Scientia Horticulturae 193 (2015) 225–230

Contents lists available at ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

The effect of paper sludge and biochar addition on brown peat and coir based growing media properties

A. Méndez[a], J. Paz-Ferreiro[b], E. Gil[a], G. Gascó[c,*]

[a] Departamento de Ingeniería Geológica y Minera, E.T.S.I. Minas y Energía, Universidad Politécnica de Madrid, C/Ríos Rosas n°21, 28003 Madrid, Spain
[b] School of Civil, Environmental and Chemical Engineering, RMIT University, GPO Box 2476, 3001 Melbourne, VIC, Australia
[c] Departamento Producción Agraria, E.T.S.I. Agrónomos, Universidad Politécnica de Madrid, Ciudad Universitaria, 28004 Madrid, Spain

ARTICLE INFO

Article history:
Received 8 April 2015
Received in revised form 8 July 2015
Accepted 17 July 2015

Keywords:
Peat
Coir
Biochar
Deinking sludge
Growing media

ABSTRACT

Peatlands are crucial sinks for carbon in the terrestrial ecosystem, but they are jeopardized by their use as fuel or as growing media. Much research has been performed aiming to find high quality and low cost substrates from different organic wastes, such as coir, compost, sewage or paper sludges, and thus decrease peat consumption. The main objective of this work is to study the effect on peat and coir-based growing media of deinking sludge (*R*) and biochar obtained by pyrolysis of deinking sludge at 300 °C (B300). For this reason, mixtures of peat or coir with deinking sludge and corresponding biochar were prepared mixing them at 50/50 *v*/*v* ratios. The results showed that it is possible to improve the chemical and hydrophysical properties of peat and coir with addition of biochar and deinking sludge. Indeed, biochar increased air space, water holding capacity and total porosity of peat-based growing media whereas for coir, the best hydrophysical properties were obtained after deinking sludge addition. Finally, the use of biochar plus peat as growing media can increase lettuce yield by more than 100% with respect to peat growing media, which can be related with the improvement of hydrophysical growing media properties. This yield increment along with the reduction of the over-exploitation of peat can justify the use of biochar as growing media in spite of the cost associated to the pyrolysis process.

1. Introduction

Agricultural production through greenhouse cultivation is today, one of the most widely techniques used to increase agricultural yields due to the control of production factors such as watering, fertilizing, relative humidity, irradiance or the quality of growing media (Fei et al., 2008). Growing media or substrates include all materials that can be used to grow plants in a variety of production systems, such as greenhouse cultivation, containerised ornamental plant production, urban agriculture or green roof (Cao et al., 2014). Peat alone or blended with inorganic components such as vermiculite; perlite and sand (Bilderback et al., 2005) has been traditionally used as substrate material because of the excellent combination of peat properties such as low pH, high interchange cationic ability or adequate porosity (Robinson and Lamb, 1975). Peat is obtained from peatlands that cover an estimated area of 400 million ha, equivalent to 3% of the Earth's land surface. Most of them, approximately 350 million ha, are in the northern hemisphere, covering large areas in North America and Eurasia. Peatlands globally represent a major store of soil carbon, sink for carbon dioxide and source of atmospheric methane. Northern peatlands store around 450 billion metric tons of carbon, which is equivalent to approximately one third of the global soil carbon stock (Strack, 2008).

Peat is a non-renewable resource; that fact combined with increasing peat price have created a need for locating alternative growing media materials (Abad et al., 2001; Boldrin et al., 2010; Cleary et al., 2005; Holmes et al., 2000). A number of studies have shown that several organic residues such as urban solid wastes, plant wastes, sewage sludges, paper wastes, spent mushroom, coconut coir and even green wastes, after proper composting, can be used with variable results as growing media in lieu of peat (Abad et al., 2005; Chong, 2005; Garcia-Gomez et al., 2002; Maher et al., 2007; Méndez et al., 2011; Ostos et al., 2008).

Nowadays, the main attention has been focused on the potential biochar use in growing media formulation. Biochar is a solid carbon-rich material obtained from pyrolysis of biomass. Biochar production has attracted widespread attention as soil amendment

* Corresponding author.
E-mail address: gabriel.gasco@upm.es (G. Gascó).

http://dx.doi.org/10.1016/j.scienta.2015.07.032
0304-4238/

(Enders et al., 2012; Lehmann and Joseph, 2009) and, only in recent years, as growing media component (Dumroese et al., 2011; Vaughn et al., 2015a,b; Zhang et al., 2014). Vaughn et al. (2015a) studied the use of biochar from several feedstocks as replacements for inorganic components such as vermiculite and perlite and digestate to replace organic components such as peat. They deduced that biochar can substitute peat in levels lower than 15% (*v*/*v*). Zhang et al. (2014) concluded that the highest quality growth medium and the highest quality ornamental plant growth was achieved mixing composted green waste with 30% of biochar and 0.7% of humic acids. Dumroese et al. (2011) found that pelletized biochar worked well when substituted for peat at a rate of 25% (*v*/*v*) but at higher levels lead to unsatisfactory results possibly due to high *C*/*N* ratios. Due to the small number of biochar types that have been considered as peat substitutes, there is a lack of information concerning their suitability for this use. Green wastes have been transformed into biochar in order to study their suitability for growing media (Tian et al., 2012). However, there is an imperative need to perform wider studies that take into account the intrinsic characteristics of the different biochars and the ratios the ratios of biochar to peat in order to produce good peat substitutes.

