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USE OF BIOCHAR IN AGRICULTURE

Uso de biocarbón en la agricultura

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ABSTRACT

The objective of this review is to show how biochar (BC) can be obtained and its effects on the physicochemical properties of soils and physiological behavior of cultivated plants. Biochar is a product rich in carbon that comes from the pyrolysis of biomass, generally of vegetable origin. It is obtained by the decomposition of organic matter exposed to temperatures between 200-900 °C in an atmosphere with low oxygen availability (pyrolysis), which can be slow, intermediate or fast. BC can contain varying levels of elements such as: carbon, nitrogen, oxygen, hydrogen, and sulfur. The primary sources to produce biochar are the forest, agroindustrial, and manure residues. BC quality and physical-chemical characteristics will depend on the type of waste or plant material for production. The high carbon contents present in organic matter, which are more resistant to biological and chemical decomposition, are stabilized by pyrolysis. BC remains stable into the soil for more extended periods (this allows BC to be considered as an essential component for the mitigation of the impacts of polluting substances). It has been found that BC application improves the physicochemical characteristics of the soil, including fertility. This improvement generates positive responses in the physiological behavior of plants such as: the increase of germination, accumulation of dry matter, photosynthesis, yield, and quality. Biochar opens essential doors for the sustainable management of agriculture in Colombia. It can be considered in agricultural regions exposed to heavy metals, in order to reduce its impact on human health.

Keywords: Carbon capture, mineralization, plant nutrition, pyrolysis.

RESUMEN

El objetivo de esta revisión es mostrar cómo es el proceso de obtención de biocarbón (BC) y sus efectos sobre las propiedades fisicoquímicas de los suelos y el comportamiento fisiológico en plantas cultivadas. El BC es un producto rico en carbono obtenido por pirólisis de biomasa generalmente de origen vegetal. Se obtiene mediante la descomposición de materia orgánica en exposición a temperaturas entre 200-900 °C en una atmósfera con baja disponibilidad de oxígeno (pirólisis), que puede ser lenta, intermedia o rápida. El BC puede contener altos niveles de elementos como: carbono, nitrógeno, oxígeno, hidrógeno y azufre. Las fuentes principales para producir biocarbón son: residuos forestales, agroindustriales y estiércol. La calidad y características físico-químicas del BC dependerán del tipo de residuos o material vegetal para la producción. Los altos contenidos de carbón de la materia orgánica en una forma más resistente a la descomposición biológica y química son estabilizados por pirólisis. El BC se mantiene estable en el suelo durante más tiempo (compuesto importante para la mitigación de los impactos de la polución de sustancias contaminantes). La aplicación de BC mejora las características fisicoquímicas del suelo, incluyendo la fertilidad. Estos cambios generan respuestas positivas en el comportamiento fisiológico de las plantas como: incremento de la germinación, acumulación de materia seca, fotosíntesis, rendimiento y calidad. El BC abre ventanas importantes en el manejo sostenible de la agricultura en Colombia. Su uso puede ser considerado en regiones agrícolas expuestas a metales, con el fin de reducir su impacto en la salud humana.

Palabras clave: Captura de carbono, mineralización, nutrición de plantas, pirólisis.

INTRODUCTION

The concentration of atmospheric CO_2 is currently ~417 mg kg^{-1} and this concentration has increased continuously as a result of human activities, such as industrial processes and changes in land use and agricultural practices. Atmospheric CO_2, along with other gases, cause a warming effect of the planet, negatively affecting the soil's chemical, physical and biological properties (Pak *et al*., 2016). Biochar (BC) is a viable option to face global warming because it helps carbon sequestration, which improves crop yield (Lehmann and Joseph, 2009). BC has also shown the potential to improve conventional agricultural productivity and profitability of farmers by favoring the plant nutritional status (Atkinson *et al*., 2010).

The origin and use of BC as a source to improve soil fertility is reported in the dark Amazonian lands locally known as "Terra Preta do Índio" (TPI) (Lehmann and Joseph, 2009). The soils of this Amazonian region have an A horizon, which is rich in carbon and nutrients (indicators of soil quality). It is a result of the accumulation of organic vegetable and animal residues which have been subjected to the intensive use of fire (de Sousa *et al*., 2015). Therefore, BC has been defined as a product rich in carbon that comes from the heating of biomass such as wood, manure or leaves in a closed container with little or no air availability (Lehman and Joshep, 2009). However, Shackley *et al*. (2012) also defined BC as biomass that has been pyrolyzed, and that has suitable physical-chemical properties for the safe and long-term storage of carbon in the environment. It involves a change in the chemical composition of the raw material, and it is irreversible.

