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ARTICLE

Reducing peat in growing media: impact on nitrogen content, microbial activity, and CO_2 and N_2O emissions[1]

Aimé J. Messiga, Xiuming Hao, Noura Ziadi, and Martine Dorais

Abstract: Renewable materials including coir, biochar, and composts are investigated worldwide in the horticultural industry to partially substitute peat in growing media. In this study, we assessed the effects of biochar and vermicompost as partial substitution of peat and compared these peat-based growing media with coir in terms of NH_4^+-N and NO_3^--N content, CO_2-C and N_2O-N emissions and their microbial biomass carbon and nitrogen. Six growing media mixtures (peat; peat + biochar 9:1 *v/v*; peat + vermicompost 9:1 *v/v*; coir; coir + biochar 9:1 *v/v*; coir + vermicompost 9:1 *v/v*) replicated three times were incubated in growth chambers during a 60 d period. At day 0 of incubation (DAI), peat amended with biochar retained around 12.81% of NH_4^+-N compared with peat alone. The concentrations of NO_3^--N peaked at 275 $mg{\cdot}kg^{-1}$ at 33 DAI for peat and 552 $mg{\cdot}kg^{-1}$ at 46 DAI for coir amended with vermicompost. The substitution of peat with biochar resulted in large CO_2-C [2070 $\mu g\ CO_2\text{-}C{\cdot}g^{-1}$ dry weight (DW)] and N_2O-N (62.78 $\mu g\ N_2O\text{-}N{\cdot}g^{-1}$ DW) emissions, but not coir. The substitution of coir with vermicompost increased N_2O-N emissions at a much lower level (47.53 $\mu g\ N_2O\text{-}N{\cdot}g^{-1}$ DW) than peat (111.82 $\mu g\ N_2O\text{-}N{\cdot}g^{-1}$ DW). Our results showed that supplements of vermicompost in peat and coir improved N supply which could benefit plant growth, while substituting part of peat with biochar increased CO_2-C and N_2O-N emissions. In contrast, no effect of biochar was observed with coir, which is beneficial for the environmental footprint of short-cycle growing crops.

Key words: ammonium, microbial activity, nitrate, nitrous oxides, organic amendments.

Résumé : Partout dans le monde, les horticulteurs étudient des matériaux renouvelables comme la fibre de coco, le biocharbon et le compost dans l'espoir de remplacer une partie de la mousse de sphaigne dans les milieux de culture. Les auteurs ont évalué l'utilité du biocharbon et du vermicompost comme produit de substitution partiel à la mousse de sphaigne, puis ont comparé la concentration de N-NH_4^+ et de N-NO_3^-, les émissions de C-CO_2 et de N-N_2O ainsi que le carbone (CBM) et l'azote (NBM) de la biomasse microbienne dans les milieux de culture contenant de la mousse de sphaigne et de la fibre de coco. À cette fin, ils ont incubé à trois reprises six milieux de culture (mousse de sphaigne; mousse de sphaigne + biocharbon 9:1 *v/v*; mousse de sphaigne + vermicompost 9:1 *v/v*; fibre de coco; fibre de coco + biocharbon 9:1 *v/v*; fibre de coco + vermicompost 9:1 *v/v*) pendant 60 jours dans un phytotron. Le jour 0 de l'incubation (JI), la mousse de sphaigne bonifiée avec du biocharbon avait retenu environ 12,81 % de N-NH_4^+, comparativement à la mousse de sphaigne seule. La concentration de N-NO_3^- a atteint un maximum de 275 mg par kg à 33 JI dans la mousse de sphaigne et de 552 mg par kg à 46 JI dans la fibre de coco amendée avec du vermicompost. Remplacer la mousse de sphaigne par du biocharbon engendre d'importantes émissions de

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C-CO_2 (2070 μg par g de poids sec) et de N-N_2O (62,78 μg par g de poids sec), ce qui n'est pas le cas avec la fibre de coco. Remplacer la fibre de coco par du vermicompost accroît les émissions de N-N_2O, mais beaucoup moins (47,53 μg par g de poids sec) qu'avec la mousse de sphaigne (111,82 μg de N-N_2O par g de poids sec). Ces résultats indiquent qu'ajouter du vermicompost à la mousse de sphaigne ou à la fibre de coco améliore l'apport de N, ce qui pourrait bénéficier à la croissance des plantes, alors que remplacer une partie de la mousse de sphaigne par du biocharbon accroît les émissions de C-CO_2 et de N-N_2O. En revanche, le biocharbon ne semble avoir aucun effet avec la fibre de coco, ce qui allègerait l'empreinte environnementale des cultures à cycle court. [Traduit par la Rédaction]

Mots-clés : ammonium, activité microbienne, nitrate, oxyde nitreux, amendements organiques.