It is well known that properties depend greatly on the raw materials and pyrolysis conditions (Cantrell et al., 2012; Hossain et al., 2011; Masek et al., 2013; Méndez et al., 2013; Song and Guo, 2012). Temperature in one of the most significant parameters in the pyrolysis process of organic materials and consequently, it has a great influence on the chemical and physical properties of the biochar (Hossain et al., 2011; Masek et al., 2013; Méndez et al., 2013). Song and Guo (2012) studied the effect of pyrolysis temperature on poultry litter biochar and found that for agriculture use, the temperature of biochar production should be between 300 and 500 °C, whereas, for carbon sequestration and other environmental uses, temperatures higher than 500 °C were suggested. Yuan and Xu (2011) recommended the use of low temperature for the amendment of acid soils using biochar from crop residues. Taking into account the above mentioned considerations, the main objective of the present work is to study the performance of biochar from slow pyrolysis of deinking sludge at low temperature (300 °C) as component of peat and coir-based growing media for horticultural production.

2. Materials and methods

2.1. Selection and preparation of raw materials

The raw materials used in this study were deinking sludge (*R*), biochar obtained from deinking sludge pyrolysis at 300 °C (BR300), commercial brown peat (*T*) and coir (*C*). Biochar was prepared as follows: approximately 200 g of deinking sludge was placed in a covered steel cup and introduced in an electric furnace. The temperature was increased at 10 °C min^{-1} until 300 °C was reached and maintained for 2 h, leading to BR300.

2.2. Preparation of growing media

Mixtures of peat or coir with deinking sludge and corresponding biochar were prepared mixing them at 50/50 *v*/*v* ratios. Individual raw materials were used as control. Table 1 summarizes the formulation of the different growing media tested in the present work.

2.3. Chemical and physical properties of growing media

The growing media were characterized as follows:

pH and EC were determined in a ratio sample:water 1:10 (weight:volume) using a Crison micro-pH 2000 and a Crison 222 conductivimeter for pH and EC determination, respectively (Thomas, 1996; Rhoades, 1996).

Table 1
Composition and formulation of different growing media.

Growing media	Components	Formulation (*v*/*v*)
T	Peat	100
C	Coir	100
R	Deinking sludge	100
BR300	Biochar from R at 300 °C	100
T–*R*	Peat/deinking sludge	50/50
T-BR300	Peat/biochar	50/50
C–*R*	Coir/deinking sludge	50/50
C-BR300	Coir/biochar	50/50

Cation exchange capacity (CEC) was determined with $NH_4OAc/HOAc$ pH 7.0 (Sumner and Miller, 1996). Later, Na, K, Ca and Mg in the extract were determined with a PerkinElmer AAnalyst 400 Atomic Absorption Spectrophotometer. N Kjeldahl content was analyzed by the Kjeldahl method (Bremner, 1996).

Extractable P was determined by the Olsen method (Watanabe and Olsen, 1965). One gram of sample and 20 mL of 0.5 M sodium bicarbonate ($NaHCO_3$) solution were shaken for 30 min. Blue color in the filtered extract is developed with molybdate- ascorbic acid reagent and measured with a Shimadzu UV-1203 spectrophotometer at 430 nm.

Organic carbon was analyzed by the Walkley–Black method (Nelson and Sommers, 1996). Oxidizable matter in the sample is oxidized by 1N of $K_2Cr_2O_7$ solution. The reaction is assisted by the heat generated when 2 volumes of H_2SO_4 are mixed with 1 volume of $K_2Cr_2O_7$. The remaining dichromate is titrated with ferrous sulphate.

Proximate analysis of individual raw materials (*T*, *C*, *R* and BR300) was performed by heating samples in an electric furnace. First, weight loss at 105 °C during 24 h was used to calculate the moisture content; following, air treatment at 600 °C in a non-oxidizing atmosphere was used to measure the volatile matter. At this temperature sample was oxidized with air. The remaining weight is the ash content, whereas fixed carbon was calculated by difference.

Also, the hydrophysical properties of the different substrates were determined by using the following methodology: A container of known volume with a drainage hole sealed at the bottom was filled with the growing medium and slowly completely saturated by gradually pouring water onto the surface. Then, the container was placed over a watertight pan and the seal was removed from the container drain hole to allow all the free water to drain out of the container over 10 min. By recording the volume of water that drains, it is possible to determine the container volume filled with air, and hence air space. Afterwards, the entire content of saturated growing medium was weighted, placed in an aluminum pan, and completely dried in 105 °C oven for 24 h. By recording the weight of the media after removing from the oven we calculated the amount of water that is dried off the media, and therefore, the volume of water held by the media (water holding capacity). The total porosity was calculated as the addition of the air space and the water holding capacity. Although there are no universal standards for substrate physical properties, there are ranges in which most potting substrates utilized in the commercial production of horticultural crops fall such as container capacity from 45 to 65%, air space from 10 to 30% (Yeager et al., 1997) and total porosity values from 50 to 85%. The bulk density of an ideal substrate should be lower than 0.40 g cm^{-3} (Abad et al., 2005). Table 2 shows acceptable range of some physical and chemical properties for container media.

