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The influence of biochar soil amendment on tree growth and soil quality: a review for the arboricultural industry.

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Abstract

Studies assessing the effects of biochar used as a soil amendment in agriculture and forestry have indicated variable results, from significant improvements in growth and health to no effect at all. Research into biochar use for trees within the urban landscape are extremely limited. This review is aimed at arboricultural practitioners and professionals involved in urban tree landscape management and provides a critical analysis of the use of biochar to support tree health and establishment. Biochar, specifically wood biomass-based biochar, has the potential to enhance tree establishment and survival. However, considerable variability in the physical and chemical properties of biochar currently limits universal application. Therefore, practitioners should aim to use biochar types suitable for the desired function, such as transplant establishment, remediation of declining mature trees, and pest/disease management. Biochar also represents a promising complimentary amendment to more established soil management techniques such as mulching and fertilization, but further long-term studies in a range of conditions typical of urban environments are required to fully understand the effects of specific biochar types on urban trees.

Keywords

Biomass, Root Growth, Soil Amendment, Soil Compaction, Tree Survival.

Introduction

Urban forests and green infrastructure not only contribute aesthetically to the municipal environment but additionally provide environmental and socio-economic benefits (Roy et al., 2012; Seamans, 2013). These benefits include lowering atmospheric pollution, temperature extremes, floodwater runoff, noise pollution, and heavy metal soil concentration (Bell et al., 2008; Donovan and Butry, 2009; Hardin and Jensen, 2007). Currently, 54% of the global human population live in urban areas, with a predicted rise to 66% by 2050 (United Nations, 2015), and therefore maximizing the benefits of green spaces and the soils that support green infrastructure in urban environments is vital (World Health Organization, 2017). Human activity in urban areas is often very intensive and has been shown to damage soil quality through the destruction of soil structure or changes in soil mineral and biological composition, which can lead to compaction, degradation, and erosion (Bullock and Gregory, 2009; Craul, 1999; Rossiter, 2007). Available soil volume is a major factor limiting the growth of urban trees (Day and Bassuk, 1994; Grabosky and Bassuk, 1996), whilst soil texture and bulk density also play a role as determinants of root growth (Roberts et al., 2006). Biochar, a highly porous material produced from biomass, may provide some benefits for improving the urban soil environment.

Biochar is a product high in complex carbon compounds, produced by pyrolysis of the feedstock biomass material at high temperatures (>300°C) in a low oxygen environment (Cha et al., 2016; Lehmann and

Joseph, 2009; Sun et al., 2014). Biochar is a common by-product of biofuel or biogas production (Laird et al., 2010; Steenari and Lindqvist, 1997), but has also shown potential as a valuable soil additive for improving plant productivity demonstrated by its many applications in agriculture (Bhattacharjya et al., 2016; Ding et al., 2017; Safaei Khorram et al., 2019; Scott et al., 2014). The exact properties of biochar, such as pH, nutrient value, stability, and its subsequent influence on the soil environment, are highly dependent on the original biomass used to produce it (Al-Wabel et al., 2017; Gai et al., 2014; Panwar et al., 2019; Suliman et al., 2017; Vandecasteele et al., 2016). The type of feedstock used to produce biochar has been identified as having a stronger impact on plant growth than production temperature (Rajkovich et al., 2012). The effect of feedstock on biochar characteristics is demonstrated in Table 1.

Biochar is primarily applied as a soil amendment to increase soil carbon content, improve soil structure, nutrient retention, and plant growth (Elad et al. 2011). In general, the addition of organic matter (OM) to soil boosts its functionality, and biochar can be used as a source of OM to aid soil recovery from anthropogenic degradation. Biochar addition to the Amazon Preta de Indio soils demonstrated its potential to improve soil fertility and structure in the very long term (Lehmann et al., 2002). Charred materials applied 9,000 years ago are still detectable in 2010 (Sohi et al., 2010). Biochar is a relatively inert compound, usually characterized by low nutrient content unless the biomass used for its production was derived from animal manure or contains a large ash content post-production (El-Naggar et al., 2019; Scott et al., 2014). Plant nutrition can, however, be improved indirectly through increased soil cation exchange capacity and enhanced retention of nutrients in biochar within the soil profile (Foster et al., 2016; Kolton et al., 2017). The recent literature examining the effect of biochar amendments on urban tree growth is relatively sparse, as the majority of studies focus on agricultural crops such as rice, wheat, tomatoes, rapeseed, and corn (Griffin et al., 2017; Larbat et al., 2012; Scott et al., 2014; Tian et al., 2020). In principle, the positive effects of biochar soil addition observed in agricultural crops should be applicable to trees, albeit over a longer duration to reflect their life span. In reality, a wide range of biochar effects on soils has been reported. The International Biochar Initiative (IBI) has attempted to set standards for biochar for use in soils, as shown in Table 2 (International Biochar Initiative, 2015), including a certification program to ensure biochar is of sufficient quality and safe for soil application.

