.org/10.1371/journal.pone.0078121

Zhang L, Sun X, Tian Y, Gong X. Biochar and humic acid amendments improve the quality of composted green waste as a growth medium for the ornamental plant Calathea insignis. Sci Hort. 2014;176:70-8. https://doi.org/10.1016/j.scienta.2014.06.021

Zhu Q, Kong L, Xie F, Zhang H, Wang H, Ao X. Effects of biochar on seedling root growth of soybeans. Chil J Agric Res. 2018;78:549-58. https://doi.org/10.4067/S0718-58392018000400549