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ORIGINAL ARTICLE

End-of-life stage of renewable growing media with biochar versus spent peat or mineral wool

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Abstract The composition of horticultural substrates for soilless greenhouse cultivation directly affects the sustainability of the cropping system but has also an indirect effect through the end-of-life stage of the spent media. Biochar amendment in growing media for use as bulk material and source of nutrients may improve the sustainability of controlled-environment agriculture. Horticultural substrates were compared at the end of soilless strawberry and tomato cultivation in six trials at commercial scale. Conventional mineral wool and peat-based blends were compared with peat-reduced and peat-free organic blends with or without 10% v/v biochar amendment. Nutrients, C stability of the growing media and their value as soil improver were measured. The organic growing media had a high potential for reuse and for C storage. Spent mineral wool was significantly richer in total P, K, Mg and Ca and significantly lower in organic C content and C stability than the other blends, with a clearly lower value as soil improver than the organic blends. Biochar amendment in renewable organic blends increases their value as soil improver and their potential for reuse: addition of 10% v/v biochar in the blend significantly increased the C content (90 g C/kg dry matter higher) and the C:N ratio of the spent growing media, but not the C stability. The pH of the biochar in the growing media decreased from 9.1 to 6.2 during cultivation while CEC increased. This research illustrates the feasibility of using biomass and biochar in cascade: first as growing medium and finally as a C-rich soil improver.

Keywords Horticultural substrates · Controlled environment agriculture · Circular horticulture · Peat replacement · Negative emission technologies · Biochar carbon removal

Abbreviations

CEC	Cation exchange capacity

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DM	Dry matter
EC	Electrical conductivity
IC	Inorganic carbon
OC	Organic carbon

Introduction

Soilless cultivation

Soilless cultivation systems based on growing media are an alternative cropping system used in climates where open air cultivation is limited (Gruda et al. 2019). Growing media are an essential part of some soilless culture systems. Growing media are also important for circular horticulture as they allow for optimal use of materials and nutrients, both in terms of blend composition and in reuse/upcycling of the spent media and the remaining nutrients at the end of cultivation (Shuttleworth et al. 2021; Vandecasteele et al. 2020; Vollmer et al. 2022). Although soilless cultivation based on growing media can be more circular in terms of water and nutrient use in comparison to soil cultivation (Elvanidi et al. 2020; Savvas and Gruda 2018; Blok et al. 2021a), soilless systems still are confronted with "waste", e.g., crop residues after harvest and the spent growing media, including the plant roots. Organic spent growing media show potential for reuse in horticulture or for use as a soil improver, as these applications reuse both the C-rich bulk materials and the remaining nutrients (Vollmer et al. 2022). The end-of-life stage of growing media impacts their environmental footprint, particularly by emissions related to the decomposition of their organic components and emissions derived from the enclosed fertilizers (Growing Media Europe 2021). The environmental impact of materials used in growing media can vary widely due to differences in the energy required for collection or mining, transport, processing, and environmental impact at their end of life (Paoli et al. 2022). In Europe, growing media applied for transplants and in greenhouses are currently mostly based on coir or peat (Blok et al. 2021b). Peat is a non-renewable resource and mining of peat emits greenhouse gases (Kern et al. 2017), which raises important concerns about its sustainability. Coir products may also have a large environmental footprint due to the processes involved in coir processing and long-distance transport (Paoli et al. 2022). Production and recycling of mineral wool slabs involves intense fossil energy use, which increases their environmental impact and drives the call to replace them with organic slabs (Nerlich and Dannell 2021). Decomposition of peat after use as growing medium in horticulture has been reported to be the largest source of greenhouse gas emissions during the use of horticultural substrates (Growing Media Europe 2021). Spent peat-based growing media are generally characterized by a high degree of biological stability (Vandecasteele et al. 2020). Besides the CO_2 emissions related to the C stability of spent media, spent media also represent a risk for nutrient losses. Circular use of growing media will affect their end-of-life impact: spent peat-based media have potential for either direct reuse or reuse as feedstock for composting or biochar production (Woods et al. 1972; Vandecasteele et al. 2020; Amery et al. 2021).

In Europe, concerns about the environment as well as the prices and availability of peat, coir and mineral materials have spurred testing of organic peat-reduced and peat-free blends that include regional and renewable materials for use in soilless tomato and strawberry cultivation (Dannehl et al. 2015; Gage et al. 2021; Moelants et al. 2021; Nerlich and Dannehl 2021; Nguyen et al. 2022). Materials in new growing media blends generally have higher initial nutrient contents compared to peat (Atzori et al. 2021). The higher nutrient content in virgin peat-reduced and peat-free blends provides an opportunity to reduce the additional fertilizer supply during cultivation but at the same time poses a risk for higher nutrient contents in spent growing media and higher nutrient emissions at end of life.

Biochar in growing media

Biochar is a negative emission technology, meaning that it represents a way to actively remove CO_2 from the atmosphere. Biochar can sequester between 63 and 82% of its initial carbon, as it will remain unmineralized in soil after 100 years at the global mean annual cropland temperature of 14.9 °C (Woolf et al. 2021). Biochar can be utilized in modern society for multiple agricultural and environmental purposes in the framework of the circular economy: biochar can be incorporated into the soil as a direct soil amendment but can also be first used in the composting process or as bulk material in growing media (Jindo et al. 2020). Unlike some other sources of exogenous organic matter, the long-term stability of biochar in soil has been extensively tested with promising results (e.g., Mondini et al. 2017; Fryda et al. 2019).