Biochar can bring significant benefits when applied to agricultural soils in combination with some fertilizers (Schulz *et al*., 2013). An increase in crop yield from 45 to 250 % has been reported, when BC is used in mineral nutrition plans of crops, such as radish, rice, corn and wheat (Atkinson *et al*., 2010; Biederman and Harpole, 2013). The water retention properties of the soil, saturated hydraulic conductivity, and nutrient availability have also been optimized with BC application (Jeffery *et al*., 2016). Spokas *et al*. (2009) also reported that the supply of sawdust BC reduced CO_2 production (associated with the respiration of methanotrophic microorganisms) and the synthesis of nitrous oxide and methane (observed in the reduced N_2O and the lower rates of NH_4 oxidation). Finally, Sohi (2012) concludes that the organic material used in the production of biochar influences the structure, porosity, as well as the density and the specific surface of BC, which favors the availability of nutrients to be subsequently absorbed by plants.

Currently, studies focused on evaluating the potential of BC as a soil amendment and carbon sink have been carried out in order to provide a solution to erosion and greenhouse gases emission problems (Sohi, 2012). However, the available information on the responses of plants grown under BC supply is still limited and need further investigation (Jha *et al*., 2010). Therefore, this review aims to show, in a general way, how BC is obtained by shedding light on the debate about the effects on the physical and chemical properties of soils and the physiological behavior of cultivated plants.

GENERAL ASPECTS OF BIOCHAR PRODUCTION

Biochar is obtained by the decomposition of organic matter exposed to temperatures between 200-900 °C in an inert atmosphere with low / no oxygen concentration. This process, known as pyrolysis (Sohi, 2012), is generally divided into fast, intermediate and slow depending on the residence time (time required to complete the pyrolysis process) and the exposure temperature of the biomass (Lhemann and Joseph, 2009). The first is characterized by a concise residence time and high temperatures (less than 2 seconds, > 800 °C) and is often used to produce bio-oil from biomass obtaining approximately 75 % yield (Mohan *et al*., 2006). The processes of slow and intermediate pyrolysis occur with a residence time of a few minutes to several hours or even days under temperatures between 300 and 800 °C, with BC yields between 25-35 % (Brown, 2009).

Different studies have shown that both the pyrolysis temperature and the material used have an effect on the production characteristics of BC for agricultural use (Sohi, 2012). Gaskin *et al*. (2008) stated that BC manufactured from animal waste (poultry litter) has a lower carbon content (close to 40 %), while in the one obtained from vegetable by-products (pine chips) it is close to 78 %. These authors also reported that BC produced from pine chips at a temperature of 500 °C in the pyrolysis process caused a higher nutrient content (P, K, Ca, Mg), compared with a temperature of 400 °C. Finally, biochar physical and chemical qualities are also conditioned by factors such as the size and density of the pyrolyzed particle, the concentration of inorganic (ash content, Ca, Mg, and inorganic carbonates) and organic (cellulose, lignin, and hemicelluloses) compounds, and the type of waste (Lehmann and Joseph, 2009; Keiluweit *et al*., 2010).

BC obtained from forages, woody plants, or cacti shows different physical and chemical characteristics due to their carbon fixation metabolisms (Ahmad *et al*., 2014). For example, BC from CAM plants (pineapple) showed a higher content of nutrients such as N, P, K, Ca, Mg, Na, Zn, Cu, Fe, and Al (Ch'ng *et al*., 2015). In this sense, Table 1 shows a summary of the main plant species that have been used in biochar production, which were grouped according to their type of carbon fixation metabolism (C3, C4, and CAM).

CURRENT USES OF BIOCHAR

One of the main dilemmas of agricultural activities is the management of large volumes of organic waste, which need to be treated appropriately in order to avoid risks of

Table 1. Summary of the different plant species used in biochar production from pyrolysis. Species are grouped according to carboxylation plant metabolism and characteristics.

