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REVIEW ARTICLE

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A biotic strategy to sequester carbon in the ornamental containerized bedding plant production: A review

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Abstract

Identifying options of climate change mitigation is of global interest to researchers. Whereas wide range of techniques of reducing greenhouse gas (GHG) emissions and carbon sequestration have been studied in row crops and forest systems, little research has been done on the ornamental horticulture. The ornamental industrial sector has indeed some negative impacts on the global environment, but also presents opportunities to reduce GHG emissions and increase C sequestration. Thus the objective of this study was to synthesize the potential contributions of some substrates used in the horticultural sector to carbon sequestration. The specific focus of the review is on the possible use of compost, vermicompost and biochar as soilless substrate substitutes for containerized ornamental plants production. Around 11 million kilograms of sphagnum peat moss are used annually in the world for horticultural production. Therefore, the potential of using compost, vermicompost and biochar as growing media is assessed on the basis of data from greenhouse studies. Peat-based substrate can be substituted up to 30% to 35% by compost or vermicompost and up to 20% to 25% by biochar. Some examples from field studies are included to conduct the life cycle assessment of using these growth media. An estimate of C storage on the long-term basis in soil indicates up to 3 million tons of CO_2 equivalent as the maximum C potential storage per year in the global productive sector if the peat-based growing media are substituted by compost/vermicompost and biochar at the ratios mentioned above. Finally, synergies between compost vermicompost and biochar are discussed when these materials are combined as growing media additives and research gaps in this area of activity have been identified for further research.

Additional keywords: biochar; compost; substrate additive; peat replacement; carbon storage; ornamental containerized plants.

Abbreviations used: CEC (cation exchange capacity); CO_2e (carbon dioxide equivalent); GHG (greenhouse gas); LCA (life cycle assessment); RMP (recommended management practices); SDW (shoot dry weight); SOC (soil organic carbon).

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Introduction

Climate change and CO_2 sequestration

There is a concern in the scientific field about climate change and its present and future impacts on human wellbeing. An increase in the atmospheric concentration of CO_2 may increase the Earth's mean temperature and change the precipitation patterns (IPCC, 2014). Thus, there is a growing interest in identifying strategies of decreasing the amount of atmospheric CO_2 by reducing anthropogenic emissions (Lal, 2009). In the meanwhile, carbon (C) sequestration capacity of natural sinks (*i.e.*, oceans, forests, peat bogs) is also decreasing because of human activities (Raviv, 2013). The process of transfer and secure storage of atmospheric CO_2 into other long-lived C pools that would otherwise be emitted or remain in the atmosphere is called 'carbon sequestration' (Lal, 2008). Therefore, in this context, C sequestration may be a natural or an anthropogenically driven process. The objective of an anthropogenically driven C sequestration process is to balance the global C budget such that future economic growth is based on a 'C-neutral' strategy of no net gain in atmospheric C pool. Such a strategy would necessitate sequestering almost all anthropogenically generated CO_2 through safe, environmentally acceptable and stable techniques with low risks of leakage (Lal, 2008).

Strategies to C sequestration

There are three main strategies of reducing CO_2 emissions to mitigate climate change: (i) reducing global energy use; (ii) developing low or no-C fuel sources; and (iii) sequestering CO_2 from point sources or atmosphere using natural and engineering techniques (Schrag, 2007). Regarding the last option, engineering techniques of CO_2 injection in deep ocean, geological strata, old coal mines and oil wells, and saline aquifers along with mineral carbonation of CO_2 constitute abiotic techniques. These techniques are expensive and prone to leakage. In comparison, biotic techniques are based on natural and cost-effective processes but have finite sink capacity (Lal, 2008).

Thus far, agriculture has been a major source of gaseous emission. Adoption of agricultural best management practices (*i.e.*, conservation agriculture, integrated nutrient management, precision agriculture, cover cropping, agro-forestry, micro-irrigation) can enhance resilience of soils and ecosystems against perturbations and also mitigate climate change. In this context, there are numerous land use and management practices, which must be discouraged. Notable among these are tropical deforestation, drainage of wetlands, cultivation of marginal/poor soils, intensive tillage, removal of crop residues, flood irrigation and biomass burning. Crop residues and animal dung must be used as soil amendments rather than as sources of household energy (Lal, 2013). Carbon sequestration in agricultural soils enhances sustainability of the land use systems. Increasing soil organic carbon (SOC) concentration in the root zone is beneficial in any situation to generate or maintain healthy soils (Lal, 2004a; Pardo *et al.*, 2017) and it also restores environmental quality and associated ecosystem services over the long time horizon (Lehmann, 2009). Carbon sequestration in ecosystems is measured by infrared gas analyzer to measure CO_2 eddy flux (Goulden *et al.*, 1996). In soils, C sequestration is estimated by difference in biomass and soil carbon content over time (Lal, 2004a).