Depending on the dose and characteristics of the biochar, this material can be used for different applications in growing media, including fertilizer (low dose, biochar with high nutrient content), liming agent (low dose, biochar with high inorganic C content), disease suppressing agent (low dose) or bulk material (higher doses, biochar with low salinity and alkalinity) (Huang and Gu 2019). As an alternative for coir and peat, biochar is a relatively new bulk material in growing media and is still under study (Atzori et al. 2021; Blok et al. 2017; Escuer et al. 2021). The use of biochar in growing media is a strategy to reduce the CO_2 footprint of horticultural substrates through a combination of (a) Renewable energy production, (b) Replacement of peat with biochar in horticultural substrates and (c) Use of spent biochar-based substrates as a carbon storage tool in soil (Fryda et al. 2019).

The effect of biochar on physical properties of container substrates depends on the particle size distribution of the biochar and the other components in the blend (Huang and Gu 2019). Based on its characteristics, biochar could be a more effective bulk material in growing media than peat, e.g., biochar has better re-wettability than peat, and biochar is highly stable, thus the substrate chemical and physical properties are less prone to changes during the period of plant growth (Jindo et al. 2020). Some biochars can serve as a source of P and K, which leads to increased availability of these minerals in container substrates as well as improved plant fertility (Altland and Locke 2013). Amery et al. (2021) conclude from their experiment that nutrient release rather than retention is expected when using biochars in growing media when nutrients are supplied by fertigation. Although biochar has been extensively tested as an alternative and renewable bulk material in growing media, the focus has rested on the following subjects: crop growth, yield and effects on physical properties of the growing medium, nutrient uptake and disease suppression. Less attention has been paid to the effect of biochar amendment on the characteristics of the spent growing media and the changes in biochar characteristics during its use as bulk material.

Aim

Moving away from the use of peat, coir or mineral wool to other blends based on renewable materials may affect the C storage potential and the risk for nutrient emissions of spent growing media. Research is needed on the characterization of the end-of-life stage of growing media based on renewable materials and the role of biochar as a bulk material for this application. In the present study we have assessed the end-of-life value in terms of reuse or use as soil improver and source of stable organic C for a range of growing media blends, including mineral wool slabs and peat-reduced or peat-free growing media blends with biochar. To the best of our knowledge, this is the first paper to assess:

(a) The end-of-life characteristics of peat-reduced and peat-free blends in terms of C storage, C and nutrient related properties.
(b) The effect of biochar addition in horticultural substrates on the end-of-life stage of spent growing media, their reuse capacity and their value as soil improver.
(c) Changes in biochar characteristics during use as bulk material in growing media.

To collect representative spent growing media, we performed six full-scale greenhouse experiments with new growing media blends with or without biochar amendment in comparison with conventional mineral wool and peat-based blends, then collected and analyzed the spent growing media at the end of the cultivation. These spent growing media are a source of organic matter with or without biochar and may therefore be appropriate for reused in a second cultivation and/or used in the field for C storage and soil improvement. The hypotheses are:

- Blend composition affects C stability, value as soil improver and potential for reuse.
- 10% v/v biochar results in spent medium with higher stability and lower N release.
- The characteristics of the biochar do not change during their use in growing media.

Materials and methods

It was important to test spent growing media (including plant roots) from full-scale trials as these blends were penetrated by strong and intense rooting due to high production rates and the related fertigation application. By collecting blends from six full-scale trials (Table S1) we provide a sufficiently reliable data for use in assessing the characteristics of spent growing media of different blends. A range of alternatives for peat or coir were used in the peat-reduced or peat-free blends, i.e., green compost, wood fiber, bark compost and biochar. Based on the six trials, three to four samples of each blend tested in different trials could be compared.

Full-scale trials

For the three tomato trials (denoted as Trial T1, T2 and T3, Table S1), Rebelski (De Ruiter Seeds, Bergschenhoek, The Netherlands) tomato variety, grafted onto Maxifort (De Ruiter Seeds, Bergschenhoek, The Netherlands) rootstock was grown on the substrates in a commercial tomato greenhouse at *Proefcentrum Hoogstraten* in Meerle, Belgium (51°27.2′N − 4°47.7′E; altitude 16 m). Tomato plants were planted at a distance of 50 cm. This resulted in a stem density of 2.5 stems m^{-2}. Each object was divided into four measurement fields established in a random design. All objects were treated with the same fertigation scheme (Table S2) in a fully closed recirculation system. Greenhouse regulation was provided by a PRIVA® climate computer (Priva, De Lier, The Netherlands).

Three full-scale greenhouse trials with strawberry (denoted as Trial S1, S2 and S3, Table S1) were executed in a closed-loop gutter system (fully closed recirculation system) with drip irrigation in a professional greenhouse growing system at Proefcentrum Hoogstraten. The system applied for trials S1 and S2 was a continued fall-spring cycle (double cropping system), i.e., an autumn culture of strawberries in a heated glass greenhouse with 5.5 m post height. This is representative for a highly intensive culture over the 10-month trial. The S3 trial was an autumn cultivation in an unheated plastic Vanden Heuvel greenhouse with a six meter post height. All trials used the strawberry hybrid *Fragaria* × *ananassa*, cultivar Elsanta, which is a June bearer and the most widely produced cultivar in Flanders (Belgium). Per tray, 6 pre-rooted plugs were grown at a plant density of 10.5 plants per m^2 greenhouse surface. Each trial had 6 treatments tested with four replicates. Each replicate had 10 trays and 60 plants, resulting in treatments of 17–18 m^2 greenhouse surface. Greenhouse and fertigation management was comparable with current practices in horticulture in Belgium and the Netherlands. The amount of fertigation water supplied to the plants is determined by solar irradiance reflecting the weather conditions (one dose per 220 joules solar irradiation), and is controlled by a PRIVA® greenhouse climate computer (Priva, De Lier, The Netherlands). The composition of the fertigation solution during the different stages of cultivation is given in Table S2.