Introduction

In horticulture, the choice of the growing medium has a vital impact on the rhizosphere microbial communities, plant nutrition and growth, product quality, and production system eco-sustainability (Grunert et al. 2016). Peat is largely used for seedling production, potting plants, and as growing media for soilless production systems as well as by gardeners. Its wide use in the northern regions is due to the reliability, performance, and affordable cost of the material (Barrett et al. 2016). In the recent years, many alternative materials have been evaluated to protect this ecologically important resource. Despite the valuable properties of peat to grow plants, the drainage and excavation of peatlands release greenhouse gas into the atmosphere (Tubiello et al. 2016; Kern et al. 2017). Thus, renewable materials such as wood fiber, bark, coir, biochar, composts, and inorganic materials are becoming key components of the horticultural industry (Carlile et al. 2015; Zulfiqar et al. 2019; Lévesque et al. 2020*a*; Van Gerrewey et al. 2020).

Coir is the fibre obtained from the thick mesocarp of coconut (*Cocos nucifera* L.) fruit. It is mainly found in the tropics where this material is used as pure or mixed growing media for soilless and containerised crop production (Abad et al. 2002). The salinity of coir is variable ranging from 0.4 to 0.6 $mS \cdot cm^{-1}$ which may require washing procedures to remove the excess salt before utilisation (Noguera et al. 2000). The pH of coir varies between 5.2 and 6.8 which is an advantage compared with peat (pH ∼4) because it does not necessitate liming to raise the pH when used for some ornamental plants. Coir is resistant to microbial degradation owing to its high lignin and cellulose content (Noguera et al. 2000). The concentration of available N in coir is generally lower than peat, limiting the risk of N-leaching (Noguera et al. 2000). However, the cation exchange capacity (CEC) of coir varies from 31.7 to 99.4 $Cmol_c \cdot kg^{-1}$ (Abad et al. 2002), and values as high as 117 $Cmol_c \cdot kg^{-1}$ were reported (Noguera et al. 2000). A major constraint to the use of coir in temperate regions including Canada is the reliance on exportation which increases the production costs (Noguera et al. 2000) and reduce its sustainability compared with local substitute materials.

Utilization of organic materials such as biochar in highly performing growing media is also becoming very promising for soilless plant production systems (Zulfiqar et al. 2019; Lévesque et al. 2020*a*). Biochar is a carbon-rich by-product derived from the pyrolysis of biomass without oxygen (Zulfiqar et al. 2019). The organic material exhibits high surface functional groups associated with high cation and anion exchange capacity (Lehmann et al. 2003). For six types of soil amended with 10%–20% biochar, NO_3^--N concentration in the leachates was reduced by 30%–50% (Dorais et al. 2017). The ability of biochar to retain N is well recognized in soil-based cultivation systems and is highlighted in growing media mixtures including biochar (Lévesque et al. 2018, 2020*a*; Messiga et al. 2020). The addition of softwood biochar in peat reduced the concentration of NH_4^+-N in the growing media mixture (Dorais et al. 2017). The fixation of NH_4^+-N onto biochar may affect the activity of microorganisms by depleting or limiting the pool of NH_4^+ available for nitrification thus causing changes in microbial biomass and N_2O emissions (Lévesque et al. 2018). Furthermore, biochar allowed the establishment of potential plant growth-promoting bacteria (Lévesque et al. 2020*b*). Contrasting results on the role of biochar on microbial growth and communities and related N cycling highlight the need for research to elucidate these interactions particularly in growing media mixtures (Lévesque et al. 2020*a*).

Vermicomposting is a process through which organic wastes are decomposed by earthworms and mesophilic microbes (Bhat et al. 2013). Vermicomposting stabilizes organic matter through interactions between earthworms and microorganisms (Edwards and Fletcher 1988). The organic C content of the resulting material decreases but increases in the availability of macro- and micronutrients, particularly N occur during vermicomposting (Atiyeh et al. 2001). It is understood that the transit of organic waste in the gut of earthworms enhances the nitrification of mineral N and increases the population and composition of nitrifying microorganisms in vermicompost (Lv et al. 2019). The activity of earthworms also creates aerobic conditions favorable for the nitrification process (Cáceres et al. 2018). In a recent study, the addition of vermicompost in peat and coir contributed to increased leafy vegetable yield of cabbage and lettuce but also increased the concentration of NO_3^--N in the growing media and leachate (Messiga et al. 2020). High leachate losses of NO_3^--N during crop growth raise the

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Table 1. Physico-chemical properties of the growing media and amendments used in the study.