Biochar degradation in the soil is extremely slow, usually occurring over thousands of years (Lehmann et al., 2006; Liang et al., 2008). There is importance in examining the efficacy of biochar as a soil amendment over an extended time period to assess cost-effectiveness for a single application for urban tree plantings, which has received little attention. Bare-rooted ornamental trees tend to be more economical to produce, transport and plant, and therefore more frequently utilized (Barnes and Percival, 2006; Davies et al., 2002). However, the lifting and processing of bare-rooted stock often decrease root mass and quality of root architecture (Watson and Himelick, 1997; Wilson et al., 2007). The result is a loss in root absorptive area (Watson and Himelick, 1997), the negative impact of which may be alleviated by biochar addition (Schaffert and Percival, 2016).

The aim of this review is to identify issues specific to the establishment of urban tree populations, collate existing information on the potential of biochar to improve the success of urban tree establishment and to present a coherent information base accessible to arboricultural practitioners. This review also aims to indicate areas of opportunity for future biochar research in the urban landscape.

Review methodology

ISI Web of Knowledge, Science Direct, and Google Scholar were utilized to conduct literature search using the following keywords; “biochar, tree growth”, “biochar, soil, urban”, and “biochar tree”, and papers published after 2012 only were included. A number of papers were rejected from the result based on title only as they were not pertaining to biochar soil amendment. The lists of references in published reviews (Stavi, 2013; Thomas and Gale, 2015; Verheijen et al., 2014), were consulted as additional sources of relevant literature. Studies that defined the product as “ash” instead of biochar were excluded due to the different production and properties compared with biochar. For those using the term “charcoal” in place of biochar, details of the product applied were determined to ensure their similarity to biochar and were provided in this review. Information for each of the 46 studies reviewed here, including biochar, soil and tree characteristics for each study, can be found in the supplementary information for this publication.

Biochar effects on soil in relation to tree growth and survival

Biochar is a likely alternative to traditional compost and fertilizer amendments for use within the urban landscape due to its broadly positive effects on tree growth and soil properties (Scharenbroch et al., 2013). However, only limited evidence on the effects of biochar on urban trees is currently available (Ghosh et al., 2016; Scharenbroch et al., 2013), with a focus on orchards, fruit-producing species (Eyles et al., 2015; Ventura et al., 2014) or on forest restoration projects (Sovu et al., 2012; Thomas and Gale, 2015). An average increase in total biomass of 41 % was reported across a range of woody species following biochar soil amendment, with angiosperms showing greater growth responses than conifers in one meta-analysis review (Thomas and Gale, 2015). Research has shown the effects of biochar on trees can be highly species-specific, however, the following sections aim to evaluate the potential of biochar to ameliorate conditions for trees growing in the urban landscape.

Root system growth

Enhanced root growth after planting can facilitate and increase the rate of establishment, especially in less desirable environments. The addition of wood-based biochar as a soil amendment reduced root biomass and increased root:shoot ratio of hybrid vpoplar (*Populus nigra L.* × *Populus suaveolens* Fischer subsp. *maximowiczii* A. Henry) through improved cation exchange capacity when compared to vermiculite and peat (Headlee et al., 2014). Pear (*Pyrus communis*) trees showed similar reactions to transplanting into biochar amended soils, with a 20% reduction in mortality, a significant increase in tree crown size by 28%, and improvements in leaf photosynthetic efficiency of 32% compared with untreated trees (Schaffert and Percival, 2016).

