


REVIEW

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Role of biochar in promoting circular economy in the agriculture sector. Part 2: A review of the biochar roles in growing media, composting and as soil amendment

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Abstract

Biochar is utilized in modern society for multiple agricultural and environmental purposes in the framework of circular economy. The aims of this study were to review the leading edge of knowledge of studies where biochar was used in the agriculture sector, as an input for growing media, composting and to improve soil physical and chemical properties along with crop yield. Usage of biochar is promising as substitute for peat and in the composting as it reduces N losses, accelerates the process and improves the quality of final composts. The right selection of feedstock and optimization of pyrolysis conditions are key factors to tailor biochar thereby improving soil properties and increasing crop yield. Potential benefits and flaws for the usage of biochar technology in the agricultural domain are broadly reviewed and thoroughly discussed.

Keywords: Peat, N losses, Cation exchange capacity, Microbial activity, Soil properties, Soil fertility, Crop yield

Introduction

The widespread interest in the utilization of biochar in agriculture has been increasing in recent years due to the beneficial properties of this material for the sustainability of agro-ecosystems. Besides the acknowledged importance to mitigate climate change by promoting C sequestration and decreasing greenhouse gases (GHG) emissions, biochar has been reported to improve soil fertility status and increase crop productivity. In addition, biochar can be a partial substitute for peat, a non-renewable resource, and improve the quality of compost, while limiting the environmental downsides of the process [1]. This is important as the high increasing rate in the global population raises the challenge for agricultural sector to

provide sufficient food without compromising the environment [2].

Biochar may have essential implications in developing a circular economy in agriculture since it can be integrated into conventional fertilization practices, especially in organically managed food production systems. Firstly, biochar could be a sustainable strategy for the management of pruning wastes in farms: for example, vast amounts of pruning from fruit orchards are annually generated causing an environmental problem if they are not adequately disposed [3]. Pyrolysis is a waste management option, which allows the conversion of the pruning wastes into biochar, a valuable soil amendment. Secondly, the obtained biochar could be integrated into traditional fertilization strategies based on the use of composts, manures and anaerobic digestates to reduce the environmental impact of the process, and, more interestingly, increase the agronomical value of the organic amendments [4].

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Several EU-financed research projects (<https://www.fertiplus.eu>; <https://www.refertill.eu>; <https://www.biochar-interreg4b.eu>) have highlighted the potential and the synergies of combining biochar and composting. Sánchez-Monedero et al. [4] reported the results of the EU FERTIPLUS project using biochar, either alone or in combination with composting, in several field-scale experiments performed under different agro-climatic conditions across the European Union. They observed agronomical benefits of biochar application on soil fertility, crop nutritional status and productivity in organically managed olive orchards in Southern Spain, conventionally managed vineyards in Northern Italy, arable crop rotations in Belgium and an intensive greenhouse tomato cultivation in South Spain. In their study, the combination of biochar and compost significantly improved soil conditions and crop performance compared to traditional agricultural practices or the single use of biochar [4].

An example of successful integration of biochar into conventional agricultural practices in a commercial vineyard was reported by Rosas et al. [5]. These authors reported on the use of vineyard residues as feedstock for the production of biochar by means of a mobile and self-assembled pyrolysis reactor. This strategy allowed the recycling of vineyard pruning to be carried out locally and the incorporation of biochar into the traditional manure composting operations of farm, consequently improving the N status of the crop and reducing the C footprint of the vineyard [6].

Several reviews [7, 8] have been published addressing biochar implications in promoting a circular economy in the agriculture sector, but most of them focused only on specific aspects of biochar utilization (i.e. crop yield, GHG emissions, soil decontamination), while there are only a few reports regarding biochar multiple-use in the agricultural domain [9, 10].

In this review, we critically examine the multiple-use of biochars for agricultural purposes in the framework of circular economy. Cutting edge in knowledge regarding the use of biochar as an input for growing media, composting and soil amendment was assessed. We hypothesize that the optimization of pyrolysis conditions and choosing the right biomass might help to tailor biochars to potentialize benefits and minimize constraints of its use as growth media, composting and to improve soil conditions for enhancing crop growth. Usage of biochar is supposed to decrease N losses and nutrient leaching, accelerate composting and enhance the agronomic value of final composts. We also suggest practices and the agronomic basis to improve fertility status and crop yield in biochar-treated soils without negatively affect storage of C in soil.