Growing media blends

Wood-based biochars were used in trials T1, S1, S2 and S3 (Table 1 and S3). The biochars were produced by TNO (The Netherlands) using a specific reactor under controlled conditions. Biochars 1 and 2 are based on mixed wood residues from park maintenance, and biochar 3 is based on beech wood. The specific surface area based on the Brunauer-Emmett-Teller (BET) analysis of these biochars is in the range of 230–350 m^2/g biochar, and the H/C ratio in atomic percentage (at%) is lower than 0.14 (at%/at%). Before mixing into the blend, biochar was moistened to a moisture content of 50% fresh weight to allow for better mixing and avoiding losses through dust formation. Due to a practical mixing error during producing the blends at pilot scale, an unintended difference in the amount of biochar added to the blend with biochar for the S2 trial occurred, resulting in a dose of only 3% v/v versus the intended 10% v/v. The biochar dose was 10% v/v for T1, S1 and S3.

The peat-based and the peat-free grow bags for the tomato trials T1, T2 and T3 (Table 2) were produced by Agaris (Gent, Belgium). The peat-based grow bag was filled with a mixture of 40% v/v blocked peat (10–30 mm), 40% v/v Irish peat (10–30 mm) and 20% v/v coir fiber (< 15 mm fraction). The peat-free grow bag was composed of 40% v/v coir fiber (< 15 mm), 30% v/v wood fiber (Kleeschulte Erden GmbH & Co, Rüthen, Germany), 20% v/v bark (*Pinus maritima*, 5–15 mm) and 10% v/v green compost (green compost from a commercial facility, certified by the

Table 1 Characteristics of the biochars used in the tomato (T) and strawberry (S) trials

Trial		S1, T1	S2	S3
Biochar type		Mixed park wood biochar	Mixed park wood biochar	Fine beech wood biochar
pH-H2O	–	9.0	9.5	9.3
EC	µS/cm	180	416	242
OC	%/DM	74	77	83
Total N		0.17	0.48	0.35
C/N	–	448	160	241
P	mg/kg DM	0.4	2.5	0.5
K		3.2	5.2	7.3
Mg		1.6	1.7	1.8
Ca		8.1	10.0	12.7
CEC	cmolc/kg DM	10.1	8.2	7.2
Particle size distribution (% m/m)	> 5 mm	2	0	0
	2–5 mm	27	28	3
	1–2 mm	38	43	64
	< 1 mm	33	26	32

CEC Cation exchange capacity, *EC* Electrical conductivity, *OC* Organic C, *DM* Dry matter

Table 2 Composition (% v/v) of the peat, peat-reduced, peat-free and biochar-amended blends used in the tomato (T) and strawberry (S) trials

Trial	S1, S2	S1, S2, S3	S1, S3	S2	T1, T2	T1, T2, T3	T1
Blend	Peat	Peat-reduced	Peat-reduced + biochar	Peat-reduced + biochar	Peat	Peat-free	Peat-free + biochar
Peat	75	45	41	44	80	0	0
Coir	15	9	8	9	20	40	36
Perlite	10	6	5	6	0	0	0
Wood fiber	0	25	22.5	24	0	30	27
Green compost	0	15	13.5	14	0	10	9
Biochar	0	0	10	3	0	0	10
Bark compost	0	0	0	0	0	20	18

Flemish compost organization VLACO, Table S4). The biological stability of the green composts (based on the oxygen uptake rate) used by Agaris was lower than the Belgian legal threshold and the composts are thus categorized as stable according to the criteria used in Belgium. The composition of the peat-free blend with biochar in T1 was 36% v/v coir fiber, 27% v/v wood fiber, 18% v/v bark (*Pinus maritima*, 5–15 mm), 10% v/v biochar and 9% v/v green compost. Haifa Multi-mix Potting Soil 14 + 16 + 18(+ micronutrients) fertilizer was added to each blend in a dose of 0.4 g/L. Lime was added in a dose of 2.5 g/L for the peat-based grow bag while no lime was added to the peat-free blend. Mineral wool slabs were Grodan Master rockwool slabs (Grodan, Roermond, The Netherlands).

All blends for S1, S2 and S3 (Table 2) were produced by Agaris (Gent, Belgium). The conventional peat-based blend contained 75% v/v peat (a mixture of blocked, Irish and white peat, 10-30 mm), 15% v/v coir chips (< 8 mm fraction) and 10% v/v perlite (3–6 mm fraction). The peat-reduced blend contained 45% v/v peat (mixture of blocked, Irish and white peat), 25% v/v wood fiber (Kleeschulte Erden GmbH & Co, Rüthen, Germany), 15% v/v green compost (from a commercial facility, certified by the Flemish compost organization VLACO, Table S4), 9% v/v coir chips and 6% v/v perlite. The composition of the peat-based and peat-reduced blends was constant for the three trials. The composition of the peat-reduced blend with biochar in S1 and S3 was as follows: 41% v/v peat (mixture of blocked, Irish and white peat), 22.5% v/v wood fiber, 13.5% v/v green compost, 10% v/v biochar, 8% v/v coir chips, and 5% v/v perlite. Haifa Multi-mix Potting Soil 14 + 16 + 18(+ micronutrients) fertilizer was added to each blend in a dose of 0.4 g/L, representing 56, 28 and 60 mg/L for N, P and K, respectively. The small dose of mineral fertilizer in all blends was applied to avoid differences in nutrient availability between the blends in the first days of the trials. Lime was added in a dose of 3.0 g/L for the peat-based blend and 1.8 g/L for the peat-reduced blend.