Coral gum (*Eucalyptus torquata*), a xeric tree species, when planted in a sandy soil with biochar amendment, improved its below-ground growth compared to no biochar addition, but not in a clay soil, which could indicate greater improvements in water retention than drainage (Somerville et al., 2019). In tropical regions of Australia, the use of eucalyptus wood biochar in the rhizosphere of the mesic tree species Spotted gum (*Corymbia maculata*) had no significant effect on root growth response under two watering regimes (drought and well-watered). However, a xeric tree species included in the same study, Coral gum (*Eucalyptus torquata*), did show an increase in root growth response in sandy soil (Somerville et al., 2019). Water content at field capacity in the sandy soil resulting from the addition of biochar could explain the increased growth response in the Coral gum-treated trees. When incorporating pine waste biochar to improve root regeneration, significantly higher root biomass was observed when planting Small-leaved lime (*Tilia cordata*) in late Spring (Fite et al., 2019). Total above and below-ground biomass production and foliar magnesium (Mg) concentrations of peach trees were significantly higher following biochar amendment at all harvesting dates compared to control trees (Atucha and Litus, 2015). Brazil nut biochar applied to the soil of two tropical tree species, applied either alone or with fertilizer, improved root biomass production up to 85% in White olive (*Terminalia amazonia*) and Bolaina Blanca (*Guazuma crinite*) (Lefebvre et al., 2019). Biochar nutrient contents, as well as its humic acid and fulvic acid content were identified as responsible for these effects (Fagbenro et al., 2015).

Water availability to plants

Increased soil matric potential has been observed, with the greatest improvements when soil is nearing field capacity (Eykelbosh et al., 2014). At the same time, woodchip biochar shows high levels of water repellency due to the hydrophobicity of lignin and cellulose it contains, potentially lowering soil water holding capacity (Brantley et al, 2015). Poultry litter biochar had an even greater water repellency, possibly due to the oil or tar content of the original biomass used to produce it (Brantley et al., 2015). Examining the performance of dwarf umbrella tree (*Schefflera heptaphylla*) roots in a potted tree study, biochar reduced matric suction by 12% and improved plant water availability within soils by 36%, in addition to increasing the water content of the soil from 12 to 17% (Ni et al., 2018). Similarly, positive results were observed in larger pot trials, hinting at the wider applicability of these findings for larger specimens (Fujita et al., 2020; Zoghi et al., 2019). Three percent (by weight) application of hardwood chip biochar achieved a 73% increase of biomass, 38% of photosynthetic rates, and 39% of stomatal conductance in pot-grown Chestnut leaved oak (*Quercus casteinifolia*) in severe water deficit conditions (40% field capacity) (Zoghi et al., 2019), and 5% application increased midday stem water potential in Red Oak (*Quercus rubra*) (Zwart and Kim, 2012). When irrigation was completely removed from potted Japanese Black pine (*Pinus thunbergii*), biochar maintained significantly higher internal water potential for 10 days compared to trees growing in untreated soil whilst increasing root biomass over time (Fujita et al., 2020). A cultivar of Manchurian Pear (*Pyrus ussuriensis* Maxim.) showed significant improvements in leaf photosynthetic efficiency after wood chip biochar application, whilst biochar also reduced moisture loss from the rhizosphere by transpiration under drought stress conditions (Lyu et al., 2016). Similar trends were observed with Black locust (*Robinia pseudoacacia L.*), with an improvement in shoot growth significantly correlated to improvements in soil water holding capacity and available P as a result of biochar application in another greenhouse pot trial (Bu et al., 2020). However, caution should be exercised in relying entirely on these results as young potted seedlings were used in many biochar trials

(Bu et al., 2020; Fujita et al., 2020; Lyu et al., 2016; Zoghi et al., 2019). Benefits of combined compost (10%) and biochar (5%) application were determined to be greater than sole application in this tropical urban environment, with increased tree growth index (33% and 50%) after 30 months, PAW (104% and 16%) after 24 months, and reduced bulk density (25% and 33%) 30 months after application in sandy clam loam and loamy sand respectively (Somerville et al., 2020).

During the vegetative period of woody grapevines over a four-year trial, yield increases were observed where biochar was applied as a soil amendment despite lower rainfall, highlighting the positive contribution of biochar during periods of drought (Genesio et al., 2015). Whilst most examples identified using tree species have resulted in positive effects of biochar on water availability and water uptake, mixed hardwood biochar tested in an apple orchard in Italy resulted in no effects on soil moisture relations or temperature in a particularly unretentive soil media (Ventura et al., 2014). In contrast, biochar combined with a clay substrate led to lower soil water content, typically below permanent wilting point (PWP), and significantly reduced the period of retaining PAW in sandy soil (Mertens et al., 2017). Authors speculated that higher evaporation potential due to the biochar application could result in reduced PAW (Mertens et al., 2017). Many other studies have identified significantly positive results in applying biochar to sandier soils for improved water retention (Basso et al., 2013; Githinji, 2014; Hariyono et al., 2020; Suliman et al., 2017), but much more exploration is required in contrasting climatic regions before definitive conclusions can be reached. It is likely that the surface area increased by biochar application improves the water holding capacity of sandy soils (Omondi et al., 2016; Wang et al., 2019). Pore size distribution and abundance differ between biochars. For example, the range of pore size for bamboo-based biochar (0.001 to 1000µm diameter) is wider than that of wood-based biochar (10-3000 µm diameter) (Thies and Rillig, 2009). This is important as pore size distribution directly influences water retention and nutrient capacity when applied to soil (Kameyama et al., 2019).