Photosynthetic Metabolism	Plant type	Species	Pyrolyzed biomass	Obtained results	Reference
C3 plants	Cereal	Wheat	Wheat straw	Increase in the content of elements such as B, Cu, Cr and Mo.	Kloss *et al*., (2012)
		Rice	Rice husks	Biochar modified for the removal of tetracycline. Adsorption capacity (58.8 mg g^{-1}) attributed to its porous structure and large specific surface area.	Liu *et al*., (2012)
	Oil	Soy	Soy straw	P (2.2 g kg^{-1}), N (23.8 g kg^{-1}), C (441 g kg^{-1}) and total base cations of 53 cmol/kg.	Tong *et al*., (2011)
		Peanut	Peanut hulls	Temperatures of 700 °C: higher C content and increased pH. T of 300 °C acidification of the aqueous solution (pH reduction from 10.57 to 7.76) and elements such as H, N, S and O were higher.	Ahmad *et al.,* (2012)
		Canola	Straw and waste	Facilitates the electrostatic adsorption of copper, specifically by the formation of surface complexes with -COOH and phenolic hydroxyl groups on the biocarbon surfaces.	Tong *et al.,* (2011)
		Safflower	Safflower seed cake	Biochar modified with KOH to measure its adsorption capacity. Contents of C (62.45%), H (1.85%), N (4.07%) and O (31.63%).	Angın *et al*., (2013)
	Fruit	Orange	Orange peels	Pyrolysis at 150 °C: specific surface area of 22.8 m^2 g^{-1}, 50% C, 1.75% N, 6.2% H and 41.0% O. Pyrolysis at 700 °C: specific surface area 201 m^2 g^{-1}, 71.6% C, 1.72% N, 1.76% H, and 22.2% O.	Chen and Chen (2009)
	Fiber and forest	Cotton	Cotton seed hulls	Greater content of elements such as: Na, Ca, K, Mg, P, and S in biochar.	Uchimiya *et al*., (2011)
		Pine	Needles, chips and wood	Pyrolysis at 100 °C: 50.87% C, 0.71% N, 6.15% H. Pyrolysis at 700 °C: 86.51 % C, 1.13% N, 1.28 % H.	Chen *et al*., (2008)
		Fir	Wood	Content of C 79.6%, N (1.02 – 1.24%), and H (3.04 – 5.48%).	Kloss *et al*., (2012)
		Poplar	Wood	Content of C 78%, N (78 – 1.07%), and H (2.66 – 4.42 %).	Kloss *et al*., (2012)
		Oak	Wood	Specific surface area between 1 – 3 m^2 g^{-1}. Rich in oxides of elements such as Ba, Al, Ca, Fe, K, Mg, Mn, Na, Si, Sr and Ti.	Mohan *et al*., (2011)
	Perennial crops	Coconut	Coconut shell	Adsorption capacity of heavy metals such as copper and lead.	Machida *et al*., (2005)
		Palm	Empty fruit bunches	Pyrolysis at 300 °C: 59.62% C, 4.02% H, 34.05% O and 2.31 % N. Pyrolysis at 700 °C: 68.63% C, 2.71 % H, 27.45% O and 1.21% N.	Sukiran *et al*., (2011)
		Coffee	Processing residues and old plants	Content of C (51 – 76%), H (5.0 – 7.2%), N (2.4 – 4.3%), S (0.05 – 0.17%), P (0.18 – 0.48%), K (0.81 – 1.94%), Ca (0.17 – 0.56%), Mg (0.20 – 0.60%) and Na (0.06 – 0.17%).	Vardon *et al*., (2013)
C4 plants	Cereal	Corn	Cob and leaves	Greater content of elements such as: Si, Al, Fe, Ca, Mg, Na, K, Ti, Mn, P, Ba, Sr and inorganic S.	Mullen *et al*., (2010)
	Grass	Grasses	Fescue grass straw	Ash content (5.7 – 19.3%), C (47.2 – 94.2%), N (0.61 – 1.24%), H (1.53 – 7.25%), O (3.6 – 45.1%) and a specific surface area between 1.8 – 139 m^2 g^{-1}.	Keiluweit *et al*., (2010)
		Bamboo	Plant waste	63.5% C, 2.9% H, 0.55% N and 33% O. Bamboo waste: 78.7% C, 3.4% H, 1.1% N, and 16.7% O.	Zhang *et al*., (2014)

(*Continued*)

Table 1. Summary of the different plant species used in biochar production from pyrolysis. Species are grouped according to carboxylation plant metabolism and characteristics.