Sampling

The spent growing media were sampled at the end of cultivation, after harvest and removal of all above-ground biomass. We define "spent growing medium" as the remaining growing medium at the end of the cultivation after removing the rooted plugs that were inserted into or placed on top of the virgin growing medium blend at time of planting.

For tomato, six grow bags per blend were selected at random from the trial. The pre-rooted plugs on top of the grow bag were cut out of the grow bag with a knife, as these plugs were put on top of the grow bag at time of planting and consist of another material than the tested blends. The remaining spent medium was removed from the grow bags, weighed, thoroughly mixed and sampled.

For strawberry, six containers per blend were selected at random from the trial and pre-rooted plugs were cut out of the growing medium with a knife, as these plugs were included at time of planting and consists of a growing medium blend (and nutrients) other than the tested blends and the nutrients supplied by fertigation. The remaining spent medium was removed from the containers, weighed, thoroughly mixed and sampled.

For trials T1, S1 and S3, the characteristics of the peat-reduced or peat-free blends with 10% v/v biochar were assessed as well. Subsamples of the spent growing media of three trials (T1, S1, S2) with biochar were air-dried and sieved using 2 and 5 mm mesh sieves. Biochar particles were hand-picked from the > 2 mm sized material with tweezers and stored for chemical analysis. The > 2 mm fraction of initial biochars was analyzed as well and their characteristics were compared with the recovered biochars.

C mineralization and N release

CO_2 emission was measured 13 times during 30 days using a LI-8100 Automated CO_2 Flux System equipped with a soil flux chamber and a non-dispersive infrared gas analyzer (LI-COR Biosciences, Lincoln, NE, USA). Two liters of material was mixed with 4 g/L Haifa Multi-mix Potting Soil 14 + 16 + 18(+ micronutrients) fertilizer (MF), moistened based on the squeeze test, and put in PVC rings (height: 12 cm, diameter: 25 cm) at 20 °C. The rings were closed at the bottom with a plastic cover. The mixtures were rewetted twice a week based on the recorded weight loss. The average CO_2 release rate was calculated and expressed as mmol CO_2/kg C/hr.

The net N mineralization of the spent growing media was assessed based on a 100 day-incubation trial: 1000 mL material was placed in a 3.5 L container with a perforated cover, moistened to reach a moisture content of 30% v/v (i.e., a dry matter content of 30%/fresh mass) and incubated at 15 °C and 70% relative humidity. The moisture content was kept at constant level: the mixtures were rewetted every two weeks based on the recorded weight loss. Mineral N (N_{min}) was extracted after 100 days of incubation in a 1:5 extraction (v/v) as described below. The net N mineralization was calculated as the difference in N_{min} after 100 days versus the initial N_{min} concentration and expressed relative to the total N content of the material.

Analyses

Sample preparation of growing media for determination of total nutrient content, dry matter content, moisture content and laboratory compacted bulk density was executed according to EN 13,040. Spent growing media were dried at 70 °C and ground. Total N content (determined according to the Dumas method, EN 13654-2) and organic C (OC) and inorganic C were measured using a Skalar Primacs SNC 100 analyzer (Skalar, Breda, The Netherlands). Total contents of P, K, Mg and Ca were determined by 5110

VDV Agilent ICP-OES (Agilent, Santa Clara, CA, USA) in the extract following digestion. For application in the growing media, digestion was executed (120 min at 105 °C) on 0.5 g dried and ground material with 4 mL HNO_3 (p.a. 65%) and 12 mL HCl (p.a. 37%) using a DigiPREP MS 200 Block Digestion System (SCP SCIENCE, Québec, Canada). For biochar, digestion of 0.2 g biochar was peformed using 8 mL HNO_3 (p.a. 65%, Chem-Lab NV) and 4 mL H_2O_2 (p.a. 30%, VWR Chemicals) in a 2:1 ratio using a Milestone ETHOS One high performance microwave digestion system (in 15 min to 200 °C, hold 15 min at 200 °C, max. 1500 W). The cation exchange capacity (CEC) was determined by ammonium acetate (p.a. > 99%, Chem-Lab NV) at pH 7.0 and KCl (p.a. > 99.5%, Chem-Lab NV), modified from the method by Rajkovich et al. (2012).

Electrical conductivity (EC) (EN 13,038) and pH-H_2O (EN 13,037) were measured in a 1:5 solid to water (v/v) suspension. Extraction (1:5 v/v) of water-soluble NO_3^--N and NH_4^+-N was performed according to EN 13,652. NO_3^--N was measured with a Dionex ICS-3000 ion chromatograph (Dionex, Sunnyvale, CA), and NH_4^+-N with a Skalar San++flow analyzer (Skalar Analytical B.V., Breda, NL).