In this regard the “4 per thousand” proposal at the 21st Conference of the Parties to the United Nations (UN) Framework Convention on Climate Change (COP21) in Paris on 2015, has called for a voluntary action plan to enhance SOC content of world soils to a 40 cm depth at the rate of 0.4% per year. The strategy is to promote SOC sequestration through adoption of the above mentioned recommended management practices (RMPs) of C farming (Lal, 2016). Thus, it is important to identify the specific plant cultures with a high capacity of C sequestration; however, the rate of SOC sequestration with adoption of RMPs may depend on soil texture and structure, rainfall, temperature, farming system, and soil management (Lal, 2004b).

Substrates in ornamental horticulture

Much of the research towards reducing GHG emissions and C sequestration has been conducted in row crop and forest systems. In comparison, a limited research has been conducted on the specialty crop industry such as ornamental horticulture. The latter is an industry that impacts rural, suburban, and urban landscapes. Although this industry may have some negative impacts on the global environment (Nicese & Lazzerini, 2013), it also has opportunities to reduce GHG emissions and increase C sequestration (Marble *et al.*, 2011). The horticultural industry was responsible for emitting 8.0 million tons of CO_2 in 1996. This was 12% more than in 1989/90 (RSFGV, 1999), and has been growing since then. The ornamental horticulture global production reached a value of \$37.1 billion in 2014. European Union (34.3%), China (15.9%) and USA (13.9%) contributed 64% of the economy (AIPH, 2017). In USA, five states (California, Florida, Michigan, North Carolina, and Ohio) accounted for 69% of that value. Principal plant´s categories are annual bedding/garden plants 33.2%, potted flowering plants 20.9%, indoor/patio use 18.4%, herbaceous perennial plants 14.8%, propagative floriculture materials 0.9%, cut flower 9.7% and cut cultivated greens 2.1%.The wholesale value for annual bedding and garden plants totalled \$1.29 billion in 2015. This value represents 69% of the total bedding and garden category. *Petunia* sp., *Geranium* sp., *Viola* sp., *Impatiens* sp. and *Begonia* sp. cultivars were the top five bedding plant crops grown in flats. These cultivars are usually grown in greenhouses. Initially, seeds/cuttings are cultivated in trays. Young seedlings are transplanted into containers/hanging baskets and grown to maturity (USDA-NASS, 2016).

Containerized plant production in horticulture primarily utilizes soilless substrates. In general, these substrates are primarily composed of organic materials such as peat moss and inorganic materials such as vermiculite and perlite (Bilderback *et al.*, 2013). However, to date, little is known concerning the C sequestration potential of the horticulture industry as a whole; which is also critical to assessing its potential contribution to mitigating the climate change (Prior *et al.*, 2011).

It is in this context that the review below is an attempt to synthesize the potential contributions of some substrates used in the horticultural sector to carbon sequestration. The specific focus of the review is on the possible use of compost, vermicompost and biochar as soilless substrate substitutes for containerized ornamental plants production.

Peat environmental concerns and peat substitutes

Nursery and greenhouse activities worldwide have been challenged to optimize their water and nutrients management (Majsztrik *et al.*, 2011). *Sphagnum* peat moss is the main substrate used in horticulture because of its homogeneous and ideal physical characteristics and high nutrient exchange capacity. As much as 10 to 11 Tg of this material may be used annually in the world for horticultural production (http://minerals.usgs.gov/minerals/pubs/commodity/peat/mcs-2015-peat.pdf). Globally, the total volume of materials used in growing media is difficult to estimate because recent data are not available for many areas of the world, including the Americas (both South and North), Australia, as well as Southeast Asia, where the process of growing out of soil has expanded in recent years but mainly into hydroponic systems in China, Japan, Thailand, and Malaysia (Carlile *et al.*, 2015).

Schmilewski (2017) reported that 34.6 Mm^3 of growing media were manufactured on 2013 in Europe, of which 93.8% was organic materials. Peat was the predominant bulky ingredient (75.1%), followed by organic constituents other than peat and compost (10.8%) and then compost (7.9%). An increase of 100% in green compost utilized as growing media in EU occurred since 2005 (Schmilewski, 2009). Traditional peat extracting countries have a strong focus on peat but there is an ever increasing interest and trend to replace peat by using other organic materials including composts. Countries without indigenous peat resources, *i.e.* the Netherlands, Italy and Belgium, also strongly depend on peat as the main growing media constituent. The principal objective of using mineral materials in growing media is to fine-tune their physical properties, and not to replace peat. In countries like Germany, Austria and Italy with emphasis on recycling bio-waste as part of their circular economies, the use of composts in growing media has increased (~ 6% between 2005 and 2013) (Schmilewski, 2009, 2017) and is likely to develop in other EU member states as targeted by the Circular Economy Strategy of the EU (EC, 2015).