Photosynthetic Metabolism	Plant type	Species	Pyrolyzed biomass	Obtained results	Reference
CAM plants	Fruit	Pineapple	Fruit peel	73% C, H (1.37 - 3.36%), O (9.88 – 12.05%) and N (0.99 - 1.23%).	Cheah *et al*., (2013)
			Leaves	45.8% C, 2.30% N, 0.46% P, 2.67% K, 0.40 % Ca, 6365 g Kg^{-1} Mg, 1143 g Kg^{-1} Na, 119 mg Kg^{-1} Zn, 47.2 mg Kg^{-1} Cu, 5062 mg Kg^{-1} Fe, and 1.50 mg Kg^{-1} Al.	Ch'ng *et al*., (2015)
			Crowns	Content of C (32.01 – 52.04%), H (4.27 – 5.97%), N (1.27 – 1.86%), O (33 – 37%), Fe (0.01 – 0.08%) and a superficial area between 0.335 a 24.46 m^2 g^{-1}.	Fu *et al*., (2016)
	Xero-phyte	Cactus	Plant waste	Removal of copper in polluted water, as it presents laminar structures with carboxylic residues on the upper external surface.	Hadjittofi *et al*., (2014)

pollution, soil erosion, eutrophication of water and the emission of greenhouse effect gases (Amhad *et al*., 2014). As a result, various technologies are currently being used for BC application. In this sense, Dias *et al*. (2010) concluded that eucalyptus BC could be used as a loading agent for the composting of poultry manure since it generates a positive effect that mitigates the degradation and humification of organic matter.

Another critical characteristic of BC is its sorption capacity (process by which another absorbs a material) of inorganic contaminants such as heavy metals (lead, chromium, copper, zinc, nickel, arsenic, and cadmium) from mining operations in both soil and water (Dong *et al*., 2011; Regmi *et al*., 2012; Hadjittofi *et al*., 2014; Trakal *et al*., 2014). This kind of pollution by organic substances has increased as a result of hydrocarbons exploitation, refining, storage and distribution, and bioremediation can take years to complete the restoration and recovery of impacted areas (Ferrera-Cerrato *et al*., 2006). Also, BC use has been reported as an exciting alternative in the cleaning of soils contaminated by agrochemicals (Ahmad *et al*., 2014). Many of these substances have accumulated as a result of the indiscriminate use of herbicides, insecticides, and other toxic molecules (Herath *et al*., 2016). For example, it has been observed that the amount of atrazine in the soil was reduced by livestock manure BC sorption (Cao *et al*., 2011). Also, the high surface and nano-porosity of BC favored the adsorption of insecticides based on chlorpyrifos and carbofuran (Yu *et al*., 2009), and decreased the levels of a pesticide such as pentachlorophenol (Xue *et al*., 2012). In addition, the use of BC has mitigated the contaminating impact of substances such as diclofenac (Jung *et al*., 2015), furfural (Li *et al*., 2014), glyphosate (Herath *et al*., 2016), ibuprofen (Jung *et al*., 2015; Mondal *et al*., 2016), levafix red (Angın *et al*., 2013), methylene blue (Wang *et al*., 2013; Zhang *et al*., 2014), naproxen (Jung *et al*., 2015) and sulfamethazine (Rajapaksha *et al*., 2015). Table 2 shows the main bioremediation effects of BC in soils.

The potential use of biochar as an alternative and complementary substrate in the production of seedlings in crops without soil has also been studied (Dispenza *et al*., 2017). Altland and Locke (2012) stated that BC-modified substrates used for the production of ornamental plants are an important source of phosphates. Bommaraju (2016) found that substrate constituted by vermicompost, peat, and BC from forest residues (50 % biochar and 50 % vermicompost) enhanced plant photosynthesis in coffee seedlings. Gu *et al*. (2013) also observed that biochar at a rate of 5-30 % v/v could replace commercial substrates such as peat of pine bark, moss or pearlite without generating negative impacts on *Gomphrena* plants growth.