Calculations and statistics

The characteristics of the blends were compared using one-way ANOVA and Scheffé's multiple comparison post-hoc test (Statistica 13.5, Statsoft Inc., Hamburg, Germany). Homogeneity of variances was checked using box plots and data normality was checked using QQ plots. To obtain data normality and homogeneity of variances, square root-transformation (OC, total P, Mg, Ca and K, CEC expressed relative to DM content) or log10 (C/P, CEC expressed relative to OC content) was used. To assess the effect of 10% v/v biochar on characteristics of spent growing media, comparison of three blends (1 peat-free and 2 peat-reduced) with or without 10% v/v wood-based biochar was done based on a paired t-test with samples from three trials (T1, S1, S3). The effect of growing medium on biochar characteristics was assessed by paired t-test comparing the biochar characteristics before vs. after using in the growing medium, based on a comparison of three biochars recovered from the growing medium (3 trials: T1, S1, S2) versus the characteristics of the >2 mm fraction of the initial biochars in these trials.

Results

Stability and nutrient content of spent growing media

Results for the four blends are presented in Table 3. Spent mineral wool was clearly and significantly richer in total P, K, Mg and Ca than the other blends. Mineral wool only contained plant roots as source of C, resulting in a significantly lower organic C content and C stability for mineral wool than the three other groups. The peat blends had significantly higher OC than the peat-reduced blends. There was no statistical difference in C stability nor total Ca, Mg or K content between the peat, the peat-reduced and the peat-free spent growing media: all three were very stable sources of organic C. Only a few significant differences were noted between spent peat and the other organic blends. In comparison with spent peat, only the peat-reduced blends had significantly lower values for OC and the C:N and C:P ratios, and only the peat-free blends had a significantly higher total P content and a significantly lower C:P ratio.

No significant differences were found among the four groups for pH, EC, dry bulk density, total N content, net N mineralization and CEC relative to OC content. A low N mineralization rate was measured in all spent substrates, without signs of any N immobilization. CEC relative to DM content was significantly lower for mineral wool than for the organic blends, probably due to the lower C content of the mineral wool. C:N and C:P ratio was lowest for the mineral wool and highest for the peat blends (with a high C:N ratio for the peat-reduced blends as well). None of the samples contained inorganic C above the limit of quantification (0.08% IC/DM).

As roots were the only organic component in the mineral wool slabs, these samples make it possible to assess the stability of the tomato roots versus the organic spent growing media blends. The roots were the less stable component of the growing media as they had the highest C mineralization rates.

The C mineralization rates for spent growing media are compared with virgin materials in Fig. 1. In terms of stability, plant fibers are the least stable virgin material, followed by green compost and bark

Table 3 Comparison of chemical composition and biological stability among spent growing media based on mineral wool (tomato, $n=3$), peat (strawberry ($n=2$) and tomato ($n=2$)), peat-reduced blends (strawberry, $n=3$) or peat-free (tomato, $n=3$) blends

		Peat	Mineral wool	Peat-reduced	Peat-free	Target value
Organic C	g/kg DM	**469 (27)**^{c}	36 (7)^{a}	247 (52)^{b}	**393 (17)**^{bc}	High
C mineralization rate	mmol CO_2/kg C.hr	**1.4 (0.3)**^{a}	14.5 (5.7)^{b}	**2.2 (0.6)**^{a}	**1.4 (0.4)**^{a}	Low
Total P	g/kg DM	**0.8 (0.3)**^{a}	2.9 (0.7)^{c}	**1 (0.1)**^{ab}	2.1 (0.4)^{bc}	Low
Total K		**2.5 (0.6)**^{a}	7.2 (0.6)^{b}	**2.5 (0.6)**^{a}	**1.8 (0.8)**^{a}	Low
Total Mg		**3.5 (0.8)**^{a}	49 (2.7)^{b}	**2.8 (0.7)**^{a}	**3 (0.1)**^{a}	Low
Total Ca		**19 (4)**^{a}	109 (1)^{b}	**16 (5)**^{a}	**17 (3)**^{a}	Low
Total N		11.3 (0.1)	7.8 (0.2)	12.7 (0.2)	10.4 (0.3)	Low
C/N	(–)	**42 (3)**^{c}	5 (2)^{a}	27 (2)^{b}	**39 (7)**^{c}	> 25
C/P		**639 (201)**^{c}	12 (2)^{a}	336 (24)^{b}	195 (28)^{b}	> 150
CEC on DM basis	cmolc/kg DM	**105 (27)**^{b}	9 (9)^{a}	**61 (8)**^{b}	**64 (4)**^{b}	High
CEC on C basis	cmolc/kg OC	222 (44)	221 (196)	177 (7)	164 (16)	High
% net Nmin	%/total N	< 1	< 1	< 1	< 1	Low
pH-H_2O	(–)	6.5 (0.3)	7.2 (0.6)	6.6 (0.1)	6.9 (0.6)	< 7
EC	µS/cm	419 (124)	512 (193)	475 (240)	452 (191)	Low
Dry bulk density	g DM/L	106 (26)	89 (27)	129 (13)	148 (26)	Low

Different letters indicate significant differences as found by One-way ANOVA and Scheffé's post-hoc test. Bold values indicate characteristics that are not significantly different from the values for spent peat (*CEC* Cation exchange capacity, *DM* Dry matter, *EC* Electrical conductivity, *OC* Organic carbon, net Nmin: net N mineralization). Values in parentheses are standard deviations for four (peat) or three (other blends) replicates. Details on the strawberry (S) and tomato (T) trials are listed in Table S1 and Table 2