In addition, environmental concerns questioning the peat use in horticulture are growing due to the number of environmental services provided by peatlands (Ostos *et al.*, 2008). They include their habitat value, carbon sink function, regulation of the local water regime and quality and flood protection (Alexander *et al.*, 2008). In fact, peat is no longer considered a renewable resource because it requires thousands of years (Hugron *et al.*, 2013) to be able to generate. Although peatlands represent an important component of the global carbon cycle, storing 23 g m^{-2} y^{-1} of C (Waddington *et al.*, 2002), that today means more than 600 Pg C (Harenda *et al.*, 2018), there are serious doubts about how current peatland will evolve under the climate change situation since these systems require very specific levels of moisture, temperature and insolation (Bragazza *et al.*, 2016).

In any case, there is a consensus about the need to find alternatives to peat as growing media for horticulture in order to reduce the current exploitation and degradation of peatlands when they are in phase of extraction (Waddington *et al.*, 2002). This point of view comes not only from the horticulture industry but also because the influence of macroeconomic issues based on the movements of consumers and decision-makers. Therefore, the challenge lies in identifying and using renewable materials with low costs of production and transportation (Gruda, 2011) and those having adequate physical-chemical characteristics. For instance in UK, environmental groups, government, and horticulture companies have organized themselves to recognize the environmental consequences of peat use in horticulture. In fact the industry is looking increasingly towards renewable raw materials such as green compost or processed timber by-products (Michel, 2010; Caron & Rochefort, 2013).

Composts appear to be a sound alternative to peat within growing media, in volumetric ratio anywhere between 30 to 50% (even up to 100% in specific cases), depending on their origin, composition, maturity and end use (Masaguer & López-Cuadrado, 2006; Raviv, 2013). Coco fibres may partly fulfil this role (Abad *et al.*, 2002). However, since the overall peat demand is growing on the market and the volume needed for peat replacement as a component of substrates greatly exceeds the availability of coco resources, replacement by coco will remain to be low. Moreover, it is expected that the price of coco is going to rapidly increase relative to other biomass in such situations (Caron & Rochefort, 2013). Therefore, the principle focus of this study has been on compost, vermicompost, and biochar, which are some of the industrial peat-based growing media substitutes (Carlile *et al.*, 2015).

Compost and vermicompost

Numerous studies have been undertaken to establish the potential substitution of peat with commercial compost and vermicompost, enhancing plant´s rooting and growth while also reducing the negative side effects (Garcia-Gomez *et al.*, 2002; Sardoei, 2014).

The UK was a pioneer in the research of compost as a substitute for peat (Prasad & Maher, 2001) due to the government decision to establish a deadline for the use of peat in horticulture, thus promoting research in this field (Sohi *et al.*, 2013). Compost from garden pruning and maintenance (green compost) was successful in that research and has since been widely used. Also compost of urban organic waste, bio-solids of sewage treatment plants together with green compost have been effectively tested as growing media in the industrial production of horticultural, forestry and ornamental seedlings (López *et al.*, 2005).

As composting technique has been expanding, each region/country has been testing the composting of its organic waste of silvo-agro industrial origin that has had more at hand. For instance, in Spain, the Lourizan Forestry Research Centre worked on composting of pine bark from sawmills (Miranda & Fernandez, 1992) to be used as growing media for forestry seedling. Later this bark-derived compost was used for the production of ornamental woody plants in container. In regions and countries where containerized ornamental production was important, this initiative was emulated by using organic materials from agro-industries. Such as in Valencia region (Spain) where an inventory of organic agro industrial by-products was carried out with the same goal of manufacturing substrates by composting aiming to utilize them in ornamental container production (Abad *et al.*, 2001). Some of these raw materials were included cork powder (Carmona *et al.*, 2003), two-phase olive oil mill waste ("alperujo") (Fernández-Hernández *et al.*, 2013), organic fraction of the guacamole industry (González-Fernández *et al.*, 2015), organic wastes of greenhouse horticultural production (Mendoza-Hernández *et al.*, 2014), citrus pulp (Gelsomino *et al.*, 2010), grape marc (Trillas *et al.*, 2006), brewery sludge (Sánchez-Monedero *et al.*, 2004), etc.

In vermicompost, researchers used different manures for their transformation by means of lombriculture techniques to identify products that could be used in horticulture. So, mainly pig manure (Atiyeh *et al.*, 2000; Arancon *et al.*, 2005; Bachman & Metzger, 2008; Lazcano *et al.*, 2009) and cattle manure (Tringovska & Dintcheva, 2012; Sultana *et al.*, 2015) were used and also sometimes green and vegetable crop wastes (Fornes *et al.*, 2012; Belda *et al.*, 2013; Morales-Corts *et al.*, 2014).

Peat based substrates were substituted at a 30-35% average ratio by compost and vermicompost in the experiences mentioned in Table 1. Both compost and vermicompost trials showed a beneficial effect related to substrate physical properties and different morphological parameters of the tested ornamental plants grown with these new materials. So, better growth (Do & Scherer, 2013; Mendoza-Hernández *et al.*, 2014; Sultana *et al.*, 2015) increases in shoot dry weight (SDW) (López *et al.*, 2003; Belda *et al.*, 2013; De Lucia *et al.*, 2013) and root collar diameter (RCD) (Álvarez *et al.*, 2001), better container capacity (CC) and water holding capacity (WHC) (Tyler *et al.*, 1993) were recorded in different experiments where the peat-based substrate was partially replaced by compost or vermicompost.