Use of biochar in growing media

Growing media can be defined as any materials, other than soils *in situ*, in which plants are produced [11]. They can be composed of a unique material or a mixture of different inputs, and their use as container for horticultural plant production has increased considerably in the last decades [12]. Peat (white and black) is the first organic material to be standardized as a growing media, and it is still by far the most essential substrate, and often the sole ingredient for growing media formulation, representing a performant, uniform and cost-effective substrate for horticultural plant production [13–15]. However, peat is not considered to be a renewable resource because of its very long regeneration time, and the peat deposits (i.e. peatlands) represent fragile ecosystems providing several ecosystem services both locally (e.g. biodiversity and water regulation) and globally (i.e. C sinks) [13]. Indeed, peatlands account worldwide for 27% of the total soil organic C stock [16], but once peat is extracted and drained, it quickly decomposes and turns into a source of GHG [13, 15, 17]. Consequently, peat extraction has been discouraged, particularly in Europe, resulting in high demand and increasing prices, making the horticultural industry to look for new materials to replace peat as growing media [15, 18].

Various materials have been evaluated for use alone or blended with peat, and several renewable and economical alternatives have been adopted by the horticultural industry, such as bark, coir pith, green compost, pine bark, rice hulls, wood fibres, perlite, mineral wool, etc. [15, 19, 20]. However, no material has been proven so far to be similar in its properties as peat in terms of both performance (e.g. plant health and growth, uniformity, water permeability, stability) and market needs (e.g. cost-effectiveness, availability, ease of preparation, handling and disposal) [13, 15, 21]. Furthermore, from an environmental point of view these substitutes may have some shortcomings due to their production requiring high amounts of energy (perlite), due to gas emission (green compost), and/or in relation to their transport or land occupation (coir pith and coconut harvesting) [22].

The most valuable characteristics of peat are (i) high water and air holding capacity; (ii) low bulk density, and (iii) high cation exchange capacity (CEC) [23–26], which are all features in common with biochar. Therefore, biochar could be a promising alternative to totally or partially replace peat. Nevertheless, the usage of biochar as growing media has been far less investigated compared to its use as a soil amendment. Only recently an increasing number of studies regarding the usage of biochar as a successful growing media have been published [15, 27]. As shown in Table 1, application of biochar on a peat-based substrate can increase the total porosity (i.e. both

Table 1 The properties of peat and wood biochar as growing media. Adapted and modified from [24]

Properties	Peat	Biochar
Homogeneous quality	Available	Available
Nutrient content/adjustability	Low/adjustable	Low/adjustable
C/N ratio	High	Very high
pH	Low	Mostly medium to high
Permeability ^a	Good	Good
Water-holding capacity ^a	Medium	High
Balanced water and air capacity ^a	Good	Good
Weeds and pathogens	Mainly free	Free
Structural stability and longevity	Medium	Exceptionally high
Reusability	Low, need pre-treatments ^b	To be tested, potentially high and requiring pre-treatments
Bulk density	Low	Low
Texture	Uniform	Uniform
Rewettability	Poor	Good
Disease suppressive properties	Neutral	Some evidence ^c
Availability (technical)	High	Currently low
Price	Low	Currently very high
GHG emissions	High	Depending on feedstock and production, but carbon neutral
Environmental damages	High	Depending on feedstock and production

^a Depending on particle size distribution (or level of decomposition in peat)

^b Alexander et al. [28]

^c At low doses of 1 to 5% [69]

macro- and micro-pores) of potting media, thus increasing the air and water-holding capacities of the medium [15, 19, 25, 27, 28]. Also, biochar would promote microbial biomass and biological activity, especially mycorrhiza community [15, 19], although very few studies have investigated the interactions between biochar and microbes in growth media to find out an optimal application rate and suitable biochar characteristics to increase plant growth [27]. Besides improving nutrient availability by increasing cation exchange capacity (CEC), biochar itself can represent a source of nutrients (e.g. N-NO₃⁻, K, P, Fe, Mn, Zn), thus potentially reducing the usage of fertilizers [15, 19, 29]. However, biochar has low N content and a high dose of biochar in growing media may increase the C to N ratio, which accelerates the immobilization of N by microorganisms [26, 30].