EFFECTS OF BIOCHAR APPLICATION ON THE PHYSICAL-CHEMICAL PROPERTIES AND *MICROBIOLOGY OF THE SOIL*

BC incorporation into the soil can alter water retention because BC porosity and high specific surface area reduce the apparent density of the soil (Rajapaksha *et al*., 2016). Additionally, it was found that the use of BC from pecan walnut shells and grass residues may favor the increase in soil temperature because it confers a dark color which is associated with the capture of solar energy. This increase in soil temperature may benefit microbial communities and germination of seeds in soils with low temperatures (Busscher *et al*., 2010). Another valuable physical property that is affected by the application of BC from olive tree pruning waste is the compaction of the soil, which was reduced, allowing a more significant root proliferation (Olmo *et al*., 2014).

BC can also modify the chemical properties of the soil, increasing the cation exchange capacity and improving soil fertility through the availability of essential and beneficial nutrients for the plant (Liang *et al*., 2006). Van Zwieten *et al*. (2010) have reported that the use of BC improved fertility by increasing the pH and Cation Exchange Capacity (CEC) in the

Table 2. Bioremediation effects of biochar application on soils.

Use	Substance	Type of Biochar	Response found	Reference
Bioremediation of heavy metals	Copper	Rice straw	Presence of functional groups with high affinity of adsorption to Cu in BC.	Jiang *et al.,* (2012)
	Cadmium	Orchard pruning waste	Significant bioavailability reduction.	Fellet *et al.,* (2011)
	Arsenic	Wood	Significant As reduction.	Hartley *et al.,* (2009)
	Lead	Oak wood	Bioavailability reduction by 75%.	Ahmad *et al.,* (2012)
	Chrome	Chicken manure	Reduction of Cr (IV) to Cr (III).	Choppala *et al.,* (2012)
	Zinc	Sewage sludge	Significant reduction in availability of the studied metal for the plants.	Méndez *et al.,* (2012)
	Nickel	Cotton seed hulls	Surface functional groups of BCs controlled metal sequestration.	Uchimiya *et al.,* (2011)
Bioremediation of organic substances	Atrazine	Cattle manure	Sorption of the molecule and atrazine partition positively related to the carbon content of BC.	Cao *et al*., (2011)
		Wood shavings	Adsorption of the molecule.	Spokas *et al.,* (2009)
		Pasture pruning	Increased herbicide adsorption.	Zheng *et al.,* (2010)
	Diuron	Eucalyptus wood	Stronger adsorption and weaker desorption of agrochemicals.	Yu *et al.,* (2011)
	Chlorpyrifos	River red gum (*Eucalyptus spp*) wood	Adsorption by surface area of the BC.	Yu *et al*., (2009)
	Carbofuran		Adsorption by surface area of the BC.	Yu *et al*., (2009)
	Carbaryl	Pig manure	Sorption of the molecule.	Zhang *et al.,* (2013)

soil, especially at application rates of 10 t ha^{-1}. On the other hand, Karhu *et al*. (2011) showed that the incorporation of 9 t ha^{-1} of BC into a soil used for agriculture increased the average CH_4 uptake and the water retention capacity close to 96 %. Additionally, it has been reported that biochar can increase the electrical conductivity (Oguntunde *et al*., 2004) and reduce the exchangeable acidity (Chan *et al*., 2008; Ch'ng *et al*., 2015), which indicates that nutrients may be more available in the soil solution. Table 3 summarizes the main benefits obtained in the physical and chemical properties of the soil with the supply of biochar.

Regarding BC impact on soil microorganisms, this aspect has gotten less attention in comparison to the physical and chemical properties of the soil (Lehman *et al*., 2011). Anderson *et al*. (2011) found that BC application promotes phosphate solubilizing bacteria, altering the carbon flux in the soil to increase the abundance of bacteria families such as *Streptosporangineae* (~6 %), *Thermomonosporaceae* (~8 %), *Bradyrhizobiaceae* (~8 %), and *Hyphomicrobiaceae* (close to ~14 %) (these last two families have an important participation in the nitrogen cycle especially in the denitrification process of NO_3^- to N_2). These results indicate that BC application promotes phosphate solubilizing bacteria, which alter the flow of carbon in the soil and increase the abundance of these microorganisms that can degrade more recalcitrant carbon compounds and potentially reduce plant pathogenic bacteria.