	Units	Coir	Peat	Biochar	Vermicompost
>2000 μm	%	10.0 (1.34)[a]	3.0 (1.13)	10.0 (0.71)	17.0 (3.26)
2000–1000 μm	%	70.0 (2.26)	60.0 (4.03)	58.0 (0.71)	81.0 (0.01)
1000–250 μm	%	18.0 (1.91)	31.0 (0.64)	24.0 (0.57)	2.0 (0.06)
<250 μm	%	2.0 (0.0)	6.0 (0.0)	8.0 (0.02)	0.0 (0.0)
Bulk density	$kg \cdot m^{-3}$	258.00 (24.04)	228.50 (26.16)	349.50 (3.54)	569.50 (20.51)
Electrical conductivity	$mS \cdot cm^{-1}$	0.31 (0.01)	0.29 (0.01)	4.81 (0.08)	3.49 (0.19)
pH		6.08 (0.02)	4.03 (0.06)	9.56 (0.08)	4.22 (0.06)
Organic matter	%	25.35 (0.35)	36.80 (0.42)	33.00 (0.28)	18.90 (0.00)
Dry matter	%	31.40 (0.57)	42.12 (2.52)	51.30 (0.14)	25.15 (0.07)
Total N	%	0.29 (0.04)	0.61 (0.02)	0.57 (0.02)	0.74 (0.00)
C/N ratio		49.50 (7.78)	33.50 (0.71)	98.50 (2.12)	14.00 (0.00)
NH_4^+-N	ppm	2.00 (0.00)	223.00 (48.08)	11.50 (9.19)	19.00 (4.24)
Phosphorus	%	0.01 (0.00)	0.03 (0.00)	0.39 (0.01)	0.03 (0.00)
Potassium	%	—[b]	0.03 (0.03)	1.58 (0.03)	0.01 (0.00)

[a]Values in parentheses represent standard deviations of means ($n = 2$).
[b]Not determined.

question of synchrony between the timing of NO_3^- release from the growing media mixtures and demand from growing plants which would be influenced by changes in microbial activity. Currently, there is limited knowledge on the interactions between vermicompost and peat as how these affect the N cycling and supply and microbial activity compared with renewable coir growing media (Lv et al. 2019; Pramanik 2010). This knowledge is crucial if vermicompost is used as partial substitute of peat in the formulation of highly performing growing media.

The benefits of partial substitution of peat by biochar and vermicompost as growing media mixtures on leafy vegetable yields were shown in a recent greenhouse study (Messiga et al. 2020). The growing media mixtures exhibited several beneficial characteristics that were captured through mineral N assessment in the leachates and as residual N after harvest. The fixation of NH_4^+-N by biochar during the first week of growth and the release of high concentrations of NO_3^--N by vermicompost. However, the timing of N fixation and release from these growing media mixtures and the activity of associated microbial activity were not clear. A better understanding of how the growing media mixtures affect N supply and the microbial activity that modulate these changes is, therefore, important. Consequently, we hypothesized that (a) partial substitution of peat with biochar will decrease NH_4^+-N concentrations compared with other peat-based growing media mixtures and (b) partial substitution of peat with vermicompost will increase NO_3^--N concentrations compared with other growing media mixtures, without impacting their environmental performance in terms of CO_2-C and N_2O-N emissions. The present study was then to assess the effects of biochar and vermicompost as partial substitution of peat, and compared peat with coir in terms of their supply of NH_4^+-N and NO_3^--N, CO_2-C and N_2O-N emissions, and their microbial biomass.

Materials and Methods

Characteristics of growing medium components

Peat was sourced from Sungro Horticulture (Canadian Sphagnum Peat Moss Grower, Grade White, OMRI Listed) and coir from CANNA COCO Natural PLANT MEDIUM (CANNA Canada Corp.). Composite samples of peat and coir were analyzed at a private laboratory (A&L Canada Laboratory Inc., London, Canada) using recommended methods (Messiga et al. 2020). The particle size distribution for peat and coir was 3% and 10% for >2000 μm, 60% and 70% for 2000–1000 μm, 31% and 18% for 1000–250 μm, and 6% and 2% for <250 μm (Table 1). The pH equated 4.03 for peat and 6.08 for coir. Total N content was 0.61% for peat and 0.29% for coir, whereas the concentration of ammonium N (NH_4^+-N) was 223 $mg \cdot kg^{-1}$ for peat and 2.0 $mg \cdot kg^{-1}$ for coir.

Biochar was sourced from Canadian AgriChar (OMRI Listed, Maple Ridge, Canada) and vermicompost from Nurturing Nature Organics Inc. (OMRI Listed, Lake Country, Canada). The particle size distribution of biochar and vermicompost was 10% and 17% for >2000 μm, 58% and 81% for 2000–1000 μm, 24% and 2% for 1000–250 μm, and 8% and 0% for <250 μm (Table 1). The pH was 9.56 for biochar and 4.22 for vermicompost. The dry matter content was 51.30% for biochar and 25.15% for vermicompost. Total N was 0.57% for biochar and 0.74% for vermicompost. The concentration of NH_4^+-N was 11.50 $mg \cdot kg^{-1}$ for biochar and 19.00 $mg \cdot kg^{-1}$ for vermicompost (Table 1).