The list presented in Table 1 is not exhaustive and could be extended through other studies (Carrión *et al.*, 2007) where for instance, disease suppressive microorganisms which have been extracted from compost are able to colonize the surface and roots of plants when applied properly (Al-Mughrabi *et al.*, 2008).

Ansorena *et al.* (2014) also argued that it is necessary to consider the limitations that bio-waste compost presents as a component of substrates and as an organic fertilizer because of its high salinity and low N concentration. Another limiting property of the compost being used as substrate may be high alkalinity. To address the latter, elemental micronized sulphur is usually added to compost (Carrión *et al.*, 2005, 2008). Also compost stability may be a key factor when compost is used as growing media to produce ornamental plants in container, so only mature compost should be utilized (Raviv, 2008, 2014).

Biochar

Biochar is another organic amendment that has the potential to be used as growing media additive and as peat substitute. Biochar is defined as a solid by-product obtained from the thermochemical conversion of biomass in an oxygen-limited environment. The process relies on capturing the off-gases from thermal decomposition of organic materials to produce heat, electricity, or biofuels (Lehmann, 2007).

'Terra preta do Indio' Amazonian soils, characterized by high levels of soil fertility, described by Sombroek (1966) started a worldwide interest to search how biochar would help to mitigate climate change (Laird, 2008; Woolf *et al.*, 2010; Montanarella & Lugato, 2013). Addition of biochar to soils can result, on average, in increased above ground productivity, crop yield, nutrient availability, microbial biomass and rhizobia nodulation among a broad range of pedo-climatic conditions. The limited number of case studies showing a negative effect of biochar on crop yield are consolidating the idea that biochar has either a null or positive effect on crop productivity (Souchie *et al.*, 2011; Alburquerque *et al.*, 2013; Biederman & Harpole,

Table 1. Growing media researches where compost and vermicompost have been used as substrate components.

Substitute type	Growing media	Raw material	% rate v/v	Plant species	Effects[a]	Reference
Compost	peat based substrate	organic fraction of urban waste	25	*Pelargonium, Salvia*	better growth	Do & Scherer, 2013
Compost	peat based substrate	sewage sludge, yard trimming and organic fraction of urban waste	25, 50	*Rosmarinus officinalis*	root collar diameter (8 to 10)% greater than control	López *et al*., 2008
Compost	peat based substrate	sewage sludge and pruning rejects	55	*Bougainvillea*	60% increase SDW	De Lucia *et al*., 2013
Compost	pine bark substrate	turkey litter	up to 16	*Cotoneaster dammeri*	increased (12 to 16)% CC and (17 to 30)% WHC	Tyler *et al*., 1993
Compost	peat based substrate	green yard waste	20	*Solanum lycopersicum*	growth equal than control	Prasad & Maher, 2001
Compost	peat based substrate	nursery pruning	40	*Lantana camara, Rosmarinus officinalis*	higher overall quality	Russo *et al*., 2016
Compost	peat based substrate	pruning from *Olea europaea, Pinus* sp. and *Picea* sp. and *Lolium perenne* clippings	20	*Lycopersicon esculentum, Cucumis melo, Lactuca sativa*	better growth	Ceglie *et al*., 2015
Compost	peat based substrate	sludge, yard trimming and organic fraction of urban waste	20, 40	*Ceratonia siliqua, Olea europea, Quercus ilex*	RCD increased (23, 30 and 10)% respectively than control	Álvarez *et al*., 2001
Compost	peat based substrate	sludge and urban waste	20, 40	*Pistacia lentiscus*	(509 to 730)% higher SDW than control	López *et al*., 2003
Compost	peat based substrate	two-phase olive mill waste (71%) with olive leaves (29%) and urea (9 kg t^{-1})	25, 50	*Solanum lycopersicum, Citrullus lanatus*	better seed germination	Fernández-Hernández *et al*., 2013
Compost	peat based substrate	sweet sorghum bagasse, pine bark and brewery slude	up to 67	*Brassica oleracea*	similar growth	Sánchez-Monedero *et al*., 2004
Compost	peat based substrate	cow manure	10	*Solanum lycopersicum*	10% increase in roots volume	Lazcano *et al*., 2009
Compost	peat based substrate	pruning waste	100	no plants	pH > 8, OM similar, CEC higher than control	Benito *et al*., 2006
Compost	peat based substrate	crops waste sawdust and laying hen manure	25	*Solanum lycopersicum, Cucurbita pepo, Capsicum annuum*	better growth	Gavilanes-Terán *et al*., 2016
Compost	peat based substrate	acacia pruning	45	*Lactuca sativa*	better growth	Brito *et al*., 2015
Compost	peat based substrate	sewage sludge	30	*Brassica oleracea*	better growth	Perez-Murcia *et al*., 2006
Compost	peat based substrate	cork, grape marc, olive marc and spent mushroom	100	*Cucumis sativus*	better resistance to damping-off	Trillas *et al*., 2006
Compost	bark based substrate	organic fraction of urban waste	50	*Physocarpus opulifolius*	increased 60% SDW	Chong, 2005

Table 1. Continued.

