Essay

Potential benefits of biochar in agricultural crop productivity

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Abstract

Biochar is a carbon-rich solid porous material obtained by the thermochemical conversion of biomass and organic materials of agricultural or forestry origin in a limited or oxygen-devoid environment. In this review paper, two objectives were set: 1) to provide an overview of biochar production techniques; and 2) conduct a review of the effect of biochar on crop growth and productivity. Studies on biochar in agriculture conducted in Mexico, production costs, as well as research trends and prospects are included. The search for scientific articles on biochar in agricultural crop productivity published in the period from January 2011 to December 2020 was carried out through the Web of Science, Dialnet, Redalyc and Scielo databases. This review shows that in the last 10 years there is an increase in research on the use of biochar in agriculture, because most research has reported positive effects on crop growth and yield, it is also necessary to increase research on biochar made with plant biomass and locally available organic materials. Most studies of biochar in agriculture have been conducted in cereals and some vegetables, so it is necessary to carry out investigations of the effect of biochar on ornamental plants, as well as on aromatic herbs and medicinal plants.

Keywords: biochar, crop yield, hydrothermal carbonization, pyrolysis, soil improver.

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Biochar is a carbon-rich solid material obtained by the thermochemical conversion of organic materials in a limited or oxygen-devoid environment (Zheng *et al*., 2016; Guo, 2020), which has physical and chemical properties suitable for long-term carbon storage in a natural environment and potentially, improvement of soil fertility (Ibarrola *et al*., 2013).

Biochar is the result of the carbonization of raw materials such as: crop residues, tree biomass, paper waste, rice husk, among others (Escalante-Rebolledo *et al*., 2016; Adeyemi and Idowu, 2017). Biochar can be obtained from almost any organic material, but it is particularly appropriate that of plant origin, especially that consisting of lignocellulosic materials, which, after water, are the predominant constituents of terrestrial vegetation (Quesada-Kimzey, 2012). The main distinction between biochar and other carbon-rich products (such as carbon and activated carbon) is that the former is applied to soil for the purpose of carbon sequestration (Steiner, 2016).

That is, plants in a natural environment decompose and carbon is released into the environment, which increases the concentration of CO_2; however, CO_2 can be reduced by converting plant biomass into biochar, since carbon is incorporated into it.

Biochar production has four main objectives (Ibarrola *et al*., 2013): 1) soil improvement; 2) use of waste; 3) climate change mitigation; and 4) energy production. The improvement occurs by adding the biochar to the soil, which favors the retention of water and nutrients, also, increases microbial activity, the second objective is achieved, by reducing waste from agriculture and other industries and giving them added value, the third objective of the biochar is to mitigate climate change by sequestration carbon from biomass and reduction of greenhouse gases (GHG), since this technology reduces the release of GHGs by storing them in the form of stable carbon in the soil and finally, renewable energy can be produced.

In recent years there has been an increase in research on the production and exploitation of biochar (Jirka and Tomlinson, 2014; Verheijen *et al*., 2014) so this review concentrates information on the potential benefits of biochar in agriculture. Two objectives were set: 1) to provide a review of biochar production techniques; and 2) conduct a review of the effect of biochar on crop growth and productivity. Research on biochar in agriculture conducted in Mexico, production costs, as well as research trends and prospects are included.

Criteria used in the search for information

The search for articles in English was carried out in the databases of Web of Science, Dialnet, Redalyc and Scielo for the articles in Spanish, published from January 2011 to December 2020. The following words in English were considered biochar, importance of biochar, biochar and soil, biochar and yield of crops, biochar in agriculture, biochar in horticulture and in Spanish: biocarbón, importancia del biocarbón, biocarbón y suelo, biocarbón y rendimiento de cultivo, biocarbón en agricultura, biocarbón en la horticultura.

From this search, 34 577 articles were obtained in both English and Spanish, then articles that focused on topics of thermodynamics, structural chemical compounds of biochar and soil microbiology were discarded, which reduced the number of articles to 5 461. Finally, 46 articles focused on the application of biochar in order to increase the productivity of agricultural crops were selected.