Some studies have even reported that biochar could be a more effective growing media than peat. For example, biochar has better re-wettability than peat, even though fresh biochar can show a quite hydrophobic nature [15, 24]. Also, biochar is highly stable; therefore, the substrate chemical and physical properties would not change over time during plant growth [15, 19]. Moreover, biochar is a versatile material: its physical and chemical properties can be modified relatively easily by selecting source materials as well as pyrolysis conditions (i.e. heating rate, pyrolysis temperature and residence time) [21]. For

instance, optimizing the water and air exchange of the medium to support plant growth modifying the particle size and pore distribution classes of biochar [26], or producing biochar with higher porosity and surface area and a lower water repellence by increasing the temperature of production and slowing the heating rate [25, 26].

The major concerns on the usage of biochar as substitute for peat are often its high salinity and the alkalinity in comparison to peat [15, 19, 21, 25–27, 31]. In order to decrease the salt content and pH, prewashing and addition of natural acids to biochar may be required, respectively [15, 25]. Biochar could also introduce potential toxic substances into the growing media such as heavy metals, dioxins and polycyclic aromatic hydrocarbons (PAHs) [27], therefore selecting appropriate feedstock and the production conditions (e.g. slow pyrolysis and high temperatures for reducing the PAHs) should be considered [32].

The effects of application of biochar into soil-less media on plant growth is highly variable since the characteristics of biochar are highly dependent on the feedstock and production system. The application rates of biochar and the original composition of the growing media also can affect plant growth. Even plant's development stage can be a further source of variability. For instance, Fornes and Belda [33] tested different biochars at different proportions of substitution to a commercial growing medium

and reported that seedlings under nursery conditions were in general more sensitive to high biochar addition (50 and 75%) compared to plants in the vegetative growing stage.

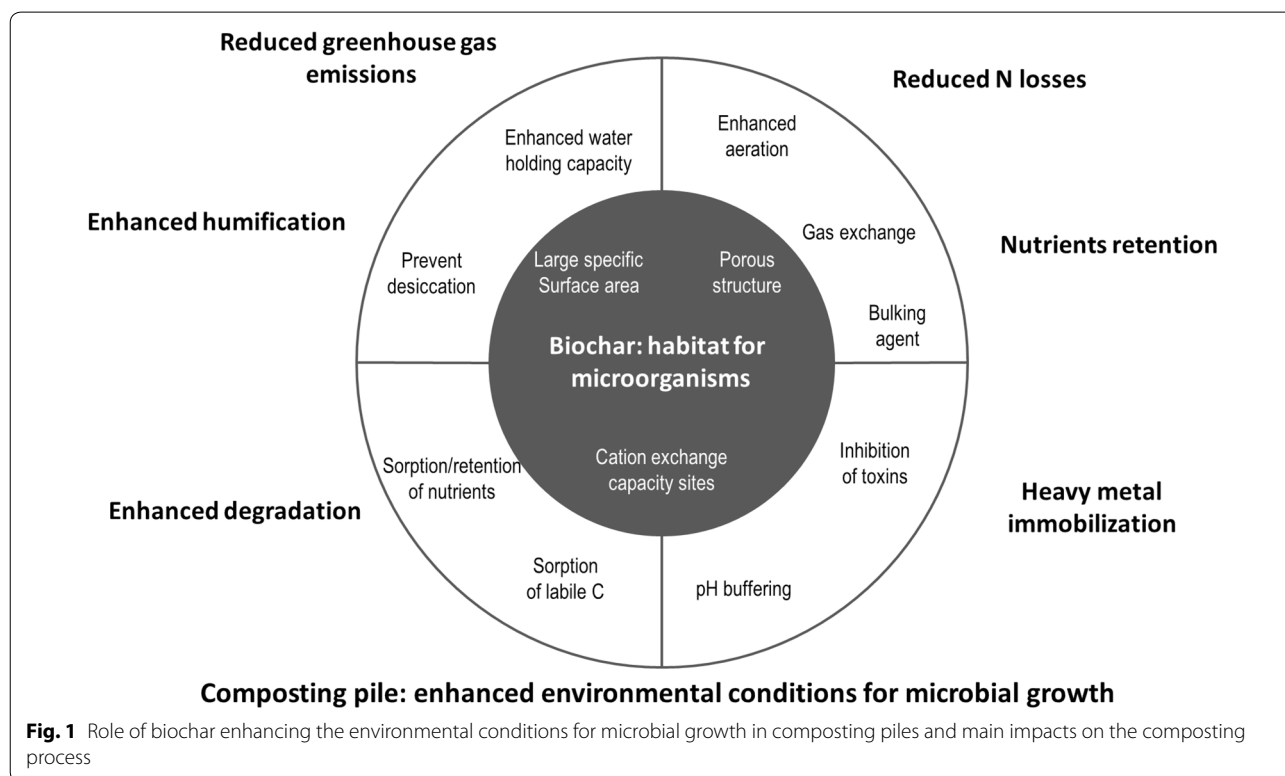
Recently Huang and Gu [27] reviewed 32 studies dealing with the addition of different biochars, made from various feedstock (e.g. wood, green-, olive mill-, pruning- or forest-waste, rice husk, sewage sludge, wheat straw and sugarcane bagasse) at different pyrolysis temperatures (from 200 up to 1200 °C) on various growing media (e.g. peat, bark, perlite, coir, vermiculite, etc.), singly or their mixtures. Most of those studies investigated the impacts on herbaceous plant species growth, while the woody plants were studied only six times. Overall, the studies reported that application rates of biochar into the substrates under 25% by volume generally resulted in similar or higher plant growth compared to the referential commercial substrate, without taking into account other factors like irrigation or fertilization [27]. On the contrary, when the application rates of biochar into the substrates increased by over 50% by volume, only 36% of the studies showed some improvement in terms of plant growth [27].