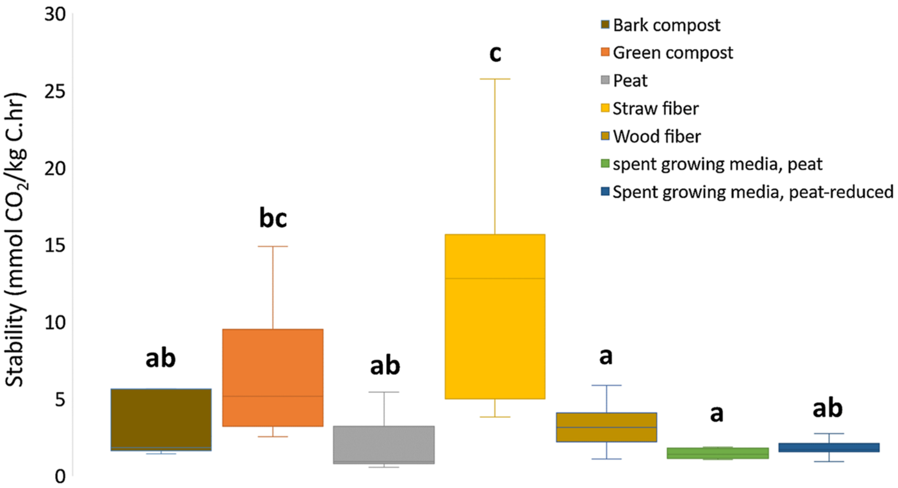

Fig. 1 Box plots with C mineralization rates (mmol CO_2/kg C.hr) in spent growing media for peat-based (green box, 8 batches), peat-reduced or peat-free blends (blue box, 8 batches) compared with data for different batches of virgin materials (bark compost (7 batches), green compost (9), peat (11), straw fiber (9), wood fiber (8)). Different letters indicate significant differences as found by One-way ANOVA and Scheffé's post-hoc test

compost, with wood fiber and peat being the most stable. In comparison with the virgin materials, both peat-based and peat-reduced spent growing media are more stable than the virgin materials. From these data one can conclude that their use as growing medium will result in a more stable blend.

For the samples where biological stability was assessed in the longer term by continued measurements of C mineralization, a clear trend of decreasing C mineralization rates was observed, or in other words, the stability increased over time (Fig. S1). The addition of an extra dose of mineral fertilizer did not result in a consistent increase in C mineralization when compared with the values during the first 30 days of incubation, which indicates that nutrients were not a limiting factor for the decomposition in the longer term.

Effect of bulk replacement by biochar on characteristics of spent growing media

Adding biochar at 10% v/v significantly ($p < 0.05$) increased the OC content of the spent growing media by 93 g C/kg DM on average (thus a relative increase of more than 25%), and significantly increased the C/N ratio from 32 to 40 on average, but reduced the CEC expressed relative to OC content by 44 cmolc/kg OC (Table 4). Total nutrient contents, stability, pH, EC, dry bulk density, C:P ratio, net N mineralization and CEC expressed relative to DM content are not significantly affected by biochar addition.

There was no indication of an effect of peat replacement or an additional effect of biochar on the microbial biomass in the spent growing media (Table S5). The differences for microbial biomass among the spent growing media blends are smaller than the differences among the virgin materials.

Changes in biochar characteristics during cultivation

To assess the effect of growing medium on biochar characteristics, the biochars recovered from three samples of spent growing media were compared with the initial characteristics of the same > 2 mm fraction of the biochar (Table 5). There was no significant effect ($p > 0.05$) on EC, Total P, K, Mg, Ca, organic C, and C/P ratio. A significant effect ($p < 0.05$) of using biochar as growing medium on the biochar characteristics were observed for pH (decrease from 9.1 to 6.2), water-extractable NO_3-N (increase from < 5 to 62 mg NO_3-N/L), total N (increase from 0.3 to 0.8%N/DM), C/N ratio (decrease from 282 to 121), and CEC (increase from 17 to 27 cmolc/kg DM). The following non-significant data were also observed: total K content of the biochar decreased during use in growing media while the P content increased.

Discussion

Blend composition affects the potential for reuse, C stability and the value as soil improver

Future use of C-rich materials for a variety of applications including C storage in soil is expected to increase, potentially resulting in a shortage of these sources of exogenous organic matter for other applications. In this paper, we assess the use of materials rich in organic matter in cascade, starting with use in the greenhouse as peat-reduced or peat-free growing medium and ending with application for C storage in arable soils. The first condition for circular use of growing media and their use as soil improver is the absence of strong net nutrient accumulation in the growing medium (Vandecasteele et al. 2023). A second condition is maintaining the biological stability.

Table 4 Comparison of chemical composition and biological stability of three spent growing media with or without 10% v/v biochar tested in trial T1, S1 and S3. Results are average values, bold values indicate statistical differences ($p < 0.05$), statistics are based on a paired t-test

		Without biochar	With 10% v/v biochar	*p* value
Organic C	g/kg DM	**348**	**441**	0.031
C mineralization rate	mmol CO2/kg C h	2.1	1.7	0.244
Total P	g/kg DM	1.4	1.6	0.476
Total K		2.6	3.0	0.204
Total Mg		2.7	2.9	0.454
Total Ca		14.5	17.2	0.090
Total N		11	11	0.976
C/N	–	**32**	**40**	0.045
C/P		277	342	0.272
CEC on DM basis	cmolc/kg DM	61	57	0.377
CEC on C basis	cmolc/kg OC	**175**	**131**	0.031
% net Nmin	%/total N	< 1	< 1	0.362
pH-H2O	–	7.0	7.1	0.286
EC	µS/cm	323	364	0.378
Dry bulk density	g DM/L	141	133	0.609

CEC Cation exchange capacity, *DM* Dry matter, *EC* Electrical conductivity, *OC* Organic carbon, net Nmin: net N mineralization