Particle size distribution of the raw materials was determined by passing 50 g of dried samples through a nest of sieves (2.0 mm, 1.0 mm and 0.5 mm mesh). The material retained on each sieve

Table 2
Acceptable range of physical and chemical properties for container media (Abad et al, 2005; Abad et al., 2001; Robbins and Evans, 2013; Yeager et al., 1997).

pH	EC (μS/cm)	CEC (mmol(+)/100g)	P (mg/kg)	Bulk density (kg/m^3)	Air Space (%)	Water holding capacity (%)	Total porosity (%)
5.0–6.5	<500	200	5–50	400	10–30	60–100	50–80

EC: electrical conductivity; CEC: cation exchange capacity Table 3. Dry Mass of raw materials used in growing media formulations.

was weighed and coarseness index (CI) expressed as percentage of particles >1 mm was determined (Jayasinghe, 2012).

2.4. Germination test

Germination test was carried out in triplicate as follows. The germination test was carried out (in triplicate) on filter paper in Petri dishes. 10 mL of aqueous extract (1/10 *w*/*v*) from *R*, BR300, *T* and *C* were added to the dishes. Ten lettuce seeds (*Lactuca sativa* L.) were placed on the filter paper and the Petri dishes were placed in a dark chamber set at 21 °C. Germination percentages and root length were assessed after 48 h. The germination index (GI) was calculated as GI (%) = %G × Le/Lc, where %G is the percentage of germinated seeds in each extract with respect to control; Le is the mean total root length of the germinated seeds in each extract and Lc is the mean root length of the control (Zucconi et al., 1985).

2.5. Plant growth experiments

Lettuce plants were established in 150 cm^3 pots, and filled 3/4 of their volume with a respective substrate. Then, six seeds of lettuce were placed in each pot (by triplicate) and the pots were introduced in an incubator 12 h light/dark cycle and constant temperature of 25 °C for 4 weeks. During this time, samples were regularly watered with distilled water and number of emerged seedlings was recorded. Neither pesticides nor fertilizers were applied before or during the study. After this period, stem length and root length of plants were measured. Entire plants were dried at 85 °C for 24 h and after, whole plant weight and shoot and root weights were obtained.

2.6. Statistical analyses

All statistical analyses were done using Statgraphics Centurion XVI (Statpoint Technologies, Warrenton, USA). Differences of means were tested using an analysis of variance (ANOVA). Means were considered to be different when $P < 0.05$ using the Tukeyís test.

3. Results and discussion

3.1. Chemical properties

Table 3 shows the results of the proximate analysis for the raw materials used in this experiment. Analysis of raw materials used in the growing media indicated that R and BR300 had higher content of ash, compared to *T* and *C*, whereas the latter had higher content of volatile organic matter (Table 2). Deinking sludge (*R*) and corresponding biochar (BR300) had basic pH (Table 3) whereas peat (*T*) and coir (*C*) showed slightly acid pH (6.8 and 6.0, respectively). The electrical conductivity (EC) is an important parameter for the use of materials as growing media, because salinity represents the main limiting factor for germination and plant growth (Bustamante et al., 2008; Gascó et al., 2005). EC of raw materials varied from 40.0 μS cm^{-1} to 65.7 μS cm^{-1} for *T* and *R*, respectively. All EC values were under the suggested reference level for an ideal growing media (Table 2, Abad et al., 2001).

Table 3
Dry Mass of raw materials used in growing media formulations.

Raw material	Proximate analysis, dry mass (wt%)		
	VM	FC	Ash
T	70.5 ± 6.3	8.3 ± 0.3	21.2 ± 2.0
C	62.8 ± 4.7	21.1 ± 1.7	16.1 ± 1.5
R	35.1 ± 1,6	0.6 ± 0.1	64.4 ± 5.5
BR300	11.5 ± 0.6	13.0 ± 0.9	75.5 ± 5.8

VM: volatile matter; FC: fixed carbon.

Cation exchange capacity (CEC) is a measure of the ability of the growing medium to adsorb exchangeable cations which are available to the plant and will resist the leaching of nutrients during watering. The highest CEC correspond to *T* and *C* whereas lowest values correspond to *R*. Pyrolysis of deinking sludge slightly increased CEC. There was not significant differences in the carbon content ($C_{K_2Cr_2O_7}$) of *T* and BR300 materials. This content was lower than carbon content of coir (*C*) and deinking sludge (*R*). After pyrolysis of deinking sludge, data summarised in Tables 3 and 4 showed that biochar BR300 is a more stable carbon material than the original deinking sludge R with higher fixed carbon and lowest volatile matter and oxidisable carbon.

The highest $N_{kjeldhal}$ content corresponded to *T* and the lowest for *C*, whereas *R* and BR300 showed intermediate *N* values. Concluding, addition of BR300 and *R* to *C* treatments could improve their *N* content, whereas for *T* their mixture with R and BR300 will not produce an excessive *N* decrement. Also, the use of BR300 on growing media would increase the content in other nutrients, such as K and Ca, which are necessary to crop growth.