Incubation experiment

Six combination of growing media mixtures were assessed during a 60 d incubation experiment in three growth chambers (Conviron Adaptis A1000, Winnipeg, Canada) at Agassiz Research and Development Centre (BC, Canada). Eight destructive samplings for the growing media mixtures were retained, and the treatments × sampling dates were arranged in a randomized complete block design with three replicates for a total of 144 experimental units (six growing media mixtures × eight sampling dates of 0, 3, 7, 12, 18, 32, 46, and 60 d × three replicates). The six growing media mixtures were prepared by mixing peat and coir with biochar or vermicompost amendments on a plastic tarp using the same proportions as described by Messiga et al. (2020) in *v*/*v*: (1) 100% peat (peat), (2) 90% peat + 10% vermicompost (peat + vermicompost), (3) 90% peat + 10% biochar (peat + biochar), (4) 100% coir (coir), (5) 90% coir + 10% biochar (coir + biochar), and (6) 90% coir + 10% vermicompost (coir + vermicompost). We weighed 30 g of each growing media mixture into 250 mL Mason jars. As such, the total amount of N associated with the growing medium was 183 mg N·jar^{-1} (6.11 g N·kg^{-1}) for peat, 181 mg N·jar^{-1} (6.04 g N·kg^{-1}) for peat + biochar, 194 mg N·jar^{-1} (6.48 g N·kg^{-1}) for peat + vermicompost, 87 mg N·jar^{-1} (2.9 g N·kg^{-1}) for coir, 105 mg N·jar^{-1} (3.49 g N·kg^{-1}) for coir + biochar, and 196 mg N·jar^{-1} (4.79 g N·kg^{-1}) for coir + vermicompost. A bottle top dispenser was used to add distilled water (approximately 7 mL) into the Mason jars to reach approximately 60% water field pore space (WFPS), and then the moist growing media was mixed with a spatula. Maximum microbial activity is achieved at 60% WFPS (Franzluebbers 1999). The Mason jars were then closed with a parafilm. A needle was used to puncture 10 holes on the parafilm sheet to allow gas exchange. The 144 Mason jars were then arranged in the three growth chambers with each growth chamber representing one replicate. The growth chambers were set at day-length of 16 h (0600–2200), day temperature of 22 ±2 °C, night temperature of 20 ±2 °C, and relative humidity of 70%. These parameters were selected to mimic the environmental conditions we used in a previous pot experiment in the greenhouse with the same growing media (Messiga et al. 2020). One extra Mason jar per growing media was placed in each growth chamber for a total of 18 additional Mason jars. These 18 Mason jars were weighed every 3 d to check moisture content. Humidity was adjusted when needed by adding distilled water every time the moisture content decreased by more than 10%. All Mason jars (162 jars) were pre-incubated in the growth chambers for 7 d.

Gas sampling and analyses

At the end of the pre-incubation period of 7 d, gas samples were collected throughout the duration of the incubation experiment on the same set of sampling jars corresponding to 0, 3, 7, 12, 18, 32, 46, and 60 d after incubation (DAI). For all gas sampling periods, two set of samples were collected: the first corresponded to time *t*0 ($T = 0$ h) and was collected the day before; the second corresponded to time *t*1 ($T = 24$ h) and was collected after 24 h. Briefly, during the preparation phase, the punctured parafilm was removed from the sampled jars, and air inside the jar was mixed using a handheld fan. The sampled jar was then tightly closed with a lid equipped with a rubber septum. The headspace of the closed sampled jar was sampled using a 50 mL syringe, and the gas was injected into a 12 mL pre-evacuated Exetainer vial (Labco, High Wycombe, UK). After 24 h, the headspace of the closed sampled jar was sampled again as described above, and the collected gas was injected into a second pre-evacuated Exetainer vial. At the end of the sampling phase, the lid equipped with the rubber septum was removed, and the air inside the sampling jar was mixed with a handheld fane, and the jar was closed with a punctured parafilm until the next sampling date. All gas samples collected were analyzed for CO_2 and N_2O concentrations using a gas chromatograph (model 3800, Varian Inc., Walnut Creek, CA, USA) equipped with an electron capture detector (N_2O) and a flame ionization detector (CO_2). Gas emissions were calculated according to the equations of CO_2-C and N_2O-N fluxes (Rochette and Bertrand 2007), and cumulative gas emissions were calculated by linear interpolations between sampling dates.