Further specific testing with different application rate, biochar type and crop type are necessary in order to prove the effective use of biochar in growing media. These latter need to demonstrate to be at least equally

functional compared to other commercially available media. However, at this stage biochar could be just be proposed as a simple additive or a minor ingredient useful for improving the characteristics of the commercial growing media. This, however, would represent a first important step where biochar might become a standard product for the growing media market [13].

Biochar for composting

One of the most promising uses of biochar is as an additive to organic waste composting. The benefits of biochar as additive in the composting process have been well documented by several studies [34–36]. The addition of biochar into the composting pile provides a suitable habitat for the microorganisms and improves the environmental condition for microbial growth (e.g. moisture, aeration and nutrient availability) (Fig. 1). The use of biochar as an additive to composting has demonstrated to increase the abundance of bacterial communities colonizing the composting matrix either alone [37] or in combination with a bacterial consortium amendment [38]. These authors reported that the changes in compost microbiology have a crucial impact in the overall composting process by reducing the length of the process and also interacting on critical nutrient cycles that lead to an enhanced quality of the end product, in terms of organic matter humification and N conservation.



The increased microbial activity and improved aeration in the composting pile with biochar lead to accelerated degradation of organic matter [36]. Steiner et al. [34] reported that the usage of biochar as a bulking agent for poultry manure composting increased the emission of CO₂, especially with high doses of biochar application. On the other hand, Dias et al. [35] and Jindo et al. [39] reported an enhancement of humification of organic matter in the composting piles with addition of biochar. They suggested that the large surface area of biochar and hydrophobic interaction could entrap easily degradable compounds and contribute to the retention of several humification precursors preventing its degradation during the composting [40].

Another meaningful impact of biochar is the reduction of N losses during composting [41]. Typical operational conditions in composting, such as high temperatures and alkaline pH, are conducive to unavoidable N losses. Losing N content reduces the agronomical value of the mature composts and ammonia emissions are responsible for unpleasant odours of composting piles. Application of biochar decreases N losses during the composting process through (i) the retention of NH₄⁺ and NH₃ in cation exchange sites and micropores of biochar; (ii) the preservation of organic N in biochar, thus preventing mineralization, and (iii) the enhancement of nitrification caused by aeration conditions [36, 41]. In fact, the particle size and porosity of biochar reduce bulk density of composting pile avoiding the presence of anaerobic spots and facilitating gas exchange in the pile, thus causing a shift in the microbial communities decreasing the abundance of microorganisms responsible for the generation of CH₄ [42] and N₂O [43].