3.2. Hydrophysical properties

Hydrophysical properties of raw materials and growing media are given in Table 5. As indicated in Table 5, the bulk densities of all raw materials and corresponding mixtures were within the ideal range. The highest value corresponded to BR300 whereas coir

Table 4
Main properties of raw materials used in growing media formulation.

Growing media	pH	EC (μS/cm)	CEC (mmol(+)/100g)	($C_{K_2Cr_2O_7}$) (wt%)	$N_{kjeldhal}$ (wt%)	P (mg/kg)	Na (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (g/kg)
T	6.8a	40.0a	103a	14.3a	0.5a	38.1a	900a	500a	11600a	500a
C	6.0b	61.3b	93.2b	32.9b	0.02b	9.9b	2700b	8300b	2000b	500a
R	8.2c	65.7b	9.1c	27.1c	0.3c	2.4c	4700c	1300c	17000c	300b
BR300	8.8d	54.0c	12.8d	15.0a	0.3d	3.9d	5900d	1600d	18500d	300b

EC: electrical conductivity; CEC: cation exchange capacity; ($C_{K_2Cr_2O_7}$): carbon content.
Values in columns followed by the same letter are not significantly different at the 0.05 level ($P = 0.05$). Means are based on 3 replicates. Mean separation was performed using Duncan's multiple range test.

Table 5
Main hydrophysical properties of growing media.

Materials	Bulk density (kg/m^3)	Air Space (%)	Water holding capacity (%)	Total porosity (%)
T	160a	7.9a	63.2a	71.2a
C	140a	11.1b	70.6b	81.8b
R	230b	14.1c	44.2c	58.3c
BR300	390c	10.0d	56.6d	66.7e
T+*R*	260b	9.1d	51.4d	60.5c
T+BR300	300d	10.3d	76.1e	86.4d
C+*R*	170a	16.7e	59.5a	76.2ab
C+BR300	230b	6.7b	80.9e	87.6d

Values in columns followed by the same letter are not significantly different at the 0.05 level ($P = 0.05$). Means are based on 3 replicates. Mean separation was performed using Duncan's multiple range test.

Table 6
Particle-size distribution of raw materials (weight%).

Materials	>2.0 mm	1.0–2.0 mm	0.5–1.0 mm	<0.5 mm	CI(<1)
T	8.8a	36.2a	38.8a	16.2a	45.0a
C	2.4b	17.1b	31.7b	48.8b	19.5b
R	62.4c	16.5b	0.9c	20.2c	78.9c
BR300	29.0d	9.7c	29.0b	32.3d	38.7d

Values in columns followed by the same letter are not significantly different at the 0.05 level ($P = 0.05$). Means are based on 3 replicates. Mean separation was performed using Duncan's multiple range test.

showed the lowest. Addition of biochar increased the bulk density of peat and coir based growing media. The selected peat (classified as brown peat) showed lower air space than ideal substrates. Addition of deinking sludge and specifically biochar increased air space to values close to suggested values for ideal substrates. Total porosity of all substrates was on the ideal range (see above). Also, biochar addition increased water holding capacity, i.e., a 20% with respect to peat and a 14.5% with respect to original coir. These results are in accordance to Zhang et al. (2014) who studied the effect of biochar and humic acid amendment on the quality of composted green waste as growing media and found that biochar addition combined with humic acids increased the water holding capacity and porosity of composted green wastes. However, these results were different to that obtained by Tian et al. (2012) who found that addition of a green waste biochar at 50% to a peat moss medium (with air space of 25.95%) had no effect on the total porosity or container capacity but significantly decreased air space. Vaughn et al. (2015b) prepared biochar-digestate based substrates with physical values into suggested ranges for total porosity. However, their values for air space and container capacity were higher and lower than the reference values. Differences among our study and previous studies (Tian et al., 2012; Vaughn et al., 2015a) could be due to the smaller particle size for the biochars used in our experiment (Table 4) and the specific characteristics of the peat used (brown peat with low air space that increases with biochar addition). The particle-size distribution of a growth medium is important because it determines pore space, gas exchange and water-holding capacities (Abad et al., 2001). Jayasinghe (2012) reported that an excess of larger particles may lead to excessive aeration and inadequate water retention and that an excess of fine particles may clog pores and decrease air-filled porosity. Growth media with a high percentage of particles between 0.25 and 2.00 mm are optimal for potted plants (Jayasinghe, 2010). Jayansinghe (2012b) established that CI for ideal medium should be between 30 and 45 wt%. Table 6 summarizes the particle-size distribution of the raw materials. BR300 and T showed CI values within the range for an ideal medium. However, C and R showed an excess of fine and larger particles, respectively.