Growing media sampling and analyses

At each of the eight sampling dates, the corresponding Mason jars were removed from the growth chambers, and four sets of 5.0 g moist growing media were taken for subsequent analyses. The first and second sets of subsamples were used for microbial biomass carbon (MBC) and nitrogen (MBN) extractions using the chloroform fumigation–extraction method (Voroney et al. 2008). Briefly, the first set (non-fumigated) was placed into a 50 mL centrifuge tube containing 30 mL of 0.25 mol·L^{-1} K_2SO_4 and shaken end-over-end for 1 h; the second set (fumigated) was placed into 50 mL glass beakers which were arranged in a desiccator and fumigated with 50 mL ethanol-free chloroform for 24 h in the dark. The growing media were then transferred into 50 mL centrifuge tubes containing 30 mL of 0.25 mol·L^{-1} K_2SO_4 and shaken end-over-end for 1 h. All suspensions (non-fumigated and fumigated) were centrifuged at 4500 r·min^{-1} for 10 min, and the supernatant filtered using Whatman filter paper. The filtrates were stored at 4 °C and analyzed within 48 h using a TOC analyzer (Shimadzu Total Organic Carbon-Visionary Series; TOC-VCPH+TNM-1, Maryland, USA). The concentrations of MBC and MBN were then calculated by using extraction coefficients of 0.35 and 0.50 for MBC (K_{EC}) and MBN (K_{EN}), respectively (Voroney et al. 2008). The third set of 5.0 g moist growing media was used for mineral N (NO_3^- and NH_4^+) analysis using KCl extraction. Briefly, 5.0 g moist growing media was extracted with 2 mol·L^{-1} KCl using a 1:10 (*w*:*v*) growing media:extractant ratio. All extracts were analyzed colorimetrically for

Fig. 1. Evolution of ammonium (NH_4^+-N) nitrogen concentrations of six growing media mixtures during a 60 d incubation period. Means followed by asterisks are significantly different at a given day after incubation (*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$).

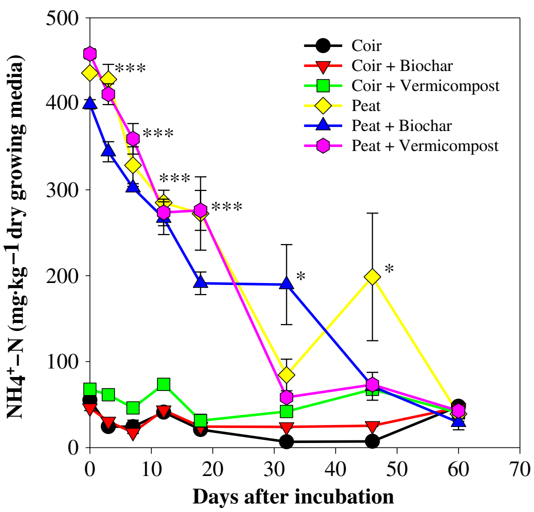
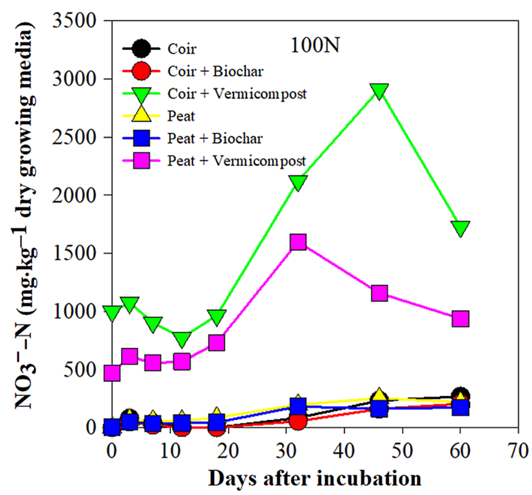


Fig. 2. Evolution of nitrate (NO_3^--N) nitrogen concentrations of six growing media mixtures during a 60 d incubation period. Means followed by asterisks are significantly different at a given day after incubation (*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$).



NO_3^- and NH_4^+ using a flow injection analyzer (Tecator FIAStar 2010) as described by Maynard et al. (2007). The fourth set was used to determine the moisture content and was placed into an aluminum cup and oven-dried at 105 °C for 48 h.

Statistical analysis

An analysis of variance based on the randomized complete block design was performed for data of NH_4^+-N, NO_3^--N, CO_2-C, and N_2O-N emissions in the growing media, using SAS PROC MIXED, version 9.3 (SAS Institute 2010), considering block as a random factor, sampling dates as repeated effects, and growing media mixtures as fixed effects. Data of cumulative CO_2-C and N_2O-N emissions and cumulative MBC and MBN in the growing media at the end of the 60 d incubation were analyzed using SAS PROC MIXED considering block as a random factor and growing media mixtures as fixed effects. Differences among least square means (LSMEANS) for all treatment pairs were tested at a significance level of $P = 0.05$.