Substitute type	Growing media	Raw material	% rate v/v	Plant species	Effects[a]	Reference
Vermicompost	peat based substrate	green and pruning wastes	30	*Petunia*	similar growth than control	Morales-Corts *et al.*, 2014
Vermicompost	peat based substrate	pig manure	30, 40	*Calendula officinalis*	more vegetative growth and flowers	Arancon *et al.*, 2005
Vermicompost	peat based substrate	chopped air-dried tomato-crop waste	75	*Calendula officinalis*	20% increase in SDW	Belda *et al.*, 2013
Vermicompost	peat based substrate	pig slurry	100	*Solanum lycopersicum*	15% increase roots volume	Lazcano *et al.*, 2009
Vermicompost	top soil	cattle manure	up to 10	*Passiflora edulis*	nursery commercial quality	Hidalgo *et al.*, 2009
Vermicompost	peat based substrate	from tomato crop waste	50	*Rosmarinus officinalis*	better growth	Mendoza-Hernández *et al.*, 2014
Vermicompost	dried sandy loam topsoil	cow manure	10	*Zinnia elegans*	better growth	Sultana *et al.*, 2015
Vermicompost	peat based substrate	pig manure	20	*Solanum lycopersicum*, *Calendula officinalis*	better growth	Bachman & Metzger, 2008
Vermicompost	peat based substrate	N/A	20	*Solanum lycopersicum*	similar emergence, growth and biomass allocation	Zaller, 2007
Vermicompost	peat based substrate	pig manure	20	*Solanum lycopersicum*	increased 12.5% fruit weight	Atiyeh *et al.*, 2000
Vermicompost	peat based substrate	cow manure	10	*Solanum lycopersicum*	60% increase in SDW	Tringovska & Dintcheva, 2012

[a] SDW: shoot dry weight; CC: container capacity; WHC: water holding capacity; RCD: root collar diameter.

2013; Carter *et al.*, 2013; Mulcahy *et al.*, 2013; Akhtar *et al.*, 2014; Thomazini *et al.*, 2015; Lima *et al.*, 2016; Olmo *et al.*, 2016).

In fact, the production of biochar from farm wastes and their application in farm soils offer multiple environmental and financial benefits (Srinivasarao *et al.*, 2013).

The priming effect concept was initially introduced by Bingeman *et al.* (1953) and may happen when biochar is added to soil. If used to describe C turnover it means an added decomposition of organic C following an inclusion of easily decomposable organic materials to the soil (Dalenberg & Jager, 1989). In the present study, the most prominent interest is related to the negative result of the priming effect of biochar because a higher retention of carbon in the substrate. No study to this effect has been found when biochar was added to peat based horticultural growing media. Nevertheless, there are several references of biochar incorporation in soil causing a negative priming effect in sandy soils which may be the most easily assimilated into the peat-based horticultural substrates (Lu *et al.*, 2014; Keith *et al.*, 2015).

Biochar has also been considered as a possible peat replacement in horticulture (Peterson & Jackson, 2014). It has shown potential as replacement for aggregates like peat moss in growing media (Sohi *et al.*, 2013). Adding biochar to growing media can result in several benefits in terms of substrate quality. Biochar generally has a high cation exchange capacity (CEC) and a high nutrient holding capacity, thereby reducing nutrient leaching. Biochar can also be considered as a source of nutrients (nitrate-N, K, Fe, Mn, and Zn) (Nemati *et al.*, 2015). This property must be taken into consideration during nutrient management planning. Most biochars are alkaline and can neutralize the acidity of a peat-based substrate, hence reducing lime requirements (Zaccheo *et al.*, 2014; Bedussi *et al.*, 2015). However, the increase of pH following a biochar application in growing media limits its application as its affects growth in plant´s germination (Buss *et al.*, 2016). In general, biochar has a low bulk density and when incorporated into a growing mix helps to reduce the risk of substrate compaction and related problems (Nemati *et al.*, 2015). Biochar can affect both water retention (Cao *et al.*, 2014) and substrate´s aeration properties depending on its particle size distribution. The incorporation of fine-textured biochar in growing media promotes water retention properties (easy and total available water) (Nemati *et al.*, 2015). Biochar particle size distribution is affected by type of biomass and the pyrolysis temperature. Choosing a biochar with the right particle size distribution is important in producing a growing mix with the desired physical properties. High-temperature biochars can bind soil-C and other nutrients on a long-term basis. In addition, higher temperature biochars have higher surface area and more micropore volumes than those of lower temperature biochars (Mukherjee & Lal, 2013).

One of the main limiting factors to the use of biochar in the growing media industry is the production of black dust during handling. Increasing the initial water content of biochar or using pelleted biochar can overcome the dust issues (Dumroese *et al.*, 2011).