Degraded soils and nutrient availability

Low nutrient availability is a frequent problem in urban environments. Interestingly, biochar studies often target degraded soils in tropical climates typical for their low nutrient content and retention capacity. Examining interactions with macronutrients, chicken manure biochar can significantly increase total N from 0.53 to 0.90 g kg^{-1}, and available P and K from 0.65 and 48.3 mg kg^{-1} to 28.0 and 226.7 mg kg^{-1} respectively, although only 2% of the N original content was shown to be available (Lin et al., 2017). Wheat straw biochar demonstrated similar results when trialed in a Chinese nutmeg-yew (*Torreya grandis*) orchard (Q. Li et al., 2020), and sewage sludge biochar has shown some degree of efficacy for improving plant growth through increasing nutrient availability to trees (Silva et al., 2016). Soil-applied biochar has the potential to stimulate soil nitrification through increases in soil ammonia-oxidizer (bacterial and archaeal nitrifiers) populations (Prommer et al., 2014), although other research did determine the N content of biochar itself is not an indicator of effect on plant biomass production (Scharenbroch et al., 2013). In a 13 week trial using Drumstick tree (*Moringa oleifera*), a highly-valued medicinal tree, the main effects of biochar on various plant parameters were positive and significant at the highest application of biochar and fertilizer individually. These included increases up to 17% in tree height and 20% in stem diameter, respectively (Fagbenro et al., 2015).

Hardwood biochar produced the most consistent improvements in yield (Spokas et al., 2012). When applied to *Eucalyptus* trees, all biochar treatments had a smaller root:shoot ratio, as well as increased leaf chlorophyll content after 30 and 60 days (Silva et al., 2016). Slight phytotoxicity was noted in the first week of experimentation after biochar application, potentially due to the release of residual volatile organics present in the sewage sludge biochar (Silva et al., 2016). Soil nitrate (NO_3-) leaching was significantly lower in a highly alkaline soil environment amended with biochar over a short-term trial in temperate conditions (Ventura et al., 2013).

In a peat-based potting mix, elevated levels of exchangeable K were observed after biochar derived from red oak was applied, which in turn led to significantly higher total biomass production in hybrid poplar (Headlee et al., 2014). Similar results were recorded when biochar was applied to aspen seedlings (Dietrich and Mackenzie, 2018). Chestnut-leaved oak showed improvements in plant productivity between 55 and 73%, and increased K uptake by 59 and 78% compared to controls at 70 and 40% of field capacity, respectively, as well as increases in soil water holding capacity when biochar was incorporated as a soil amendment (Zoghi et al., 2019).

Although biochar derived from a hardwood (*Acacia ssp.*) had no significant effect on nitrate (NO-3) or K leaching compared to unamended soil, an increased concentration of P in the leachate was observed potentially as a result of increased pH, a potentially negative impact of biochar on soil P availability (Hardie et al., 2015). In addition, the volume of this leachate collected was significantly higher in the biochar treatment, which may not be advantageous in an urban soil situation. This could potentially result from larger pore size distribution and near-saturated hydraulic conductivity of biochar-amended soils (Hardie et al., 2015). Sawdust biochar increased the supply of P and Ca immediately after surface application; these two nutrients are known to limit sugar maple growth in the Ontario region of Canada (Sackett et al., 2015), although greater alterations in soil nutrient balance and cycling were observed after a time period sufficient to fully incorporate biochar into the soil. In low productivity soils depleted of carbon pools and low in pH, biochar at the highest dose rate improved soil P availability and subsequent biomass of Fujian cypress (*Fokienia hodginsii*) by 36% compared to untreated controls (Tarin et al., 2020).

Fruit trees have exhibited improved growth in response to the combined application of biochar and compost, as shown in an apple orchard in Iran where trees were grown in degraded and low fertility soil (Safaei Khorram et al., 2019). Plant-based biochar application under young apple trees increased trunk girth after three years in sandy loam (Eyles et al., 2015), reduced the incidence of poor growth, chlorotic leaf area, and dead leaf presence (Xinfeng, 2017), as well as increased soil nutrient retention in both silty clay loam and sandy loam soils (Hardie et al., 2015; Ventura et al., 2013). Blueberry fruit benefitted from biochar application as improved fruit nutritional quality was observed, resulting from improved nutrient availability in low fertility and weakly acidic soil in a temperate monsoon climate (Zhang et al., 2020). Nectarine tree growth did not improve significantly after biochar application in an established orchard under low soil stress conditions (Sorrenti et al., 2016). Other studies have shown no effects on tree growth, mainly where soil conditions are less stressful and more optimal for root growth and development, indicating that the beneficial effects of biochar may be less detectable in soils already in optimal condition (Ventura et al., 2014).