Techniques for producing biochar

There are several thermochemical technologies to produce biochar: pyrolysis (slow, fast and ultrafast), gasification and hydrothermal carbonization (HTC) (Zheng *et al*., 2016; Adeyemi and Idowu, 2017). According to Quesada-Kimsey (2012), pyrolysis and gasification techniques require that the material (biomass or waste) be dried prior to the carbonization process; however, this stage can be omitted with the hydrothermal carbonization technique (Figure 1), which represents an advantage since the process is carried out in an aqueous medium and the humidity of the biomass does not affect the elaboration of the biochar, so this technique allows the use of waste with high water content or residues from freshly cut crops.

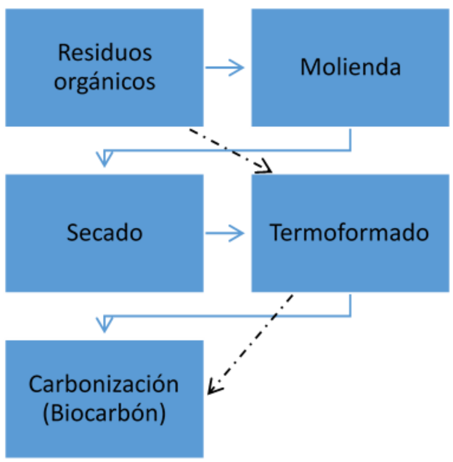

Figure 1. Diagram of the dry carbonization process (pyrolysis). Arrows with dashed lines indicate the process of hydrothermal carbonization (HTC). Adapted from Quesada-Kimsey (2012).

With the thermochemical techniques mentioned above, three main products are produced: solid (biochar), liquid (bio-oil) and synthesis gas (syngas) (Table 1). In general, slow pyrolysis produces more syngas and biochar, fast pyrolysis tends to produce more oils and liquids, while gasification systems produce large amounts of syngas and little biochar, in contrast hydrothermal carbonization produces more biochar and little syngas.

Table 1. Final product yield from different thermochemical technologies to produce biochar (Ibarrola *et al*., 2013; Kambo and Dutta, 2015).

Technique	Temperature and duration	Solid (biochar, %)	Liquid (bio-oil, %)	Gas (syngas, %)
Slow pyrolysis	~500 °C, days	35	30	35
Fast pyrolysis	~500 °C, seconds	12	75	13
HTC	180-260, hours	70	25	5
Gasification	>800°C, hours	10	5	85

HTC: hydrothermal carbonization.

Recent studies have proposed the use of biomass or agro-industrial waste (animal manure, wheat straw, among others) as raw materials for the immobilization, extraction or recovery of nutrients such as N, P and K through the hydrothermal carbonization process (HTC) (Ekpo *et al.*, 2016; Melo *et al*., 2016; Adeyemi and Idowu, 2017). The HTC technique is a process that employs aqueous media and moderate temperatures (150-350 °C), which produces a solid material called hydrochar (Kruse *et al*., 2013; Arteaga-Pérez *et al*., 2015).

Biochar in crop growth and productivity

The interaction between physical, chemical and biological properties determines soil fertility, which can be positively modified with the addition of biochar and can favor crop growth and yield. Silva *et al*. (2017) evaluated three biochar at doses of 0.0, 2.5, 5, 7.5 and 10% v/v in bean cultivation (*Phaseolus vulgaris*) and found that, regardless of the biochar used, these promoted further development of the bean plant with an increase in the dry mass of root and stem, the number of pods, the number and dry mass of grains, compared to the control treatment. In general, the doses of 10, 7 and 7% of biochar from rice husk, sawdust and silage sorghum, respectively, generated the largest number of pods, number of grains and consequently, greater production of dry matter in bean grain.

Xu *et al*. (2015) tested a biochar from peanut shell in ferrosol-like soil in peanut cultivation and reported that the application of the biochar at doses of 9.2 t ha^{-1} improved the commercial quality of the grain (jumbo quality). Pérez-Salas *et al*. (2013) applied melina wood biochar (*Gmelina arborea*) to bananas (*Musa* AAA) and reported a 104% increase in plant height compared to the control, at 101 days after transplantation.

Alburquerque-Méndez *et al*. (2013) reported that when applying biochar of pine chip and olive pruning residues, they did not observe statistical differences in sunflower growth, which could be due to the very nature of this type of biochar, being rich in carbon but relatively poor in nutrients; they also mention that biochar can improve the physical characteristics of the soil and that it has no negative effects on sunflower growth, so it can be used as a carbon reservoir in agricultural and forest soils. In contrast, negative effects of biochar applied to soil have been reported; that is, unfavorable changes in the physical, chemical and biological properties of the soil, which can cause reduction in growth and yield in some crops.