It has also been reported in some phytopathological studies that biochar and its associated microorganisms have a suppressive effect on plant diseases similar to those possessed by the compost (Elad *et al.*, 2010; Elmer & Pignatello, 2011; Kolton *et al.*, 2011; Zwart & Kim, 2012; Gravel *et al.*, 2013).

Several successful propagating ornamental plant experiments have been reported where peat and some other components were replaced by biochar (see Table 2). The inclusion of biochar into substrates showed that plant´s quality and growth were similar to those from the standard peat substrates. Besides, some extra benefits were also observed in reducing nutrients and water loss, decreasing substrate bulk density, and creating a beneficial environment for microorganisms. In these experiments the peat-based substrate was substituted by biochar at a 20 to 25% average ratio (Table 2).

The wide range of raw materials to produce biochar include wood, bark and remains of coniferous (Zwart & Kim, 2012; Gravel *et al.*, 2013; Gu *et al.*, 2013; Fascella, 2015; Dispenza *et al.*, 2016) deciduous trees (Graber *et al.*, 2010; Elmer & Pignatello, 2011; Northup, 2013; De Tender *et al.*, 2016), agricultural (Dumroese *et al.*, 2011; Sharkawi *et al.*, 2014; Vaughn *et al.*, 2015a; Kim *et al.*, 2016) and gardening residues (Tian *et al.*, 2012; Nieto *et al.*, 2016) and biosolids (Méndez *et al.*, 2016). The benefits derived from the addition of biochar included improvements of morphological parameters of plants growth but also those of the physical (Kaudal *et al.*, 2015; Dumroese & Landis, 2016), chemical (Altland & Krause, 2012; Kaudal *et al.*, 2015) and biological (Elmer & Pignatello, 2011) properties of the substrate and the resistance of plants to fungal infections (Elad *et al.*, 2010; Zwart & Kim, 2012).

Carbon footprint reduction in containerized ornamental plants production

Several LCA (Life Cycle Assessment) studies have been conducted in different regions to determine which materials and activities contribute more to the GHG effect in ornamental horticulture. One of these studies assessed the material and energy inputs required to produce a *Petunia* × *hybrida* plant from initial propagation to delivery at a regional distribution centre. Impacts were expressed in terms of their contributions to the carbon footprint or global warming potential of a single finished plant in a 10-cm diameter container. Results showed that peat consumption represented 7.7% of the overall CO_2e (carbon dioxide equivalent) emissions (Koeser *et al.*, 2014).

Two LCA studies conducted in Italy (De Lucia, 2013; Vecchietti *et al.*, 2013) considered compost as growing media substitute. The use of different rates of sewage sludge compost in the preparation of growing media for potted *Bougainvillea* was evaluated to assess its efficiency for the replacement of peat and to quantify the environmental impact of such alternative substrates. The data from LCA showed that the addition of compost reduced the environmental impact of the plant nursery. Specifically, the use of compost reduced ODP (ozone layer depletion index) by 23-42% and also the primary non-renewable energy consumption index by 40-80% when compost was added to the mixture (as 25%-70% of compost inclusion respectively in both indexes).

Altieri & Nicholls (2012) and Martínez-Blanco *et al.* (2013) reported the positive effects of compost application as nutrient supply and carbon sequestration and also opined that the benefits were quantifiable, and tools for their consideration with LCA were available. Regarding the supply of plant nutrients, between 5 and 60% of the N applied with compost was mineralized, depending on the time frame considered. Figures range between 35 and 100% for P and between 75 and 100% for K. Carbon sequestration rates have shown to be higher in the short term (up to 40% of the applied C) and decreasing to 2–16% over a 100-year period (Martínez-Blanco *et al.*, 2013). Hence, those benefits should be regularly included in LCA studies, although their quantification needs to be improved.

Russo *et al.* (2008), in another LCA study on cyclamen in container production reported that as the peat is a non-recyclable organic material, it can find a substitute in the green composts obtained by the treatment of municipal garden green wastes and pruning wastes.

Finally, another study, conducted in Germany reported the amount of reduced GHG emissions by substitution of peat with biochar. This substitution could

Table 2. Growing media researches where biochar has been used as substrate component.