BC application can condition associations between plants and microorganisms. For example, Kolton *et al*. (2011) found that BC incorporation in the soil enhanced bacterial communities (*Flavioibacterium*) associated with the root of mature sweet pepper (*Capsicum annuum* L.) plants. On the other hand, Warnock *et al*. (2010) observed that the abundance of arbuscular mycorrhizas decreased proportionally with the application of pine chip BC in *Plantago lanceolata* L. plants. It was found that the abundance of arbuscular mycorrhizas decreased proportionally with the application of BC, and these changes were accompanied by increases in both the pH and phosphorus availability in the soil; this indicates that the pH may be influencing the abundance mechanisms of mycorrhizae. In this sense, many of the studies have found that the microbial biomass increases as a result of BC application, but significant changes occur in the composition of the communities and in the enzymatic activities. These changes may explain the biogeochemical effects of BC on the nutrient cycle, the presence of phytopathogenic organisms and the growth of crops (Spokas *et al*., 2009; Elad *et al*., 2010; Solaima *et al*., 2010). However, very little is known about the mechanisms

Table 3. Main effects of biochar application on the physical and chemical properties of the soil.

Affected property		Effect	Reference
Physical	Apparent density	Reduction of apparent density due to the porosity of BC.	Kuzyakov (2009)
	Color	Changes in the color of the soil surface, which are visible after the application of BC.	Vacari *et al.,* (2011)
	Water retention	Increased water retention due to the porosity and high specific surface area of BC.	Kuzyakov (2009)
	Infiltration	Reduction of soil infiltration.	Busscher *et al.,* (2010)
	Compaction	Reduction of soil compaction.	Olmo *et al.,* (2014)
	Penetration resistance	Decreased resistance to penetration with BC application.	Busscher *et al.,* (2010)
	Temperature	Increased soil surface temperature in early stages of germination and growth of wheat crops with application of BC.	Vacari *et al.,* (2011)
Chemical	pH	Soils alkalinization by increased pH.	Sorrenti *et al.*, (2016)
	Electric conductivity	Increase in the electrical conductivity of the soil in the presence of BC compared to soil without BC.	Oguntunde *et al.,* (2004)
	CEC	Increased cation exchange capacity.	Liang *et al.*, 2006
	Total organic C	Increased total carbon.	Van Zwieten *et al.*, (2010)
	Dissolved organic carbon (DOC)	Increased amount of DOC in the soil.	Rajapaksha *et al.,* (2016)
	NO_3^-	Reduction of NO_3^- washing by 75% in the second year.	Ventura *et al.,* (2013)
	Interchangeable Na	Increased exchangeable sodium.	Chan *et al.,* (2008)
	Interchangeable K	Increased interchangeable potassium.	Van Zwieten *et al.*, (2010)
	Soluble K	Increased soluble potassium in soil.	Asai *et al.,* (2009)
	Available P	Increased amount of available phosphorus in soil.	Ch'ng *et al.*, (2015)
	Interchangeable Ca	Increased exchangeable calcium.	Van Zwieten *et al.*, (2010)
	Interchangeable Mg	Increased exchangeable magnesium.	Chan *et al.,* (2008)
	Interchangeable Al	Reduces aluminum availability.	Van Zwieten *et al.*, (2010)
	Interchangeable acidity	Reduces interchangeable acidity.	Ch'ng *et al.*, (2015)

through which BC affects the abundance and composition of microbial communities (Lehman *et al.*, 2011).

EFFECT OF BIOCHAR APPLICATION ON PLANT PHYSIOLOGY

Chan *et al*. (2008) observed that combined applications of BC of waste paper mills and chemical synthesis fertilizers favored the growth of radish plants since BC improved N fertilizer-use efficiencies. Also, parameters such as plant height, stem diameter, and dry matter were increased by BC in teak (*Tectona grandis*) seedlings. Finally, Van Zwieten *et al*. (2010) and Olmo *et al.* (2014) also found that BC improved seed germination and root growth in wheat plants.

BC application improved the absorption of nutrients in kiwi (Sorrenti *et al*., 2016) and apple (Ventura *et al*., 2013) plants. Ch'ng *et al*. (2015) also reported that BC (manufactured with pineapple leaves) improved the contents of nitrogen (~80 %), phosphorus (~200 %), potassium (~400 %), calcium (~100 %), and magnesium (~150 %) in corn leaves. Besides, BC can help crop quality since it favors the accumulation of fatty acids such as palmitic, stearic, oleic, and linoleic in soybean (Waqas *et al*., 2017). The extraction of leachates from substrates with BC supports that fact that such natural enhancer is rich in nutrients, which favor plant growth when incorporated into the soil or substrates (Bommaraju, 2016). Sun *et al*. (2017) evaluated the molecular properties of water-soluble extracts (WSE) of BC prepared from wheat and corn plant residues. They found that these substances promoted grain germination and increased the coleoptile length of corn seedlings, specifically in the WSE obtained from corn BC.