During the composting process biochar itself is known to undergo biological weathering causing the oxidation of its surface, increasing its CEC and the sorption of soluble C and humic-like fractions, therefore increasing its functionality [44]. The coating of biochar surface with these biologically active compounds and the enhanced retention of nutrients are thought to be behind the positive effect of composted biochar on soil fertility [45].

Notwithstanding the above-mentioned results, studies investigating the impact of co-composted biochar on plant growth reported contrasting observations. For example, Schulz et al. [46] and Agegnehu et al. [47] have found positive impact of the co-composted biochar on soil fertility mostly due to the supply of organic C and nutrients to the soil, but other researchers have not found any synergistic effect of the combination of biochar and compost on plant growth. Other authors [48, 49] have recently reviewed the impact of co-composted biochar in plant growth and concluded that the improved plant

growth was triggered by the addition of compost rather than the biochar.

Biochar effect on crop growth and productivity

Usage of biochar generally has positive effects on crop growth and productivity [50–54]. Several meta-analyses have shown that the mean crop yield increase with addition of biochar ranged between 10 and 13% [55–58]. In addition, Biederman and Harpole [59] analysed 371 independent studies and observed a significant increase in both aboveground productivity and crop yield with addition of biochar compared with control conditions.

Positive effects of biochar amendment on crop yield have been found mainly in acidic soils by increasing pH [58–60] and in coarse-textured soils by enhancing aggregation, nutrient retention and water-holding capacity [55, 57]. Significant increase in the crop yield was also observed by usage of low C/N ratio biochar from animal wastes [55, 58], attributed to the direct supply of nutrients by increasing rates of biochar added to soil.

The responses of crop productivity to biochar amendment varied with crop type. Significantly positive responses were observed with legumes, vegetables and grasses [57]. With the application of biochar, the globally most important commercial crops such as rice, wheat, maize and soybean significantly increased their crop productivities by approximately 16, 17, 19 and 22%, respectively [58].

The meta-analysis of Crane-Droesch et al. [56] highlighted the importance to study the effect of biochar on an appropriate time scale, as they found that the crop yields in soils amended with biochar significantly increased over time in several studies of their database. It is important to note that, however, open field experiments cover only one growing season [58] and hence the long-term effects of biochar on crop yield are not reported. Biochar has a substantially longer mean residence time in soils compared to conventional organic soil amendments [58] and therefore the positive effects of biochar would likely persist longer than that of traditional organic amendments [61, 62]. Therefore, there is a need of long-term experiments for a comprehensive assessment of the impact of biochar on soil properties and crop productivity.

Biochar effects on soil properties relevant for plant growth and productivity

Several studies reported that biochar amendment generally has a positive effect on many physical, chemical and biological properties related to the soil capacity to sustain crop growth and productivity [47, 50–53, 61]. Studies reported in Table 2 highlight the impact of biochar application on main soil properties affecting crop productivity.

Table 2 Impact of biochar application on main soil properties affecting crop productivity