This may be because most research is done in the short term (Mukherjee and Lal, 2014), so it would be necessary to do research in the medium and long term, as well as in several growing cycles (Carter *et al*., 2013). In this sense, Guo (2020) indicates that to maximize the benefits of the application of biochar as a soil improver and that it eventually favors the growth and yield of agricultural crops, it is important to consider three aspects: the source or organic material with which the biochar was produced, the dose of application and the type of soil. Table 2 shows doses of biochar application and its agronomic effect on several crops.

Table 2 . Biochar application dose and agronomic benefits in various agricultural crops.

Raw material	Technique	Temperature (°C)	Biochar application dose	crop	Agronomic benefit (increase over control treatment without application of biochar)	Reference
Corn straw	Pyrolysis	450	5%	Soybean (*Glycine max* L.)	4.8% in plant height and 8% in weight of dry biomass	Liu *et al*. (2020)
Vine shoots	Pyrolysis	400	3%	Sorghum (*Sorghum bicolor* L.)	52% in dry weight of the root	Videgain-Marco *et al*. (2020)
Grape pomace	Pyrolysis	300	2%	Maize (*Zea mays* L.)	255% in weight of dry matter	Manolikaki and Diamadapoulus (2019)
Various species	Pyrolysis	200-450	16 t ha^{-1}	Soybean (*Glycine max* L.)	25.5% in weight of dry matter	Petter *et al*. (2019)
Wheat straw	Pyrolysis	300	7%	Sorghum (*Sorghum bicolor* L.)	344% in weight of dry matter	Iftikhar *et al*. (2018)
Wheat straw	Pyrolysis	350-500	50 t ha^{-1}	Tomato (*Solanum lycopersicum* Mill.)	96% and 106.5% in yield (t ha^{-1}) in first and second cycle, respectively	Agbna *et al*. (2017)
Wood chips	Gasification	670	20%	Gerbera (*Gerbera jasmesonii*)	16.67% in weight of fresh matter	Block *et al*. (2017)
Corn straw	Pyrolysis	700	20 t ha^{-1} (0.7%)	Soybean (*Glycine max* L.)	16.6% in weight of dry matter.	Scheifele *et al*. (2017)
Corn straw	HTC	200	20 t ha^{-1} (0.7%)	Soybean (*Glycine max* L.)	13.2% in weight of dry matter	

Raw material	Technique	Temperature (°C)	Biochar application dose	crop	Agronomic benefit (increase over control treatment without application of biochar)	Reference
Sewage sludge	Pyrolysis	450-650	40 t ha^{-1}	Eucalyptus (*Eucalyptus grandis* L.)	466% in weight of dry matter	Silva *et al*. (2017)
Pine sawdust	Pyrolysis	700	5% (105 t ha^{-1})	Sorghum (*Sorghum bicolor* L.)	26% in plant height and 32% in yield (dry matter per plant)	Laghari *et al*. (2016)
Pine sawdust	Pyrolysis	400	1% (22 t ha^{-1})	Sorghum (*Sorghum bicolor* L.)	24% in plant height and 22% in yield (dry matter per pot)	Laghari *et al*. (2015)
Wheat straw	Pyrolysis	525	3% (90 t ha^{-1})	Barley (*Hordeum vulgare* L.)	8.3% in weight of dry matter	Kloss *et al*. (2014)
Vineyard pruning	Pyrolysis	400	3% (90 t ha^{-1})	Red clover (*Trifolium pratense* L.)	18% in weight of dry matter	
Olive pruning	Pyrolysis	449	1%	Sunflower (*Helianthus annuus* L.)	31% in weight of dry matter	Alburquerque *et al*. (2014)
Fir wood waste	HTC	180	4%	Barley (*Hordeum vulgere*)	15.4% in yield (weight of dry matter per pot) in the second cycle	Bargmann *et al*. (2014a)
Beet flakes	HTC	190	4%	Barley (*Hordeum vulgere*)	46.3% in weight of dry matter	Bargmann *et al*. (2014b)
Beet flakes	HTC	190	4%	Bean (*Phaseolus vulgaris*)	147% in weight of dry matter	
Beet flakes	HTC	190	2%	Leek (*Allium ampeloprasum*)	61.3% in weight of dry matter	