Studies have been reported regarding the synergistic activity between BC application and other sources of nutrients with some exceptions. In this regard, Seehausen *et al.* (2017) found antagonistic effects between BC application and substrates from mushroom production on the maximum leaf area and stomatal conductance of *Abutilon theophrasti*. For this reason, it is important not to make generalized conclusions about the synergistic effects of BC application on plant yield. In this sense, Kishimoto and Sugiura (1985) (as cited in Chan and Xu, 2009) found that the application of 5 and 15.25 t ha^{-1} of BC (from unknown woods) in a soybean crop affected yield, reducing it by 37 % and 71 % respectively, due to the increase in pH that caused nutritional deficiencies in the plants. Similar responses were observed by Asai *et al.* (2009) in the quantification of "SPAD chlorophylls", finding the lowest values in the treatments with biochar application, which was attributed to the reduction in nitrogen availability in the soil. Finally, Table 4 summarizes the main effects of biochar application on the physiological behavior in plants.

PERSPECTIVES

The use of BC opens essential opportunities for the sustainable management of agriculture in Colombia. As mentioned before, BC can be considered in systems in which vegetables are irrigated with contaminated water (Miranda *et al.*, 2011) and in perennial crops exposed to heavy metals due to activities related to mining and hydrocarbon exploitation (Jiménez, 2015), in order to reduce their impact on human health. In this sense, the cocoa crop is cultivated in contaminated soils with high cadmium content; in these scenarios, biochar can be an important alternative in bioremediation of heavy metals (Lau *et al.*, 2011). Another interesting opportunity is to evaluate the different sources of plant and animal material as alternatives to be used in the pyrolysis process, especially by-products such as sugar cane bagasse (Rodríguez *et al.*, 2009), the leaves and empty fruits of oil palm crops (Sukiran *et al.*, 2011), corn, sorghum and rice chaffs, cotton waste, as well as waste from livestock activities (pig, poultry and cattle manure). The knowledge of the effects on the physiology of cultivated plants is one of the main challenges that should be taken into consideration. A clear example is the use of solid vegetable residues of coffee production systems as the pulp obtained from the fruit processing represents about 43.58 % of the coffee fruit on a fresh weight basis (Montoya, 2006). It has been reported that about 2258 kg ha^{-1} of coffee pulp are produced annually (Rodríguez, 2007). Collectively, about 162 900 t of fresh pulp are generated per each million bags of 60 kg of dried parchment coffee that is exported from Colombia. If not used correctly, the pollution caused by these residues would be equivalent to the one generated by the excrements and urine of a population of 868 736 inhabitants (Rodríguez, 2009). For this reason, alternatives such as the application of BC can improve the productivity, quality and profitability of farmers.

On the other hand, it has been shown that BC application causes small and potentially transitory changes in the functioning of agroecosystems (Jones *et al.*, 2011). Studies

Table 4. Summary of the different effects of biochar application on the physiological activity of variables in plants.

Plant species	Physiological variable	Type of BC	Application rate	Responses found	Reference
Radish	Germination	Paper mill waste	10 t ha^{-1}	Increased germination.	Van Zwieten *et al*., (2010)
	Dry matter	Grass pruning residues, cotton waste and plant pruning	10 - 100 t ha^{-1}	Increased dry matter accumulation.	Chan *et al*., (2008)
		Paper mill waste	10 t ha^{-1}	Increased dry matter accumulation.	Van Zwieten *et al*., (2010)
	Yield	Grass pruning residues, cotton waste and plant pruning	10 - 100 t ha^{-1}	Increased yield.	Chan *et al*., (2008)
Soy	Dry matter	Paper mill waste	10 t ha^{-1}	Increased dry matter accumulation.	Van Zwieten *et al*., (2010)
	Fatty acids	Pine waste	10:90 (p/p)	Higher fatty acids accumulation.	Waqas *et al*., (2017)
	Yield	Unknown wood	0.5 t ha^{-1}	Increased yield in 51%.	Kishimoto and Sugiura (1985) cited by Chan and Xu (2009)
			5 and 15.25 t ha^{-1}	Yield reduction by 37% and 71% respectively due to nutritional deficiencies associated with increased pH.	