Table 5 Comparison of chemical composition of the > 2 mm fraction of biochars in trials T1, S1 and S2 before or after use as bulk material in growing media

		Virgin biochar	Biochar after use in growing media	*p* value
OC	g/kg DM	897	867	0.423
Total N		**3.2**	**7.7**	0.031
pH-H2O	–	**9.1**	**6.2**	0.013
EC	µS/cm	199	293	0.208
C/N	–	**282**	**121**	0.024
NO_3-N	mg/L biochar	**< 5**	**63**	0.034
Total P	g/kg DM	0.6	3.0	0.320
Total K		3.6	1.4	0.140
Total Mg		1.5	1.5	0.955
Total Ca		7.1	10.9	0.533
CEC	cmolc/kg DM	**17**	**27**	0.040

Results are average values, bold values indicate statistical differences, statistics are based on a paired t-test

CEC Cation exchange capacity, *DM* Dry matter, *EC* Electrical conductivity, *OC* Organic carbon

A high biological stability was observed in this study for peat-based growing media as well as for the blends with partial or complete peat replacement. The high biological stability (i.e., low CO_2 release) previously observed for spent growing media based on peat or coir was now confirmed for blends with partial or complete peat or coir replacement. Draining of peatlands before peat mining results in an important release of CO_2. The CO_2 release from spent growing media is much lower: the spent peat-based growing media are characterised by a high C stability (i.e., low CO_2 release rates). Spent peat is thus a stable form of C, although a higher decomposition rate is assumed in LCA studies, which include scenarios with a complete decomposition of spent peat in a 10-year period after use in horticulture. This rate of decomposition would result in 71% of the emissions related to use of peat as growing medium (Growing Media Europe 2021). An oxidation rate of 5% of the peat carbon content per year is proposed as a guideline for studies on decomposition of peat (Cleary et al. 2005), while Hayes et al. (1997) propose an average value of the half-life for peat of 16 years.

Organic spent growing media were found to be more stable than composts and some other virgin materials used in horticultural substrates. The biological stability is relevant in terms of the C storage potential of the spent growing media when applied to the soil as well as for oxygen supply when reusing the growing medium, as a highly degradable substrate may result in O_2 deficiency for the plant roots (Nerlich and Dannehl 2021). The results of the protocol for stability assessment of the pure materials in this paper are positively correlated to the decomposition rate in the longer term after incorporating the material into the soil, with measurement based on C mineralization during soil incubation (Vandecasteele 2023). There are several potential reasons for this increase in stability during use as growing medium. One may be related to the Ca enrichment of the growing medium due to fertigation (Vandecasteele et al. 2023). Ca-mediated stabilization of soil organic carbon has been proposed by Rowley et al. (2018, 2021). Another explanation may be the decrease in C:N of the growing medium during use. Initially, growing media have a high C/N ratio but this ratio decreases during the cultivation due to N being taken up by the roots from the fertigation in combination with N accumulated in the bulk material (Vandecasteele et al. 2023). Although C:N ratio is not a stability indicator, if may reflect a change in the composition of the material that affects its microbial degradation.

The transition from peat-based growing media to peat-free organic growing media with biochar does not impact the value of the spent growing media for reuse or for soil improvement, while the CO_2 footprint turns from C positive for peat-based growing media to C negative for the peat-free organic growing media. Hypothesis 1 (Blend composition has an effect on C stability, the value as soil improver and on the potential for reuse) is thus rejected. In terms of nutrients, peat-reduced or peat-free blends are characterized by higher initial total nutrient concentrations than peat-based blends, especially when the blend contains compost and/or biochar. Previously only a small accumulation or even a reduction of P and K in peat-reduced or peat-free blends was observed for strawberry and tomato when compared with the initial composition (Vandecasteele et al. 2023). Nutrients in the spent growing media also represent an economic value and CO_2 emission reduction potential, as they may replace chemical fertilizers (Vollmer et al. 2022).

Lower N and P contents (and the related higher C/N and C/P ratios) in spent horticultural substrates in general indicate a lower risk for N and P related emissions. The C/P ratio of the peat-reduced (336) and peat-free (195) spent growing media is clearly higher than for manure (34), compost (77) and digestate (32) (Vanden Nest et al. 2020). Organic spent growing media thus show greater potential to increase the C levels in the soil without strongly increasing the P load of the soil. The C/P ratio is important to balance the input of both C and P into the soil, but materials with a high C/P ratio may also result in higher C sequestration in the soil, as P addition can decrease soil organic carbon sequestration and stabilization (Spohn et al. 2022).