Raw material	Technique	Temperature (°C)	Biochar application dose	crop	Agronomic benefit (increase over control treatment without application of biochar)	Reference
Rice husk	Gasification	900-1100	50 g kg^{-1}	Lettuce (*Lactuca sativa*)	903% in weight of fresh matter	Carter *et al*. (2013)
Quail residues	Pyrolysis	500	98.4 g per pot	Soybean (*Glycine max* L.)	229.4% in weight of dry matter	Suppadit *et al*. (2012)
Cow dung	Pyrolysis	500	15 t ha^{-1}	Maize (*Zea mays* L.)	150% in grain yield and 64.6% in plant height	Uzoma *et al*. (2011)

HTC: hydrothermal carbonization.

As can be seen in Table 2, most research has been carried out on cereal and some vegetable crops, however, the effect of biochar on the growth of ornamental, aromatic and medicinal plants needs to be investigated, especially because of the economic and social importance of these horticultural crops. Recently biochar in addition to being used as a soil improver, it is also used in the production of container and greenhouse crops.

In this sense, biochar is used in mixture with commercial substrates such as peat (*peat moss*), perlite, coconut fiber, vermiculite, among others, to improve its physical and chemical properties (Blok *et al*., 2017; Huang and Gu, 2019). For example, Guo *et al*. (2018) propose that biochar can be used up to 80% mixed with the substrate Shunshine® Mix #1 in greenhouse poinsettia production, without affecting the visual quality of the plant or the growth rate.

These same authors concluded that poinsettia plants grown with 20% biochar showed higher growth (8.3%) than the control treatment without biochar. On the other hand, Blok *et al*. (2017) reported that wood-based biochar, and residues of tomato and sweet pepper can replace commercial peat by 20% and 10% on a volume-based basis without affecting the growth of chrysanthemum and gerbera grown in pots, respectively. These results raise the possibility that biochar can be used in mixtures of organic substrates in order to partially replace the use of non-renewable commercial peat (*peat moss*), which would reduce production costs and a more sustainable agronomic management.

Biochar research in Mexico

According to the articles published in indexed journals in the last 10 years, in Mexico research on biochar for agricultural purposes is scarce. The following is a brief description of the research that has been carried out: Orozco-Gutiérrez and Lira-Fuentes (2020) evaluated five temperatures (350, 450, 550, 650 and 750 °C) in the elaboration of bamboo biochar produced by slow pyrolysis and obtained that the best temperature for the production of bamboo biochar was at 550 °C with conversion yield of 27%, in addition, with this treatment the highest values in the physicochemical properties appeared with 11.2% of volatile matter, 8.1% of ashes and 72% of carbon. Velázquez-Maldonado *et al*. (2019) reported that for the production of rice husk biochar, the addition of maleic and citric acids at 10% as catalysts, generate the highest conversion yield (66%).

The same authors indicated that the three macronutrients with the highest concentration were Ca, N and K, while for micronutrients the ones with the highest concentration were Fe and Mn, as well as the element Na. Velázquez-Machuca *et al*. (2019) evaluated the potential use of biochar from sewage sludge obtained from a wastewater treatment plant in Morelia, Michoacán, as an agricultural soil improver by considering as indicators the physical and chemical properties of the material, as well as the nutrient content and its low concentration of toxic metals. This research concludes that the biochar elaborated can be used as an improver of agricultural soils due to its high content of nutrients and has low environmental risk due to its low content of toxic metals.

For their part, Medina and Medina (2018) built and evaluated the performance under field conditions of an autothermal and mobile biochar-pyrolysis prototype, with a useful volume of 1.7 m^3 of crushed biomass. In the equipment mentioned above, which had the capacity to process between 300 and 400 kg of biomass per day, they produced biochar from avocado pruning residues, with a yield of 16% in biochar.

On the other hand, Concilco-Alberto *et al*. (2018), when evaluating a commercial bamboo biochar in the growth and yield of forage oats, reported that the best treatment was 25 t ha^{-1} of biochar with conventional NPK fertilization (120-60-00), as it increases plant height by 34% and fresh matter by 103% compared to the control treatment. Escalante-Rebolledo *et al*. (2016) conducted a review of the nature, history, manufacture and use of biochar in soil. As can be seen, in Mexico there is a growing interest in the use of biochar, but more research is needed to strengthen the use of biochar in agricultural production systems.