Substitute type	Growing media	Raw material	% rate v/v	Plant specie	Effects[a]	Reference
biochar	peat based substrate	*Pinus* sp wood	5, 10, 15, 20, 25 and 30	*Gomphrena 'Fireworks'*	similar growth as control	Gu *et al*., 2013
biochar	peat based substrate	*Pinus* sp wood	5, 10, 20	*Acer rubrum, Quercus rubra*	alleviate disease progression and physiological stress caused by *Phytophthora* canker pathogens	Zwart & Kim, 2012
biochar	peat based substrate	*Abies alba, Larix decidua, Picea excels, Pinus nigra*	60	*Euphorbia* × *lomi*	better growth	Dispenza *et al*., 2016
biochar	peat based substrate	*Quercus ilex* wood	3% w/w	*Fragaria* × *ananassa*	160% increase in SDW	De Tender *et al*., 2016
biochar	peat based substrate	hardwood	20, 30, 40	*Calendula officinalis, Petunia* × *hybrida, Impatiens*	SDW similar or greater than control	Northup, 2013
biochar	peat based substrate	hardwood dust	10	*Asparagus*	increased arbuscular mycorrhizal root colonization	Elmer & Pignatello, 2011
biochar	peat based substrate	hardwood pellets and pelletized wheat straw	10,15	*Calendula officinalis*	increased plant height	Vaughn *et al*., 2013
biochar	peat based substrate	*Abies balsamea, Picea glauca* and *Picea mariana* softwood bark	50	*Pelargonium hortorum*	similar growth as control	Gravel *et al*., 2013
biochar	peat based substrate	crushed wooden boxes	25, 50, 75	*Helianthus annuus*	similar growth as control	Steiner & Harttung, 2014
biochar	peat based substrate	pruning residue	50, 75	*Lactuca sativa*	better growth as control	Nieto *et al*., 2016
biochar	peat based substrate	green waste	50	*Calathea rotundifola* cv. Fasciata	22% total biomass increase	Tian *et al*., 2012
biochar	peat based substrate	biomass	1, 5, 10	no plants	moderation of extreme fluctuations of nitrate levels	Altland & Locke, 2012
biochar	peat based substrate	agricultural or forestry residues	25	no plants	enhanced hydraulic conductivity and greater water availability	Dumroese *et al.*, 2011
biochar	peat based substrate	biosolids	10	*Lactuca sativa*	better growth as control	Méndez *et al*., 2016
biochar +digestate	peat based substrate	wood pellets, pelletized wheat straw and field pennycress presscake + potato anaerobic digestate	25	*Solanum lycopersicum, Calendula officinalis*	increased growth of tomato plants and equal marigold as compared to control	Vaughn *et al*., 2015a

Table 2. Continued.

Substitute type	Growing media	Raw material	% rate v/v	Plant specie	Effects[a]	Reference
biochar	peat based substrate	conifers wood	60	*Euphorbia* × *lomi*	higher stem diameter, leaves area, root length and number of flowers than control	Fascella, 2015
biochar	coco fiber	forestry and gardening waste	10	*Calendula officinalis, Petunia × hybrid*	better growth as control	Fornes *et al*., 2013
biochar	coconut fiber and tuff	*Citrus* wood	5	*Capsicum annuum, Solanum lycopersicum*	better pepper growth and enhanced tomato plant height and leaf size.	Graber *et al*., 2010
biochar	coconut fiber-tuff	*Citrus* wood	1, 3, 5% w/w	*Capsicum annuum, Solanum lycopersicum*	resistance against two foliar fungal pathogens (*B. cinerea* and *L. taurica*)	Elad *et al*., 2010
biochar	coir peat	biosolids and greenwaste	up to 60	no plants	similar physical and chemical benefits than control	Kaudal *et al*., 2016
biochar	coir peat+pine bark compost	biosolids and greenwaste	20, 40, 60	no plants	desirable physical properties such as high water holding capacity, low bulk density, air filled pore space and high surface area	Kaudal *et al*., 2015
biochar	rice husk	rice husk	25	*Cucumis sativus*	better growth as control	Sharkawi *et al*., 2014
biochar	coir dust, perlite and vermiculite	rice husk	5% w/w	*Brassica oleracea*	150% increase in SDW	Kim *et al*., 2016

[a] SDW: shoot dry weight.

avoid emissions of up to 4.5 Mg of CO_2e by each Mg of peat substituted (2.8 Mg CO_2/Mg by biochar inclusion plus 1.7 Mg CO_2 Mg by peat substitution) (Steiner & Harttung, 2014).

In the studies and experiments mentioned above, peat based substrates were substituted at a 30-35% average ratio by compost and vermicompost and 20-25% by biochar. We have calculated reduced GHG emissions by considering these substitution ratios as well as average bulk density levels of peat based growing media, compost/vermicompost and biochar. We have taken into account that every year about 11 Tg of peat are consumed in horticulture. If 20% of worldwide peat used in horticulture would be in containers production, about 3 Tg CO_2e will be the C potential storage per year that this container productive sector will be able to generate when peat based growing media has been substituted as above mentioned.

Research gaps

Globally, there is a lack of information about the total volume of materials used in growing media in countries with an important production in South and North America, Australia and Southeast Asia (Carlile, 2008; Schmilewski, 2017).

Research on how to use compost and vermicompost as partial replacement of peat based growing media to produce ornamental plants has been more addressed by research studies (Raviv *et al*., 1986; Edwards & Burrows, 1988; Carrión *et al*., 2007) than the use of biochar. There are also a number of research gaps about how to combine either compost or vermicompost with biochar to substitute peat in this ornamental horticulture industry. That is why we have tried below to identify potential research projects able to get answers to the pending questions.