10% v/v biochar in the blend has a clear effect on the spent medium

No differences in yield were observed between the peat blends and the peat-reduced blends for both tomato and strawberry (Moelants et al. 2021; Vandecasteele et al. 2023). We therefore conclude that biochar as bulk material performs as well as the other materials in the blend. Lévesque et al. (2020) indicate that biochar can act as replacement for perlite (5–15% v/v) in growing media. Chemical functional groups in biochar could serve as exchange sites for nutrients and benefit the application of biochar as growing media (Vaughn et al. 2013). An added value of biochar (beyond its value as negative emission technology and its use as bulk replacement for spent growing media) is its positive effect on the characteristics of the spent growing media. Biochar as an additive to compost and growing media may improve the composting process and may have an added value for the growing medium (Sanchez-Monedero et al. 2018; Jindo et al. 2020). Biochar has been reported to improve the composting process and digestate processing while reducing N losses and GHG emissions, with a clear effect on the characteristics of the resulting compost (Sanchez-Monedero et al. 2018; Weldon et al. 2022). In contrast, biochar amendment in the growing medium blend had only a limited effect on these characteristics, and did not result in either higher biological stability or a lower N release, so hypothesis 2 (‘10% v/v biochar results in a spent medium with higher stability and lower N release’) is rejected. The spent growing media with biochar had a significantly higher OC content, C:N ratio and CEC op OC, which mainly points to a net effect of mixing materials with different values for these parameters. Even with only 10% v/v biochar addition there is already a strong effect on the value of the spent growing media as soil improver. On the other hand, when biochar is added during composting, similar doses as applied in the current study are used, with distinct effect on the process. It is expected that when using biochar in growing media at rates higher than 10% v/v, more pronounced effects on the characteristics of the growing medium may occur, but this should be confirmed in future research. Application rates of biochar in substrates under 25% v/v generally resulted in similar or higher plant growth compared to the referential commercial substrate (Huang and Gu 2019). Use of biochar as a stand-alone material in growing media is not yet possible in most cases, mainly due to excessively high pH and EC values for the pure biochar (Rathnayake et al. 2021).

A higher stability for the blends with biochar was expected, but this was not confirmed by the data. Biochar may (a) Directly affect the C mineralization of the other organic material in the blend through positive priming, or (b) It may indirectly affect the root biomass in the spent growing medium. Biochar is a more stable material in the blend (Woolf et al. 2021), which indicates a positive priming effect on C mineralization of the other materials in the blend (Messiga et al. 2021). Biochar application in the field may result in short-term positive priming of native soil organic carbon (accelerated decomposition), followed by negative priming (slower decomposition) and buildup of soil organic carbon in the long term (Zimmerman et al. 2011; Yu et al. 2018; Chen et al. 2021). Priming effects have been reported for growing media as well (Messiga et al. 2021). The root biomass was a less stable component in the growing medium, as illustrated by the higher C mineralization rates measured for tomato roots in spent mineral wool. Differences in blend composition, fertigation regime or crop may affect the root growth, the root characteristics and the total root biomass. In the trials, samples from strawberry (peat-based blends and peat reduced-blends) and tomato (peat-based blends and peat-free blends) cultivation were compared. For the peat-based blends, no difference was observed in stability between strawberry and tomato blends (and the included roots). If biochar in the blend results in more root development, this may explain the lower stability of the spent growing media of these blends, and the higher net C mineralization would then be an indirect effect of biochar amendment. No significant differences were observed in root biomass for the tomato trials, however (Moelants et al. 2021). Further quantification of differences in root biomass and stability in the transition from mineral wool or peat towards renewable growing media is a topic for further research. The short-term effect of biochar on the growing medium stability requires more research. Ding et al. (2018) evaluated 27 incubation studies and reported that native soil carbon was positively primed over the first 200 days, after which the C dynamics turned to negative priming. Long-term incubations of spent growing media with or without biochar should provide data on negative priming effects of biochar-amended spent growing media in the longer term.

Biochar characteristics change during their use in growing media

Aging of biochar in the growing medium or in the soil may affect the chemical and physical properties of the biochar. There was a significant change in some of the biochar characteristics for the biochar recovered from the spent growing media versus the same size fraction of the initial biochar, and thus Hypothesis 3 (The characteristics of the biochar do not change during their use in growing media) was rejected. The changes point to effects on the biochar surface due to interaction with the other materials in the growing media, the fertigation, the plant roots, or a combination. Chemical and physical biochar properties are affected by presence in the soil in the long term when used as a soil amendment, during composting and anaerobic digestion where biochar is used as an additive in these processes, or through active activation by chemical treatments (Takaya et al. 2016; Rechberger et al. 2017; Sanchez-Monedero et al. 2018). The hydrophobic surfaces of freshly produced biochars became more hydrophilic during aging in an acidic soil (Rechberger et al. 2017).

A clear decrease in pH of the biochar particles was observed although the biochar amendment did not affect the pH of the spent growing medium; no effect of 10% v/v biochar in the blend on the pH of the spent growing media was noted. Co-composting of organic matter with biochar increases the CEC of biochar, mainly due to oxidation by microbial activity (Borchard et al. 2012; Khan et al. 2016; Prost et al. 2013). The sorption of soluble organic matter and its functional groups by biochar may also contribute to the effect of increase of CEC and sorption capacity of biochar (Borchard et al. 2012; Prost et al. 2013). The CEC of biochar can increase further due to the attraction of the negatively charged functional groups (Oliveira et al. 2017). Changes in biochar characteristics previously observed during composting (Borchard et al. 2012; Kamman et al. 2015; Khan et al. 2016; Prost et al. 2013) have now also been reported for biochar used in growing media in the current paper. The change in biochar characteristics during their use as bulk material observed in this study can also be considered as an advanced aging process which may affect their chemical and physical properties when the growing medium is reused or is used as a soil improver. This is also a topic for future research.

A limited but significant enrichment of the biochar particles with N was observed during use as growing medium. The N enrichment may be the result of N sorption or microbial N retention on the biochar surface, but this was not sufficient to affect the C:N ratio of the growing medium blend with biochar nor the other N related characteristics. In general, the N sorption capacity of biochars and the amount of N retained within biochars in bioavailable form remains small (Keskinen et al. 2021; Rasse et al. 2022; Viaene et al. 2023).

This study provides evidence that soilless cultivation can be considered as a bio-reactor, as it has potential to increase the value of composts and other materials for reuse, the value for C storage and soil improvement, and results in the activation of the biochar during use of renewable materials in horticultural substrates.

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Declarations

Conflict of interests The authors declare no conflict of interests.

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