Biochar impact on soil pH in relation to plant growth

Biochar is often alkaline, however, existing soil buffering capacity usually results in less than significant changes in soil pH following biochar soil amendment. Chicken manure biochar significantly increased soil pH from 4.8 to 5.2 (Lin et al., 2017), although this was still within the range of acceptable pH for a large number of tree species. The pyrolysis temperature has been shown to be the deciding factor of pH of biochar products as opposed to feedstock, although biochar with greater ash contents such as manure biochar can increase pH more significantly (Al-Wabel et al., 2017). Biochar application to low pH degraded soil also increased pH values which subsequently improved biomass production of Fujian cypress (*Fokienia hodginsii*) by 36% (Tarin et al., 2020). An increase in autotrophic nitrifying bacteria in response to increased pH could in part explain the increased biomass observed (Ghosh et al., 2012).

At higher application rates of biochar (25%-50% by volume), a decrease in soil pH reduced the photosynthetic rate in conifers and fundamentally rendered the soil incompatible with conifer seedling growth (Sarauer and Coleman, 2018), highlighting the need to design appropriate biochar amendment soil application rates. The use of biochar in the forestry setting identified the need for future research into the impact of biochar on soil and trees in alkaline soils and under Mediterranean or drier conditions

(Stavi, 2013). As urban soils are often variable within a small area, practitioners should fully assess the existing soil conditions, and where applicable high pH biochar should be avoided for use on alkaline soils or for tree species preferring acidic conditions.

Impact on soil biological conditions for tree growth

Improved microbial activity as a result of biochar amendment has been observed through community DNA analysis, with the most beneficial results achieved when biochar was applied jointly with an N-P-K (12:62:0) fertilizer (Zhou et al., 2019). Microbial population increase in response to biochar is highly dependent on using a biochar feedstock to optimize colonization, provide shelter for organisms or alter soil conditions such as moisture to favor microbial activity (Ameloot et al., 2013). Improving soil microbial activity can be an important goal when rejuvenating degraded soils, although few studies have examined the effect of biochar on microbial activity in relation to urban trees. An investigation of soil under a Chinese fir (*Cunninghamia lanceolata*) rotation indicated leaf biochar was more effective at increasing soil bacterial diversity than wood chip biochar, particularly P-solubilizing bacteria (Zhou et al., 2020). In contrast, microbial biomass and respiration rates generally decreased with wood pellet biochar application to containerized Black chokeberry (*Aronia melanocarpa*) 'Viking' and Sugar maple (*Acer saccharum*) (Sax and Scharenbroch, 2017), suggesting that pelletized biochar of woody biomass origin may not be an optimal amendment to improve soil microbial activity and provides further evidence of the importance of biochar source material.

Use of biochar in contaminated or saline soils

High salinity and accumulation of pollutants such as lead, cadmium, and polycyclic aromatic hydrocarbons (PAHs) are problematic during the tree establishment phase in the urban environment. Phytotoxicity of heavy metals in the soil is a common occurrence in urban environments (Li et al., 2013). Biochar-mediated salt tolerance has been observed as a result of the application of wood chip biochar in White gum (*Eucalyptus viminalis*) and Black wattle (*Acacia mearnsii)*, two species commonly used for soil reclamation (Drake et al., 2016). Biochar also mitigated salt damage in potted cherry laurels grown under saline soil conditions by reducing sodium retention and K leaching (Di Lonardo et al., 2017). Increasing application rates of rice husk biochar significantly decreased cadmium bioavailability, and in turn, increased seedling height, diameter, and biomass of oak seedlings (Amirahmadi et al., 2020). Hardwood biochar also shows potential to improve soil chemical quality in Montreal urban soils by reducing the bioavailability of trace metals and de-icing salts (Seguin et al., 2018). Although compost amendment was found to be superior in reducing the availability of zinc, lead, cadmium and copper when compared to wood chip biochar in urban soil, biochar still reduced levels considerably (Kargar et al., 2015). Comprehensive literature reviews conducted on biochar in relation to reducing soil contaminants under agricultural and forestry situations report a consensus that biochar application has more positive than negative benefits (Ogbonnaya and Semple, 2013; Rizwan et al., 2016). In addition, the extensive knowledge of using biochar as a method of adsorbing contaminants in wastewater and soil may be of direct relevance in urban landscapes with polluted soils (Devi and Saroha, 2014; Patra et al., 2017; Paz-Ferreiro et al., 2014; Puga et al., 2015; Tan et al., 2016).