Biochar production costs

Detailed information on biochar production costs is limited, however, there are some investigations where technological and economic estimates have been made. In Mexico, Medina and Medina (2018) built a mobile slow pyrolysis equipment made of stainless steel for the production of biochar from avocado waste, with an estimated cost of 32 500 dollars with a capacity of 1.7 m^3 of useful volume, equivalent to between 300 to 400 kg of wood, which depends on the size and humidity of the chip.

The useful life of the equipment is considered 7 years, with intensive use of 19 h daily during the 365 days of the year and 23 years with moderate use of 8 h daily during the same period. However, the return on investment will be a function of economic analysis.

These authors mention that the equipment manufactured presents competitive costs with respect to equipment produced in other countries, for example, equipment made North America with a transformation capacity of 200 kg of biomass per load, costs 350 000 dollars plus an additional cost of 25 000 dollars for training.

On the other hand, Ibarrola *et al*. (2013) report that the sugar industry could invest in Adam Retort type kilns with production capacity of 100 to 400 t per year and estimated production costs between 10 and 100 dollars per ton of biochar; they also attributed this cost variation to the production capacity of the mills, of the technology available to separate and collect the biochar. The same authors mention that in a study conducted in the United Kingdom, it was concluded that the breakeven point for the commercialization of biochar fluctuates from 205 to 540 dollars per ton, delivered and deposited in the field, although production costs can be reduced between 28 to 416 dollars per ton of biochar, by using traditional furnaces and increasing the production of biochar.

Jirka and Tomlinson (2014) mention that biochar and biochar mixtures are marketed in several countries in North America, Europe, Asia, Oceania and Africa with an average price of 2.65 dollars per kg. Most companies engaged in biochar production make their sales from their website and nurseries, which means that it is sold to high-end niche markets for end use in gardening, nurseries, landscaping and other small-scale products.

The same authors point out that it is difficult to predict the profits of biochar because the main barriers to the expansion of the industry are ignorance on the consumer side, technological limitations and access to financing. In this regard, Filiberto and Gaunt (2013) indicate that it is necessary to carry out evaluations of the economic viability of the use of biochar, since so far there are only general estimates due to the uncertainty surrounding the indirect impacts of the application of biochar to the soil, which prevent an accurate assessment of production costs. As can be seen, there is no general consensus on the costs of producing biochar, that is, more research is needed with this approach based on local socio-economic conditions.

Research trends and perspectives

From the reviewed literature, the following research trends and perspectives were identified.

From a process point of view

Determine the optimal conditions for the production of biochar by evaluating thermochemical techniques, temperature, heating time, reactor pressure and addition of catalysts. These factors influence the physical and chemical properties of biochar.

Characterization of physical and chemical properties of biochar made from locally available plant biomass to promote sustainable management. Enrichment of biochar with specific minerals and their subsequent incorporation into agricultural soils. Evaluation of biochar as an alternative to remedy soils contaminated with heavy metals and herbicides.

From the point of view of agricultural use

To evaluate doses of biochar in different types of soils in the medium and long term, its effect on the physical and chemical properties of soils, as well as on crop growth and yield. To assess the effect of the application of biochar to the soil in combination with chemical fertilizers, since its positive effect on plant growth has been observed; however, studies are needed to clarify the mechanisms of synergism.

To assess the effect of biochar on growth and yield in ornamental plants, as well as in aromatic herbs and medicinal plants, because most studies of the effect of biochar have been conducted in cereals and some vegetables. To investigate the effect of biochar on microbial activity and its interaction with plants, as well as the synergistic effect with the use of mycorrhizas. To investigate the incorporation of biochar in the soil to mitigate the adverse effect of the presence of polluting elements or substances.

To investigate mixtures of biochar with non-renewable organic substrates, such as commercial peat, in order to reduce their use in protected agriculture. Biochar can be an alternative to replace or decrease the use of non-renewable organic substrates, both in the production of seedlings and in the production of high-value horticultural crops.

Conclusions

This review shows that in the last 10 years there has been an increase in research on the use of biochar in agriculture, because most studies have reported positive effects on the growth and yield of agricultural crops.

There is a need to increase research into biochar made from locally available plant biomass and organic materials. Because most studies of biochar in agriculture have been conducted on cereals and some vegetables, research into the effect of biochar on ornamental plants, as well as on aromatic herbs and medicinal plants, is necessary.

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