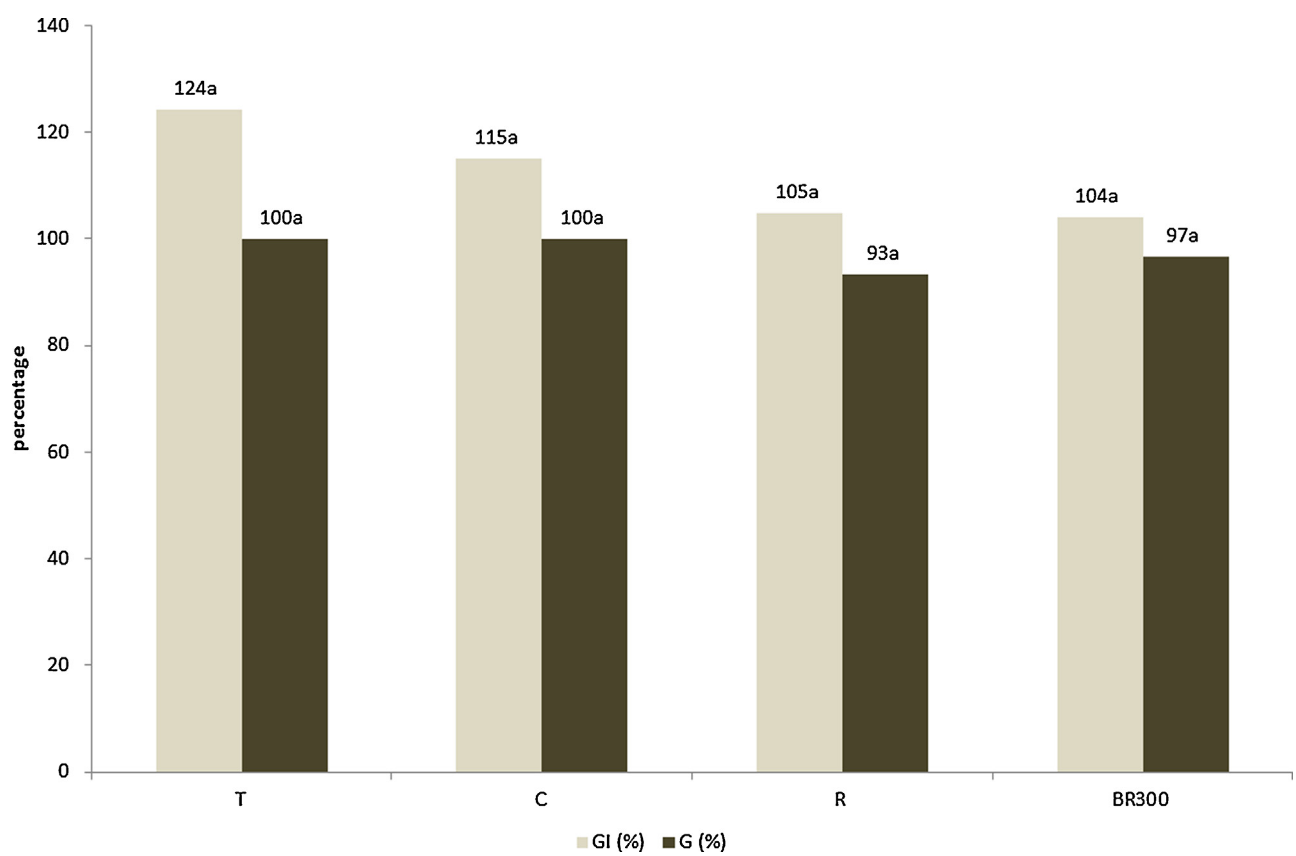

Fig. 1. Percentage germination (G, %) and germination index (GI, %) of Lactuca sativa seeds geminated in extracts of peat (*T*), coir (*C*), deinking sludge (*R*) and biochar (BR300).