Results

Evolution of mineral nitrogen concentrations

For peat-based growing media mixtures, the concentration of NH_4^+-N decreased from 430 mg·kg^{-1} at 0 DAI to 37 mg·kg^{-1} at 60 DAI (Fig. 1). On the other hand, the concentration of NH_4^+-N of coir-based growing media slightly varied from 58.2 mg·kg^{-1} at 0 DAI to 39.5 mg·kg^{-1} at 60 DAI. During the first days of incubation, peat amended with biochar had lower NH_4^+-N concentrations compared with peat alone and peat amended with vermicompost; NH_4^+-N concentration in peat amended with biochar was lower than peat alone by 12.8% at 0 DAI, 19.7% at 3 DAI, and 8.0% at 7 DAI. Little changes were observed for coir amended with biochar compared with coir alone. However, coir amended with vermicompost had higher NH_4^+-N concentrations (23.1% at 0 DAI, 152.3% at 3 DAI, 89.5% at 7 DAI, 78.4% at 12 DAI for coir alone; 47.4% at 0 DAI, 101.8% at 3 DAI, 161.6% at 7 DAI, 68.5% at 12 DAI for coir amended with biochar) compared with the other coir-based growing media. Vermicompost had no significant effect when mixed with peat, except at 46 DAI, which was 63.12% lower.

In contrast to NH_4^+-N, NO_3^--N concentrations increased steadily up to a peak around 32 and 46 DAI for peat and coir amended with vermicompost, respectively (Fig. 2). Specifically, for peat amended with vermicompost, NO_3^--N concentration peaked at 32 DAI with 275 mg·kg^{-1} followed by a decreasing trend down to 44.7 mg·kg^{-1} at 60 DAI (Fig. 2). For coir amended with vermicompost, NO_3^--N concentration peaked at 552 mg·kg^{-1} at 46 DAI followed by a decreasing trend down to 251 mg·kg^{-1} at 60 DAI (Fig. 2). For coir and peat alone and coir and peat amended with biochar, NO_3^--N concentration during the incubation period remained close to 0 mg·kg^{-1} between 0 DAI and 18 DAI, then increased steadily up to 50 mg·kg^{-1} (coir) and 33 mg·kg^{-1} (peat) at 60 DAI (Fig. 2).

Evolution of CO_2-C and N_2O-N during the incubation period

During the respective sampling dates, peat amended with biochar had the highest CO_2-C emission rate, whereas peat amended with vermicompost had in average the lowest CO_2-C emission rate; the peat alone having an intermediate emission rate (Fig. 3*a*). After

Fig. 3. Evolution of (*a*) hourly CO_2-C and (*b*) cumulative CO_2-C emissions by six growing media mixtures during a 60 d incubation period. Means followed by asterisks are significantly different at a given day after incubation (*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$).

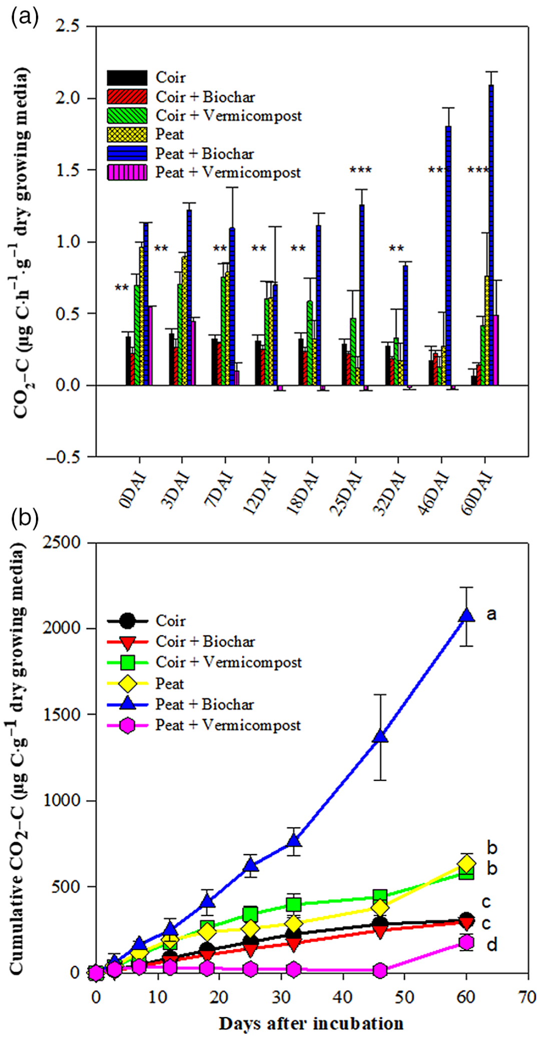
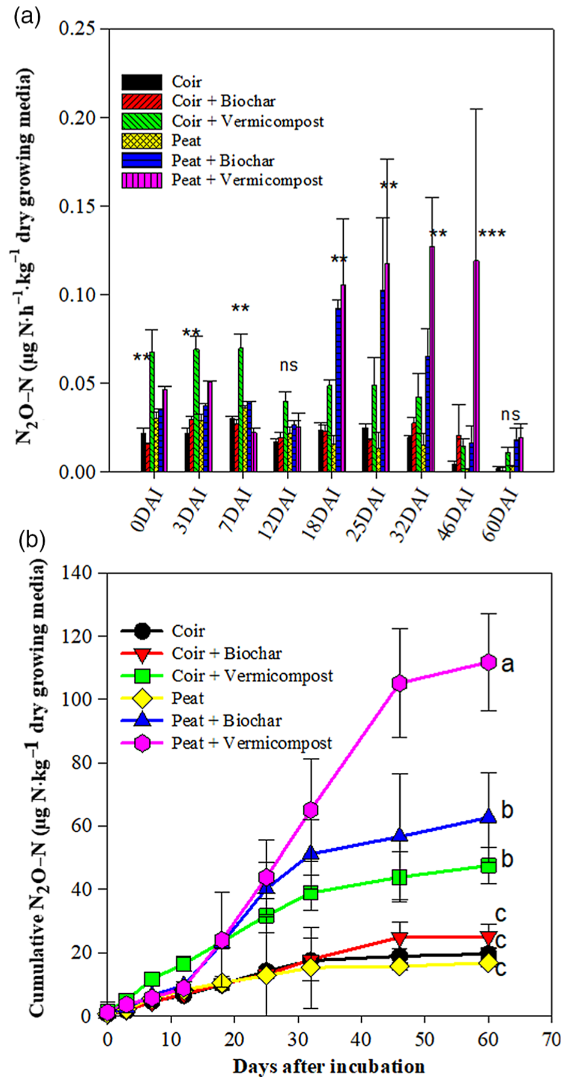