Potential use for soil stability in structural soils

Structural soils are used in the urban landscape for the specific purpose of reducing compaction. These soils often feature large aggregates, load-bearing structural frames, or a combination of the two to limit damage to the soil rooting environment. Previous work has demonstrated shoot growth can be 114% higher when using suspended pavement structural soil, and 37% higher when using structural cells compared to conventional planting pits. (Ow et al., 2018). Likewise, in a number of urban planting trials throughout Singapore, improvements in above-ground growth were recorded when biochar was added to structural soils to establish African mahogany (*Khaya grandifolia* and *Khaya senegalensis*), Monkeypod tree (*Samanea saman*), and Northern yellow boxwood (*Pouteria obovata*) (Ow et al., 2018). These results indicate that there may be a role for biochar in combination with these highly specialized soil types. Contrary to this, however, although an increase in growth was observed with a biochar stone blend known as Stockholm soil, growth was not as great compared to using structural cells alone (Ow et al., 2018). Limited peer-reviewed research has been conducted on the potential use for biochar inclusion in the structural soil mix, however this practice has been widely adopted through the Stockholm Biochar Project in Sweden (Embrén, 2016).

Combination of biochar and other amendments

Applying biochar and fertilizer in combination has often been shown to induce synergistic effects by improving fertilizer use efficiency in several crop plant species (Kamau et al., 2019; Rafique et al., 2020). Such a response has also been observed in two tropical tree species, *Guazuma crinita* and *Terminalia amazonia*, where granulated NPK 20-20-20 application with brazil nut husk biochar significantly increased height, diameter, the total number of leaves, and above- and below-ground biomass of both species compared to granulated fertiliser alone (Lefebvre et al., 2019). It was noted that greater synergetic effects of biochar and fertilizer addition were present with the early successional tree species *Guazuma crinita*. Some positive impacts of joint application between biochar and a proprietary NPK 9-6-3 organic fertilizer were also observed when studying tree growth of *Pyrus communis* 'Williams' Bon Chrétien' (Schaffert and Percival, 2016). Combining the above products enhanced fruit yield per tree and canopy coverage by 12%– 49% respectively and also increased tree vitality [chlorophyll fluorescence, leaf chlorophyll content (SPAD), photosynthetic rates] compared to the use of each amendment individually (Schaffert and Percival, 2016). In the Singapore urban environment, combined compost and biochar application yielded positive benefits on tree health and growth of *Suregada multiflora* and *Samanea saman* trees, whereas biochar applied alone showed a greater improvement in soil conditions only (Ghosh et al., 2015). No effects were recorded when biochar was combined with an inorganic fertilizer to establish Drumstick tree (*Moringa oleifera*) seedlings (Fagbenro et al., 2015), however earlier research by the same lead author did indicate a significant increase in dry matter yield with a combined application on the same species (Fagbenro et al., 2013). Aside from this, biochar produced from Quickstick (*Gliricidia sepium*), a hardwood commonly planted for shade in cocoa plantations, was deemed a sufficient replacement of inorganic fertilizer in the same study. In contrast, when comparing compost and biochar as effective amendments for urban tree growth, both were shown equally beneficial, with no added benefit from combined use on Spotted gum (*Corymbia maculata*) (Somerville et al., 2020) and several poplar, willow and Locust (*Robinia ssp.*) trees (von Glisczynski et al., 2016). In an orchard setting, application of biochar and compost as a mixture significantly increased soil properties such as water-holding capacity and aeration (i.e. decreased bulk density), while some positive effects on trunk diameter and shoot numbers of three-year-old apple were observed for the first two to three years (Safaei Khorram et al., 2019). Similar results on trunk diameter were observed on an apple orchard in the warm temperate climate of southern Tasmania, Australia, although observations were made that biochar may not be sufficiently beneficial in an environment with high inputs of nutrients and irrigation to warrant the cost of application (Eyles et al., 2015).