Assuming that biochar is a panacea without strong scientific evidence and credible data, may aggravate controversies and dilemmas (Perry, 2011; Mukherjee & Lal, 2013; Lal, 2015). This is a key point considering biochar's characteristics variability due to raw materials and production systems (Lorenz & Lal, 2014). For instance, in some studies identical biochars produced different results with different plant species (Vaughn *et al.*, 2015c). Some but not all biochars have been shown to improve water retention and increase overall plant growth in sand-based rooting media. Impact of biochar on improvement of water retention and increase overall plant growth in sand-based root zones may happen with some but not with all biochars (Vaughn *et al.*, 2015b). Also, it would be necessary to identify from which tree species or type of waste material biochar would be most desirable for use in horticultural potting substrates (Vaughn *et al.*, 2015a).

Results from some biochar studies begin to provide evidence of mitigation strategies, which can be implemented in container plant production to help growers benefit from C offset programs, adapt to future legislation, and improve the environmental impact from container plant production without negatively affecting crop growth (Marble *et al.*, 2012). So, more product carbon footprint analyses are necessary to map out the climate impact in different horticultural production systems (Soode *et al.*, 2015). It would be also useful to know what CO_2 percentage could ornamental horticulture represent respect to global horticulture production.

Additionally, there are some experiments that demonstrate the synergy of combining biochar with compost in soil (Schmidt *et al.*, 2014). This positive association is caused mainly because the combination of both materials improved its fertility, not only in a short time span, but also on a medium and long term basis (Fischer & Glaser, 2012). Compost and vermicompost have shown a good synergy with biochar, but literature about this combination in ornamental horticulture is rather scanty. Just one study using vermicompost and biochar to produce ornamentals in containers was found (Alvarez *et al.*, 2017). Both materials were mixed with no prior composting. A complete set of 24 combinations, where a peat-based substrate was partially replaced by 0 to 50% of dairy manure vermicompost and 0 to 12% of biochar produced by pyrolysis of *Pinus monticola* wood at high temperature (600 to 800 ºC). Better *Petunia hybrida* and *Pelargonium peltatum* plant growth and flowering was obtained in some of the mixtures of biochar/vermicompost with no more than 30% of vermicompost content than in the control group. Even if most plant responses are related to morphological parameters it would be interesting to also test physiological parameters as they may provide results regarding plants growth after transplanting into soil (Alvarez *et al.*, 2018).

There are some other studies where that kind of mix was applied to soil and assessed plant or soil responses (Schulz & Glaser, 2012; Ngo *et al.*, 2013; Rodríguez-Vila *et al.*, 2014). So, more experience combining compost or vermicompost with biochar to substitute peat-based substrates in ornamental horticulture should be promoted to learn whether their synergy would be interesting for the industry and with the objective of carbon sequestration. There are a number of publications where biochar was added to other organic materials to be co-composted or composted together and a synergy was evident during this combined process enhancing the final compost produced. Even if there is no evidence yet of the proven results when using this kind of final product to replace peat in ornamental production, these trends are briefly discussed herein because it would be pertinent to research this subject (Dias *et al.*, 2010; Jindo *et al.*, 2012, 2016; Schulz *et al.*, 2013; Antonius *et al.*, 2015; Barthod *et al.*, 2016; Malińska *et al.*, 2016).

The ornamental containerized plant sector needs to develop a better understanding of plant nutrient requirements, better technology to assess root zone conditions, and better fertilizers or practices that would be able to match ornamental plant nutrient requirements during the growing season in containers. With a satisfactorily resolution of this sector, Majsztrik *et al.* (2011) and Raviv (2013) concluded that horticulture can provide ecological services such as efficient and long-term carbon sequestration, while restoring soil fertility through the use of organic amendments. In this context evaluating how to include compost, vermicompost and biochar (and their mixes) may minimize leaching of nutrients from containers due to irrigation. This subject is also a researchable priority.

As Nemati *et al.* (2015) commented, compost, vermicompost and biochar are still not a standardized product, and its properties may differ depending on the source or the production process. The growing media industry cannot accept these variations and requires a high quality, homogenous, and consistent components. Therefore, it is important to launch a standardization program to certify those materials which meet quality standards for use in the growing media industry. In this sense, it is important to bridge the gap between research findings and commercial production of ornamental plants by assessing the experimental results at a commercial scale (Vaughn *et al.*, 2015c; Derrien *et al.*, 2016).

Economically, biochar has a greater potential to replace aggregates than peat in growing media mainly due to the high cost of these aggregates compared with that of the peat. Additional research is needed to evaluate the impact of biochar on growth and development of plants.

Conclusions

The use of organic materials as compost, vermicompost, and biochar as peat substitutes in the ornamental containerized bedding plant production, is an interesting biotic strategy to store carbon in garden soil. In the case of biochar the stored C could be maintained for centuries improving the life cycle analysis of this process.

Several studies have produced interesting results, but additional research is needed to evaluate those materials and how to combine them as compost-biochar or vermicompost-biochar which may produce similar or better plants while also similarly or better support the transplanting process.

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