Property class	Property	Effect	Mechanism/explanation	References
Positive impacts				
Physical	Structure	Increased aggregation	Enhanced cohesion by binding of biochar to organo-mineral complexes	[62]
	Porosity	Increase	Porosity of biochar, increased aggregation and reduction of soil packing	[64]
	Density	Decrease	Low density of biochar particles and interaction of biochar with soil increasing aggregation	[63]
	Water-holding capacity	Enhancement	Large specific surface area and porosity of biochar	[63]
	Infiltration rate	Increase	Increase in pore space and water flow by mixing of large biochar particles with smaller soil inorganic particles	[63]
	Colour	Dark colour	Alteration of thermal dynamics that favours rapid germination	[66]
Chemical	Soil organic matter	Increase	Input of highly recalcitrant C	[57]
	Element cycling	Regular functioning	Increase in the pool size and turnover of labile organic nutrients, surface adsorption and effects on soil biota	[65]
	Nutrient availability	Enhancement	Direct supply of nutrients surface adsorption of elements	[54, 67]
	Cation exchange capacity	Enhancement	Porous structure, large and mainly negative surface area of biochar. Adsorption of highly oxidized organic matter on biochar surfaces. Biotic and abiotic oxidation of biochar organic functional group	[65]
	pH	Increase	Biochar alkalinity, high pH buffer capacity, biochar functional groups	[64]
Biological	Soil habitat	Refuge of microorganisms against predators	Biochar pores fits microorganisms but not micro-arthropods predators	[64]
	Microorganism abundance	Increase in microbial biomass	Biochar improvements to soil habitat, bulk density, pH and elements and water cycling	[51]
	Microorganism diversity	Increased abundance of bacteria over fungi	Modification in the c/n ratio of readily mineralizable substrate	[62]
	Microorganism activity	Increase in CO ₂ and enzyme activity	Degradation of available substrates from biochar	[76]
	Plant growth	Increase in root biomass	Increase in the content of plant growth-promoting hormones	[68]
	Plant disease resistance	Induction of systemic resistance	Input of chemical elicitors	[69]
Negative impacts				
Chemical	Nutrients (P, N, Fe, B)	Immobilization	Excessive alkalinity	[58]
	N availability	Decrease	Microbial N immobilization	[67]
	Heavy metal and metalloids	Enhanced mobility	Excessive pH increase	[71]
Biological	Microbial and plant activity	Decline	Excessive content of toxic substances	[58]

Regarding physical properties, biochar increases the resistance of aggregates of soil as a result of enhanced cohesion via binding interaction between mineral particles and biochar [62]. Biochar was also found to reduce bulk density and increase porosity [63, 64], hydraulic conductivity and infiltration capacity [65]. Further, the dark colour of biochar alters soil thermal dynamics and facilitates rapid germination of seeds [66].

With respect to soil chemical properties, biochar affects soil nutrient availability both directly by supplying nutrients (i.e. N, P, K, Ca, Mg, S, Fe, Mn, Cu, Zn and Si) contained in the biochar, and indirectly by affecting soil properties that increase the availability of nutrients [54]. Biochar can indirectly affect nutrient availability in soils because of its high active surface and the occurrence of several and heterogeneous surface functional groups

affecting adsorption, surface complexation and ligand exchange reactions, which ultimately control the plant-available nutrients in soils [67].

Biochar increases soil CEC due to its porous structure and large and mainly negative surface area due to dominance of negatively charged surface functional groups and the adsorption of highly oxidized organic matter on biochar surfaces [65]. Soil CEC may further increase with time due to biotic and abiotic oxidation of organic functional groups as demonstrated by long-term soil application studies [61]. A soil with a higher CEC can adsorb cationic nutrients in more considerable amounts and for a longer time than a soil with a lower CEC, preventing nutrients from losses and leaching and thereby increasing the nutrient availability for plant uptake [65].

The physical and chemical properties of biochar create a benign environment for microorganisms favouring their growth and activity in soils. The physical properties of biochar favouring microorganisms include: (i) high porosity that acts as a refuge for microorganisms protecting them from micro-arthropod predators; (ii) greater surface area that increases opportunity for microbial colonization; (iii) micropores (< 2 nm) and mesopores (2–50 nm) that store water necessary for microbial metabolism, and (iv) black colour, which provides heat and thus accelerates microbial growth and enzyme activity [64]. The chemical properties of biochar favouring microorganisms include: (i) a higher surface charge, which binds microbial cells, chemical compounds and ions, and (ii) availability to microbes of nutrients and dissolved organic carbon that are desorbed or solubilized from the biochar [62].

Biochar increases microbial diversity in the soil. The abundance of bacteria increases over fungi due to the modification of the C/N ratio of readily metabolizable substrates in soils [62]. A positive effect of biochar on the abundance of arbuscular mycorrhizal fungi and biological nitrogen fixation in legumes following biochar application to soil was also recorded [54].

Concerning the biochar interaction with the plant-hormone relationships, biochar stimulates plant growth by increasing indole-3-acetic acid content and root biomass under high salinity condition [68]. Regarding plant protection against disease, plants amended with biochar decrease the disease severity by regulating the plant salicylic acid content [69, 70].