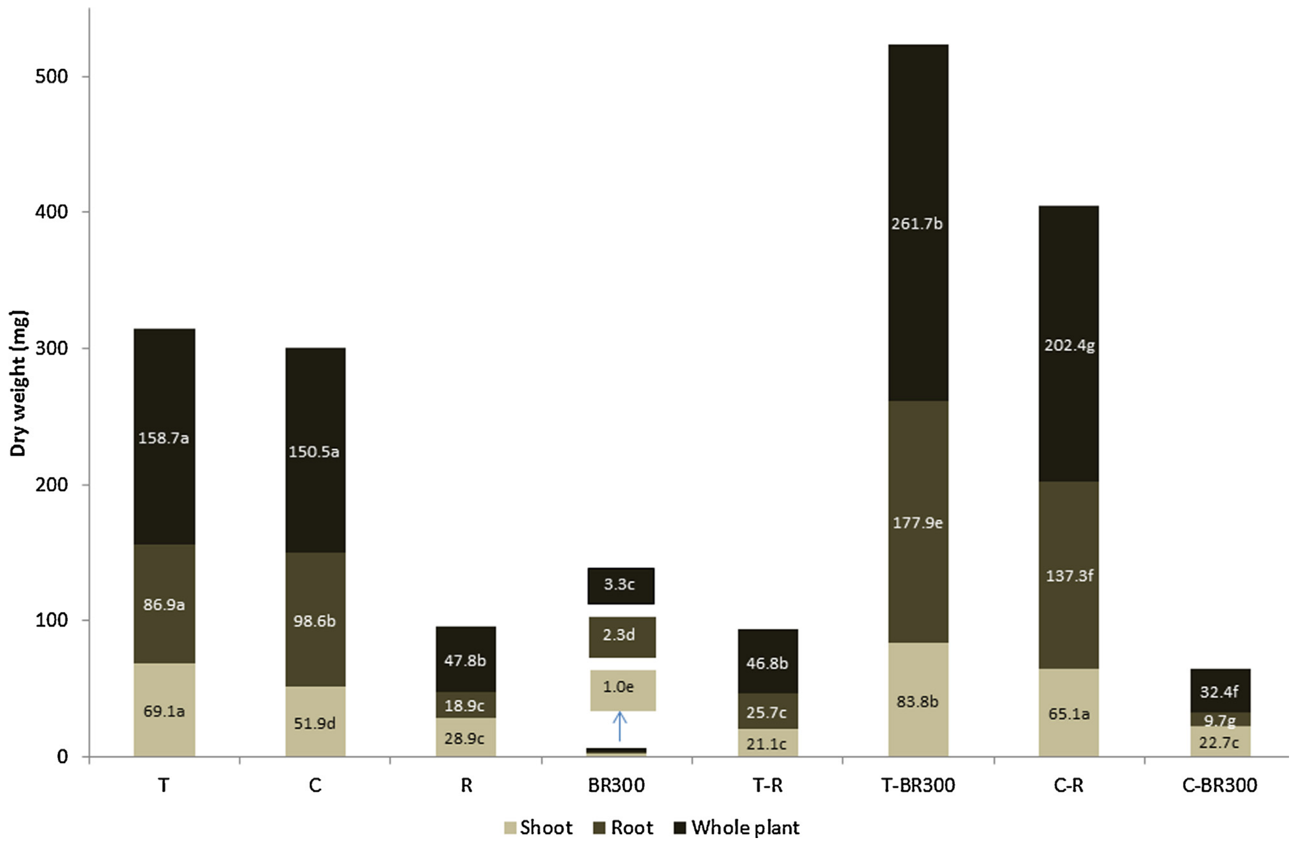

Fig.2. Whole plant, shoot and root weights of Lactuca sativa grown for 4 weeks in substrates consisting of peat (*P*), coir (*C*), deinking sludge (*R*), biochar (BR300) and mixtures of different materials (50/50, *v*/*v*).

A mixture of *C* and *R* in 50/50 *v*/*v* could improve their hydrophysical properties as indicated in Table 5. Finally, addition of deinking sludge to coir-based substrates led to significantly increased air space as well as reduced water holding capacity leading to ideal values for growing media (Table 2).

3.3. Germination index

According to Zucconi et al. (1985) and Emino and Warman (2004), GI values under 50% suggest a high phytotoxicity; between 50 and 80% suggest moderate phytotoxicity, whereas above 80% suggest no phytotoxicity. When GI exceeds 100%, the material can be considered as phytonutrient or phytostimulant. No significant differences in GI were observed among the four raw materials (Fig. 1). GI was higher than 100%, indicating that all four raw materials are phytonutrient for lettuce seeds. The GI of the 4 materials was in the same range of values obtained for different mixtures of peat and compost and vermicompost of green pruning rest by Morales-Corts et al., 2014, but higher than the values obtained with 100% compost and vermicompost in the same study. This fact suggests that the use of biochar could be an alternative to the use of compost obtained from pruning rest. Moreover, our GI values were also similar to the results obtained for grape marc compost, peat and sand by Carmona et al. (2012).

3.4. Lettuce growth

Dry weight of lettuce was affected by the growing media mixtures used in this study (Fig. 2). The total biomass production increased with treatments following the sequence: *T*–BR300 > *C*–*R* > *T* ≈ *C* > R ≈ *T*–*R* > i–BR300 > BR300.

The shoot and root lettuce weight followed similar patterns of variation, respectively: *T*–BR300 > *C*–R ≈ T > C > R ≈ C–BR300 ≈ T–R > BR300 and T–BR300 > C–R > C > T > T–R ≈ R ≈ C–BR300 > BR300. Indeed, lettuce biomass increased significantly after the addition of biochar to peat and deinking sludge to coir. The increase in biomass production after biochar addition was 64.9% with respect to the peat treatment, which could be related with the increment of water holding capacity. This percentage is higher than the results obtained by Tian et al. (2012) who used biochar from low temperature pyrolysis of green waste as peat substitute for the cultivation of the ornamental plant *Calathea rotundifola* cv. Fasciata and found that biochar addition (50%) to peat increased the biomass production by 22% in comparison to peat alone.

For coir-based substrates, the highest total biomass, shoot and root lettuce weight production was obtained after addition of deinking sludge whereas biochar addition decreased these parameters. This could be related to improved hydrophysical properties (Table 4) and/or higher nitrogen and slightly elevated pH, which have been reported optimal for lettuce growth (Carter et al., 2013).

4. Conclusions

Based on the results from this study, adequate growing media for Lactuca sativa could be formulated by mixing biochar with brown peat and original (unprocessed) deinking sludge with coir. Deinking sludge and biochars from pyrolysis of deinking sludge at 300 °C did not show adequate chemical and hydrophysical properties for their individual use as growing media. However, their addition to brown peat (in 50 vol%) improved some of their properties as growing media.