Fig. 4. Evolution of (*a*) hourly N_2O-N and (*b*) cumulative N_2O-N emissions by six growing media mixtures during a 60 d incubation period. Means followed by asterisks are significantly different at a given day after incubation (*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$).



60 DAI, the cumulative CO_2-C emission was 180 μg $CO_2\text{-}C{\cdot}g^{-1}$ dry weight (DW) for peat amended with vermicompost, 638 μg $CO_2\text{-}C{\cdot}g^{-1}$ DW for peat alone, and 2070 μg $CO_2\text{-}C{\cdot}g^{-1}$ DW with peat amended with biochar (Fig. 3*b*). Thus, the partial substitution of peat with biochar increased the cumulative CO_2-C emissions by 3.2 times (636–2070 μg $CO_2\text{-}C{\cdot}g^{-1}$ DW), whereas the substitution of peat with vermicompost decreased the cumulative CO_2-C emissions by 3.5 times (636–179 μg $CO_2\text{-}C{\cdot}g^{-1}$ DW). In contrast to peat, the partial substitution of coir with biochar did not modify the cumulative CO_2-C emissions, whereas the substitution of coir with vermicompost increased the cumulative CO_2-C emissions by 0.9 time (306–582 μg $CO_2\text{-}C{\cdot}g^{-1}$ DW).

During the first week of incubation, coir amended with vermicompost had the highest N_2O-N emission rate among all growing media mixtures (Fig. 4*a*). However, peat amended with vermicompost followed by peat amended with biochar had higher N_2O-N emissions between 18 and 46 DAI. The cumulative N_2O-N emission after 60 DAI was affected by the growing media mixtures. The cumulative N_2O-N emissions varied from 16.77 μg $N_2O\text{-}N{\cdot}g^{-1}$ DW with peat alone to 111.82 μg $N_2O\text{-}N{\cdot}g^{-1}$ DW with peat amended with vermicompost (Fig. 4*b*). The partial substitution of peat and coir with vermicompost increased N_2O-N emissions compared with their substitution with biochar. Indeed, peat with biochar increased the cumulative N_2O-N emissions by 3.7 times compared with peat alone (16.78–62.78 μg $N_2O\text{-}N{\cdot}g^{-1}$ DW), whereas the substitution of peat with vermicompost increased the cumulative N_2O-N emissions by 6.7 times (16.78–111.82 μg $N_2O\text{-}N{\cdot}g^{-1}$ DW). Similar trend, but at a much lower level, was observed

Fig. 5. Evolution of microbial biomass carbon of six growing media mixtures during a 60 d incubation period. Means followed by asterisks are significantly different at a given day after incubation (*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$).