Desirable biochar characteristics and application rate

Even though the majority of evidence collated in this review was gathered from studies investigating trees planted outside urban areas, the findings are likely to be applicable to urban tree plantings that have to contend with a multitude of stressful abiotic conditions. Large scale urban pit plantings in Sweden, for example, have shown the benefit of biochar amendment has more than surpassed the cost of application, with marked growth and survival improvements over 10 years (Embrén, 2016). Greater retention of water and nutrients by biochar may allow for smaller tree root systems to satisfy the transpirational demand of the above-ground part. Alterations of soil carbon content, levels of compaction, and electrical conductivity are likely to result from any biochar soil amendment, but subsequent effects on tree growth and physiology tend to be interactive, dependent on climate and species (Thomas and Gale, 2015).

As suggested by the International Biochar Initiative, biochar must be designed and created for a specific purpose (International Biochar Initiative, 2015). Currently, there is no literature reporting long-term studies detailing which biochar characteristics improve tree growth in urban environments. Biochar designed to maximize its surface area and pore variability in soil, for example, would be desirable for use in urban soils due to a then higher capacity to retain moisture and improve aeration (Novak et al., 2012). Water repellency is a factor in biochar produced from materials with large quantities of lignin and cellulosic components (Gray et al., 2014), and this should be considered along with the porosity of the char. Biochar produced at temperatures of above 450°c is preferable for use in urban soils, as the resulting char has lower water repellency, increased porosity, and stability in soils (Gray et al., 2014; Mao et al., 2019; Novak et al., 2012). Most nutrient-related soil improvements in response to biochar discussed in this review were derived from animal or agricultural waste biomass. Indicating these may be beneficial to improve short term soil nutrient status on those species assessed (H. Li et al., 2020; Lin et al., 2017; Silva et al., 2016), supported by previous agricultural reviews on the subject (Al-Wabel et al., 2017; Scott et al., 2014).

Biochar nutrient content is generally not a priority for use in urban tree pits, as fertilizer addition typically takes place. However, fertilizer effects are short-term and therefore negligible in terms of tree life spans. However, biochar contributing higher levels of K has been reported that in turn promote tree growth and survival, as well as improving microbial activity, and should be favored in low fertility soils (El-Naggar et al., 2019).

Application rate should be considered for each type of biochar feedstock, but in general, most trials with a positive effect from biochar application conclude application rates between 4 and 10% by volume (v:v) improve either soil or plant health conditions. Several trials in the urban environment found wood chip biochar applied at 5% to 10% v:v produced positive effects on soil moisture or tree growth parameters in sandy soils (Somerville et al., 2020, 2019). From a practical perspective, the weight of biochar can vary significantly depending on the feedstock. Therefore, to ensure the correct amount is applied for surface area contact, percentage by volume is a more appropriate measure. We would suggest 5% v:v application to soil within the rhizosphere not exceeding 10%, as applications above 25% have resulted in detrimental impacts, including reduced plant productivity and the presence of phytotoxicity (Sarauer and Coleman, 2018). Applications can be either top-dressed or mix into the soil through air tillage or manual incorporation method, but application with compost should be preferred to increase the efficacy of the biochar amendment. Biochar consistently achieved greater benefits when applied in combination with either organic fertilizer or another organic matter input such as compost (Ghosh et al., 2015; Robertson et al., 2012; Safaei Khorram et al., 2019; Schaffert and Percival, 2016; Somerville et al., 2020; Sorrenti et al., 2016). Finally, particle size has been shown to affect cation exchange capacity, soil moisture retention, soil bulk density, and root biomass (REFS), so maximizing surface contact with the soil are important. Irregular shapes particles will also effectively increase water storage in coarse soils like those with a high sand content (Liu et al., 2017). Wood chip biochar with a range of sized particles sieved will provide optimum surface contact with the soil to aid the soil:plant continuum. However, pore size distribution within the biochar is far more imperative to provide a wider range of benefits for improving soil conditions for urban planted trees (Blanco-Canqui, 2017), particularly employing biochar with a larger proportion of pores within the PAW capacity pore size range (0.2–30 µm) (Hardie et al., 2014).

Conclusions

Ideally, tree species should be selected for their tolerance to the sub-optimal soil conditions encountered in the harsh urban environment. The reality is, however, that selection is based on factors such as availability, economic cost, historical use, or aesthetic impact. The survival of trees planted in urban zones is more important than their productivity, best illustrated by the high cost of tree planting in urban environments and the fact that the benefits of trees to human populations increase exponentially with tree maturity. We show that biochar can enhance tree survival by several mechanisms, mostly related to improved soil function. Even a small increase in tree survival rates could make biochar application cost-effective for use by local authorities or tree caretakers. Future research needs to decipher the impact of biochar on tree tolerance against environmental stresses in the urban environment, with a focus on longer-term studies and the use of diverse biochar types.