The addition of deinking sludge or biochar caused different growth response depending on whether the media had peat or coir. Plant biomass was significantly higher when plants were grown in peat and biochar media compared to peat media alone. Similarly, plant growth was improved in media containing coir and deinking sludge, compared to media with coir only. Despite the high cost of pyrolysis, use of biochar as ingredient in growing media could be justified because of superior crop yield (lettuce shoot) compared to peat alone, as well as the fact that peat is a non-renewable resource. The results of this study have a high environmental relevance as it may involve the replacement of a non-renewable resource (peat) by biochar made from deinking sludge pyrolysis or the use of deinking sludge to improve the properties of coir as substrate component.

References

Abad, A., Noguera, P., Burés, S., 2001. National inventory of organic wastes for use as growing media for ornamental potted plant production: case study in Spain. Bioresour. Technol. 77, 197–200.

Abad, M., Fornes, F., Carrion, C., Noguera, P., Maguieira, A., Puchades, R., 2005. Physical properties of various coconut coir dusts compared to peat. Hortscience 40, 2138–2144.

Bilderback, T.E., Warren, S.L., Owem, J.R., Albano, J.P., 2005. Healthy substrates need physicals too! HortTechnology 15, 745–751.

Boldrin, A., Hartling, K.R., Laugen, M., Christensen, T.H., 2010. Environmental inventory modelling of the use of compost and peat in growth media preparation. Resour. Conserv. Recycl. 54, 1250–1260.

Bremner, J.M., 1996. Nitrogen-total. In: Bigham, J.M. (Ed.), Methods of Soil Analysis. Part 3. Chemical Methods. ASA-SSSA, Madison, Wisconsin, pp. 1085–1121.

Bustamante, M.A., Moral, R., Paredes, C., Pérez-Espinosa, A., Moreno-Caselles, J., Pérez-Murcia, M.D., 2008. Agrochemical characterisation of the solid by-products and residues from the winery and distillery industry. Waste Manage. 28 (2), 372–380.

Carmona, E., Moreno, M.T., Avilés, M., Ordovás, J., 2012. Use of grape marc compost as substrate for vegetable seedlings. Sci. Hortic. 137, 69–74.

Cantrell, K.B., Hunt, P.C., Uchimiya, M., Novak, J.F., Ro, K.S., 2012. Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. Bioresour. Technol. 107, 419–428.

Cao, C.T.N., Farrell, C., Kristiansen, P.E., Rayner, J.P., 2014. Biochar makes green roof substrates lighter and improves water supply to plants. Ecol. Eng. 7, 2018–2027.

Carter, S., Shackley, S., Sohi, S., Boun Suy, T., Haefele, S., 2013. The impact of biochar application on soil properties and plant growth of pot grown lettuce (Lactuca sativa) and cabbage (*Brassica chinensis*). Agronomy 3, 404–418.

Chong, C., 2005. Experiences with wastes and composts in nursery substrates. Hort. Technol. 15, 739–747.

Cleary, S., Roulet, N.T., Moore, T.R., 2005. Greenhouse gas emissions from Canadian peat extraction, 1990–2000: a life-cycle analysis. Ambio 34, 456–461.

Dumroese, R.K., Heiskanen, J., Englund, K., Tervahauta, A., 2011. Pelleted biochar: chemical and physical properties show potential use as substrate in container nurseries. Biomass Bioenergy 35, 2018–2027.

Emino, E., Warman, P., 2004. Biological assay for compost quality. Compost Sci. Util. 12, 342–348.

Enders, A., Hanley, K., Whitman, T., Joseph, S., Lehmann, J., 2012. Characterization of biochars to evaluate recalcitrance and agronomic performance. Bioresour. Technol. 114, 644–653.

Fei, Y.H., Huang, Y., Yan, C., Chao, R., He, W.Q., 2008. Influence of greenhouse cultivation on agricultural soil environment. J. Agro-Environ. Sci. 1, 243–247.

Garcia-Gomez, A., Bernal, M.P., Roig, A., 2002. Growth of ornamental plants in two composts prepared from agroindustrial wastes. Bioresour. Technol. 83, 81–87.

Gascó, G., Lobo, M.C., Guerrero, F., 2005. Land application of sewage sludge: a soil columns study. Water SA 31 (3), 309–318.

Holmes, S., Lightfoot-Brown, S., Bragg, N., 2000. Peat Alternatives, A review of performance, future availability and sustainability for commercial plant production in the UK, Report ADAS Horticulture & DEFRA, Horticulture & Potatoes Division.

Hossain, M.K., Strezov, V., Chan, K.Y., Ziokowski, A., Nelson, P.F., 2011. Influence of pyrolysis temperature on production and nutrient properties of wastewater sludge biochar. J. Environ. Manage. 92, 223–228.

Jayasinghe, G.Y., 2010. Sugarcane bagasses sewage sludge compost as a plant growth substrate and an option for waste management. Clean Technol. Environ. Policy 14, 625–632.

Jayasinghe, G.Y., 2012. Synthetic soil aggregates as a potting medium for ornamental plant production. J. Plant Nutr. 35, 1441–1456.