(*Continued*)

Table 4. Summary of the different effects of biochar application on the physiological activity of variables in plants.

Plant species	Physiological variable	Type of BC	Application rate	Responses found	Reference
Rice	Dry matter	Eucalyptus chips	45 g kg^{-1}	Higher accumulation of foliar and total dry matter.	Noguera *et al*., (2010)
	Yield		45 g kg^{-1}	Significant increase in the weight of grains.	Noguera *et al*., (2010)
	C/N		45 g kg^{-1}	Reduction in the C/N ratio in the plant.	Noguera *et al*., (2010)
	Flow of sap in the xylem and SPAD chlorophylls	Rose and teak waste	0 - 16 t ha^{-1}	Increased sap flow in the xylem of rice plants. There is a significant reduction in SPAD chlorophyll values related to the decrease in N availability.	Asai *et al.,* (2009)
Wheat	Germination	Paper mill waste	10 t ha^{-1}	Increased germination.	Van Zwieten *et al*., (2010)
	Root-aerial part ratio	Peanut hulls; Fir bark	0, 12.5, 25 and 50 t ha^{-1}	The shoot – root ratio of wheat decreased in all biochar application rates.	Collins (2008)
	Yield	Commercial BC of oak, beech, and hazelnut forests	30 and 60 t ha^{-1}	Yield increased 32.1% and 23.6% respectively in the first year.	Vacari *et al.,* (2011)
	Absorption of water and nutrients, dry matter and yield	Olive pruning waste	40 Mg ha^{-1}	Reduced resistance to penetration, greater water and nutrients uptake, increased proliferation of fine roots, accumulation of dry matter and yield.	Olmo *et al*., (2014)
Abelmoschus esculentus (L.) Moenc	Specific leaf area, stomatal conductance, photosynthesis, water use efficiency	*Lantana camara* stems	0, 10 and 30 g kg^{-1}	BC promotes infiltration rate and improves water retention in the soil, increasing photosynthesis, water use efficiency and yield.	Batool *et al.,* (2015)
Corn	Germination	Corn and wheat waste	-	Increased coleoptile length.	Sun *et al*., (2017)
	Adsorption of nutrients	Poultry manure	8 t ha^{-1}	Increased soil availability of N, P, K, Ca and Mg. Greater absorption of nutrients by the plant.	Ch'ng *et al*., (2015)
	Dry matter	Poultry manure	8 t ha^{-1}	Increased dry matter accumulation in leaves, stems and roots.	Ch'ng *et al*., (2015)
	Yield	Commercial biochar of wood (sources and conditions not available)	8 - 20 t ha^{-1}	Improved corn grain yield.	Major *et al*., (2010)
Kiwi	Adsorption of nutrients	Peach and vine pruning waste	20 g kg^{-1}	Increased exchangeable Fe in the soil, greater absorption of nutrients by the plants.	Sorrenti *et al*., (2016)
Banana	Nutrient uptake	Wood	11.25 t ha^{-1}	Increases potassium absorption.	Steiner (2007)
Apple	Adsorption of nutrients	Peach and vine pruning waste	10 ton ha^{-1}	Reduced NO_3^- washing in 75% in the second year compared to the control.	Ventura *et al*., (2013)

have reported the benefits of BC used in the restoration of ecosystems with different intensities of deterioration, especially in the production of forage from alfalfa plants, where a higher forage yield and improvement in soil quality have been achieved (Fiallos-Ortega *et al*., 2015). This shows that the use of BC in the restoration of degraded soils in Colombia can be an exciting alternative.

CONCLUSIONS

In general terms, BC is a valuable tool that can be used in soils as a mitigation strategy for environmental pollution. It also serves as a carbon sink substance, improves the physical and chemical characteristics of the soil and has been proven to have high potential in agricultural use, increasing the yield and quality of cultivated plants. Additionally, it is an exciting alternative in the management of solid residues of vegetable (cherries obtained from coffee plants, rice husks, or pruning residues) or animal (poultry, cattle, and pig manure) origin.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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