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Biochar raw material	pH	C:N ratio	CEC (cmol (+) kg^{-1})	EC (dSm^{-1})	Ash content (%)	Bulk density (g cm^{-3})
Pelletized sawdust (Fields-Johnson et al., 2018; Lin et al., 2017; Ow et al., 2018; Rafique et al., 2020; Sackett et al., 2015)	6,3, 7.5, 8.3	10.5 - 13.2	6.2 – 6.4	3.3	3.11 – 25.7	0.13
Wood residues (Coniferous) (Fujita et al., 2020; Phillips et al., 2020; Pluchon et al., 2014; Sarauer and Coleman, 2018)	6.2 – 8.3	66.9	18.6 – 22.9	2.2- 3.7	40.3% (@980°C)	0.17 – 0.44
Wood residues (Hardwood) (Di Lonardo et al., 2017; Safaei Khorram et al., 2019; Shan and Coleman, 2020; Somerville et al., 2020)	6.8 – 9.7	60.4 - 138	30	2.6	19.8	0.33 – 0.42
Chicken manure (Domingues et al., 2017; Lin et al., 2017)	9.8 – 11.9	11.9	41	5.8 – 7.4	48.8 - 56	NC
Rice husk (Amirahmadi et al., 2020; Häring et al., 2017; Wiersma et al., 2020)	8.1 - 9.1	70.7	18.28	NC	45.2	0.18 - 0.22

Nut husk (Lefebvre et al., 2019; Rajkovich et al., 2012)	7.66 - 9.6	158 - 181	5.9 - 11.8	1.6 - 1.42	1.69 - 7.8	NC
Bamboo (Ye et al., 2015)	8.5 – 10.2	24.48 - 28.92	NC	NC	9.5 – 14.2	NC
Orchard prunings (Genesio et al., 2015; Sorrenti and Toselli, 2016; Ventura et al., 2014)	9.8	63.53	101	NC	NC	0.33
Sewage sludge (Paneque et al., 2016; Silva et al., 2016)	7.5, 8.41	6.12	NC	7.29	25.6	NC

Table 1 Summary of the main characteristics of biochar, as affected by raw material used for pyrolysis. NC = not communicated

Basic utility properties (Category A)	Toxicant assessment (Category B)	Advanced analysis & soil enhancement properties (Category C)
Moisture (% total mass)*	Germination inhibition assay *Pass/Fail*	Mineral nitrogen (NH_4+ & NO_3-) (mg kg^{-1})*
Organic Carbon (C_{org})(% of total mass)*10% Minimum; Class 1: ≥60%, Class 2: ≥30% and <60%, Class 3: ≥10% and <30%*	Total Polycyclic Aromatic Hydrocarbons (mg kg^{-1}) *6 – 300 mg kg^{-1}*	Total phosphorus & potassium (mg kg^{-1})*
H:C_{org} (molar ratio) *0.7 maximum*	Dioxins/Furans (PCDD/Fs) (ng kg^{-1}) *17 ng kg^{-1}*	Available phosphorus (mg kg^{-1})*
Total Ash (% total mass)*	PCBs (mg kg^{-1}) *0.2 – 1 mg kg^{-1})*	Total Calcium, Magnesium & Sulfur (mg kg^{-1})*
Total Nitrogen (% total mass)*	Arsenic *(13-100)*, Cadmium *(1.4-39)*, Chromium *(93-1200)*, Cobalt *(34-100)*, Copper *(143-6000)*, Lead *(121-300)*, Molybdenum *(5-75)*, Nickel *(47-420)*, Selenium *(2-200)*, Zinc *(416-7400)*, Boron*, Chlorine*, Sodium* (mg kg^{-1})	Available Calcium Magnesium & Sulfate-S (mg kg^{-1})*
pH*	Mercury (mg kg^{-1})	Volatile matter (% total mass)*

	1-17 mg kg^{-1}	
Electrical conductivity (dS/m)*		Total surface area ($m^2\ g^{-1}$)*
Liming (if pH > 7.0) (% $CaCO_3$)*		External surface area ($m^2\ g^{-1}$)*
Particle size distribution* % <0.5 mm; % 0.5-1 mm; % 1-2 mm; % 2-4 mm; % 4-8 mm; % 8-16 mm; % 16-25 mm; % 25-50 mm; % >50 mm		

Table 2 Biochar material test categories adapted from IBI's biochar standards version 2.1 (2015); Categories A & B are required analyses and Category C is optional but recommended, for all biochar intended for use in soil, with threshold limits included. (denotes no thresholds required for parameter, only need values declared.)*