Potential limitations of biochar application on crop yields

Notwithstanding that most of the studies have shown positive effects of biochar application on crop yield, also negative impacts on plant productivity have been reported (Table 2) [61, 71]. A first cause of the negative

effect of biochar amendment is the excessive content of potential toxic substances of biochar. In fact, biochar may contain toxic compounds such as PAH, heavy metals and salts that can impair plant germination and growth as well as soil microorganisms activity [58]. The contents of toxic compounds in biochars depend on the type of feedstock and pyrolysis conditions and in most cases PAHs content was inversely correlated with pyrolysis time and temperature [32].

Secondly, negative alteration of soil properties might occur after biochar addition. This can be explained by the following reasons: (i) decreased N availability as a result of microbial N immobilization in soil amended with high C/N ratio biochars [67]; (ii) excessive pH increase of neutral and alkaline soils beyond the optimum for soil fertility (i.e. over-liming) leading to immobilization of key nutrients, such as P, Mn, Fe and B; (iii) increase in the mobility of toxic metals or metalloids [71]; (iv) negative priming effect in soil that interferes with the mineralization process, reducing the availability of nutrients. Feedstock type, temperature range and biochar rate of application are the key factors determining negative priming effect [72–74].

Coupling soil fertility status with carbon sequestration agent

Biochar application in soil has received positive attention for its beneficial contribution to agro-ecosystems from both the agronomical and environmental prospects. Biochar amendment has been described as a win-win strategy as it allows for both increased soil C sequestration and crop yield. However, there are trade-offs between these two aims of biochar use, as it is not possible for both benefits to be simultaneously maximized. Biochar that is tailored to maximize C sequestration is supposed to have less impact on soil fertility than biochars designed to maximize soil quality and plant productivity [61]. Biochar with high agronomic value, indeed, is likely to present a limited C sequestration potential due to the use of oxidation to artificially accelerate biochar aging and increase soil CEC [61]. Biochar in soil undergoes physical and biochemical processes which contributed to increase its surface area and adsorption capacity for nutrients. Chemical oxidation is a practical approach to accelerate the natural aging process of biochar and have been proposed as a strategy to improve the agronomic properties of biochar. Biochar with increased CEC will adsorb cations and reduce nutrient leaching, but the oxidation process leads to a loss of C, hence reducing C sequestration potential [61]. Furthermore, oxidation of biochar may result in decreased resistance of the biochar to decomposition in soil, further reducing C sequestration potential of biochar [75].

Conclusion

Usage of biochar showed good potential and beneficial contributions to increase sustainability and promoting circular economy in the agriculture sector. However, biochar represents also a new technology whose usage needs to be more strongly supported by a wider base of studies unraveling the inherent variability of conditions in which this technology can be applied.

Usage of biochar as replacement for peat in growing media is promising, but it is still far from being widely practised. Thus, at this stage biochar could be suggested as an effective additive partially replacing peat for improving the characteristics of the commercial growing media. Biochar in composting process enhances organic matter degradation, agronomic value of final composts, and decreases N losses and GHG emissions, but some studies did not find any synergistic effect of the combination of biochar and compost on plant growth.

Biochar as soil amendment in field application has shown to improve physical properties and fertility status of soil and increase crop yield, especially in soils with low pH, coarse texture and/or low nutrient availability.

Indeed, despite multiple-benefit use, biochar is not a standardized material, thus its property and its effect may vary from one matrix to another. A proper combination among biochar type, the purpose of its use and optimum application rate should be explored. Selecting the right biomass and optimization of pyrolysis conditions are key factors to tailor high agronomic value biochar for its proper use in the agricultural domain. Further research should be conducted to evaluate the economic benefit along with the environmental and agronomical perspectives for the implementation and intensive use of biochar in the framework of circular economy.

Abbreviations

CEC: Cation exchange capacity; GHG: Greenhouse gases; PAH: Polycyclic aromatic hydrocarbons.

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Authors' contributions

KJ, GM, MASM and CM wrote the manuscript; YA, FSH, CAS, CM and KA collaborated to the text redaction and formatted the whole text. All authors read and approved the final manuscript.

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