Lehmann, J., Joseph, S., 2009. Biochar for environmental management: an introduction. In: Lehmann, J., Joseph, S. (Eds.), Biochar for Environmental Management. Earthscan, London, pp. 1–9.

Maher, M., Prasad, M., Raviv, M., 2007. Organic soilless media components. In: Raviv, M., Heinrich, J. (Eds.), Soilless Culture: Theory and Practice. Elsevier, Amsterdam, pp. 459–504.

Masek, O., Brownsort, P., Cross, A., Sohi, S., 2013. Influence of production conditions on the yield and environmental stability of biochar. Fuel 103, 151–155.

Méndez, A., Barriga, S., Guerrero, F., Gascó, G., 2011. Thermal analysis of growing media obtained from mixtures of paper mill waste materials and sewage sludge. J. Therm. Anal. Calorim. 104, 213–221.

Méndez, A., Terradillos, M., Gascó, G., 2013. Physicochemical and agronomic properties of biochar from sewage sludge pyrolysed at different temperatures. J. Anal. Appl. Pyrolysis 102, 124–130.

Morales-Corts, M.R., Gómez-Sánchez, M.A., Pérez-Sánchez, R., 2014. Evaluation of green pruning wastes compost and vermicompost, slumgum compost and their mixes as growing media for horticultural production. Sci. Hortic. 172, 155–160.

Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon and organic matter. In: Bigham, J.M. (Ed.), Methods of Soil Analysis. Part 3. Chemical Methods. ASA-SSSA, Madison, Wisconsin, pp. 961–1010.

Ostos, J.C., Lopez-Garrido, R., Murillo, J.M., Lopez, R., 2008. Substitution of peat for municipal solid waste and sewage sludge based composts in nursery growing media: effects on growth and nutrition of the native shrub *Pistacia lentiscus* L. Bioresour. Technol. 99, 1793–1800.

Rhoades, J.D., 1996. Salinity, electrical conductivity and total dissolved solids. In: Bigham, J.M. (Ed.), Methods of Soil Analysis Part 3. Chemical Methods. ASA-SSSA, Madison, Wisconsin, pp. 417–435.

Robbins, J., Evans, M.R., 2013. Production in a Greenhouse or Nursery. Part II—Physical and Chemical Properties. FSA6098. University of Arkansas.

Robinson, D.W., Lamb, J.G.D., 1975. Peat in Horticulture. Academic Press, London.

Song, W., Guo, M., 2012. Quality variations of poultry litter biochar generated at different pyrolysis temperatures. J. Anal. Appl. Pyrolysis 94, 138–145.

Strack, M., 2008. Peatlands and Climate Change. International Peat Society. Jyväskylä.

Sumner, M.E., Miller, W.P., 1996. Cation exchange capacity and exchange coefficients. In: Bigham, J.M. (Ed.), Methods of Soil Analysis. Part 3. Chemical Methods. ASA-SSSA, Madison, Wisconsin, pp. 1201–1229.

Thomas, G.W., 1996. Soil pH and soil acidity. In: Bigham, J.M. (Ed.), Methods Of Soil Analysis Part 3. Chemical Methods. ASA-SSSA, Madison, Wisconsin, pp. 475–489.

Tian, Y., Sun, X., Li, S., Wang, H., Wang, L., Cao, J., Zhang, L., 2012. Biochar made from green waste as peat substitute in growth media for Calathea rotundifola cv. Fasciata. Sci. Hortic. 143, 15–18.

Vaughn, S.F., Kenar, J.A., Eller, F.J., Moser, B.R., Jackson, M.A., Peterson, S.C., 2015a. Physical and chemical characterization of biochars produced from coppiced wood of thirteen tree species for use in horticultural substrates. Ind. Crop. Prod. 66, 44–51.

Vaughn, S.F., Eller, F.J., Evangelista, R.L., Moser, B.R., Lee, E., Wagner, R.E., Peterson, S.C., 2015. Evaluation of biochar-anaerobic potato digestate mixtures as renewable components of horticultural potting media. Ind. Crop. Prod., in press. DOI: http://dx.doi.org/10.1016/j.indcrop.2014.10.040

Watanabe, F.S., Olsen, S.R., 1965. Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts from soils. Soil Sci. Soc. Am. Proc 29, 677–678.

Yeager, T., Gilliam, C., Bilderback, T.E., Fare, D., Niemiera, A., Tilt, K., 1997. Best Management Practices, Guide for producing container-grown plants. Southern Nursery Association, Atlanta.

Yuan, J.H., Xu, R.K., 2011. The amelioration effects of low temperature biochar generated from nine crop residues on an acidic Ultisol. Soil Use Manage. 27, 111–115.

Zhang, L., Sun, X.Y., Tian, Y., Gong, X.Q., 2014. Biochar and humic acid amendments improve the quality of composted green waste as a growth medium for the ornamental plant Calathea insignis. Sci. Hortic. 176, 70-78.

Zucconi, F., Monaco, A., Forte, M., De Bertoldi, M., 1985. Phytotoxins during the stabilization of organic matter, in: Gasser, J.K.R. (Ed.), Composting of agricultural and other wastes. Elsevier, London.