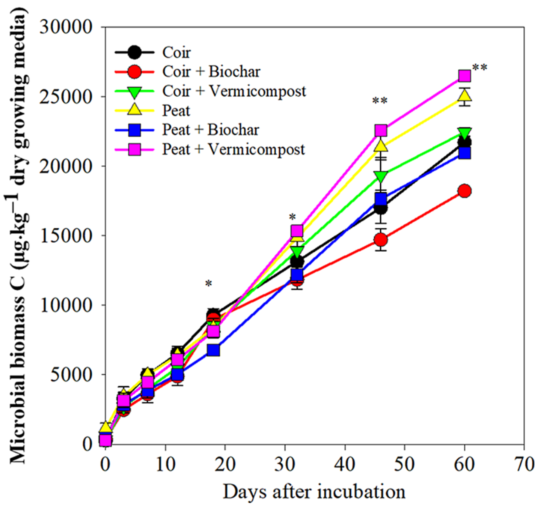
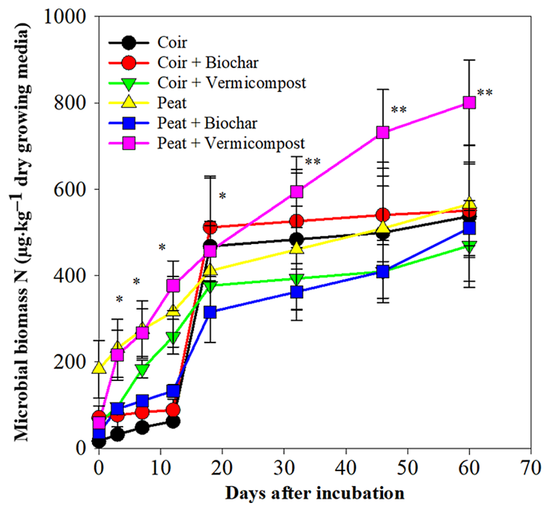


Fig. 6. Evolution of microbial biomass nitrogen of six growing media mixtures during a 60 d incubation period. Means followed by asterisks are significantly different at a given day after incubation (*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$).



for coir amended with vermicompost where the cumulative N_2O-N emission increased by 1.3 times (19.57–47.53 µg N_2O-N·g^{-1} DW). On the other hand, peat and coir alone had a similar low-cumulative N_2O-N emissions.

Evolution of MBC and MBN during the incubation period

The cumulative MBC was significantly affected by the growing media at 18, 32 46, and 60 DAI. The cumulative MBC varied from 18.2 µg·g^{-1} DW with coir amended with biochar to 26.5 µg·g^{-1} DW with peat amended with vermicompost (Fig. 5). The partial substitution of peat or coir with biochar decreased the cumulative MBC compared with peat and coir alone or amended with vermicompost. Thus, at 60 DAI, the substitution of peat with biochar decreased the cumulative MBC by 16.0% (24.9–20.9 µg·g^{-1} DW), whereas the substitution of peat with vermicompost increased the cumulative MBC by 5.7% (24.9–26.4 µg·g^{-1} DW). Similarly, the partial substitution of coir with biochar decreased the cumulative MBC by 16% (21.7–18.2 µg·g^{-1} DW), whereas its amendment with vermicompost increased the cumulative MBC by 3.2% (21.7–22.4 µg·g^{-1} DW).

The cumulative MBN was significantly affected by growing media and sampling dates. It varied from 0.47 µg·g^{-1} with coir amended with vermicompost to 0.80 µg·g^{-1} with peat amended with vermicompost (Fig. 6). The partial substitution of peat with biochar decreased MBN by 10% (0.57–0.51 µg·g^{-1} DW), whereas the substitution of peat with vermicompost increased MBN by 41% (0.57–0.80 µg·g^{-1} DW) compared with peat alone. On the other hand, the partial substitution of coir with biochar had no significant effect on MBN, whereas its substitution with vermicompost decreased MBN by 13% (0.54–0.47 µg·g^{-1} DW). It is interesting to observe that there was a spike in MBN accumulation between 12 and 18 DAI, and then a plateau was reached, except for peat amended with vermicompost that continued to increase. For example, for coir amended with biochar MBN increased by 25% between 0 and 12 DAI, and by 623% between 0 and 18 DAI. Similar patterns were obtained with the other treatment combinations.

Discussion

Dynamics of mineral nitrogen (NH_4^+-N and NO_3^--N) during the incubation

High initial NH_4^+-N concentrations in peat-based growing media could result from ammoniation, a process through which ammonia is sorbed onto peat at high temperatures (Nommik 1967). A study conducted in Quebec showed that at ammoniation rates above 30 g NH_3 kg·dry peat^{-1}, exchangeable NH_4^+-N is the dominant N fraction in ammoniated peat (Abbes et al. 1995). Ammoniated peat has several benefits for plant growth including enhanced N uptake, root length, and root growth rate (Abbes et al. 1995). However, a recent greenhouse study showed that the use of this material as growing media can result in high concentrations of NH_4^+-N in the leachates at early growth stages when the plant root system is not yet developed to take up or scavenge the inorganic N (Messiga et al. 2020). In greenhouse production systems with nutrient recirculation, the synchrony between plant N needs and N supply can be achieved through the recycling of the leached inorganic N back to the growing media. This source of N could be particularly beneficial for microgreen productions with short growth cycle (7–21 d) and relatively low

N requirement compared with longer growing crops where this source of N will be negligible.

Although all peat growing media had high initial values, it is interesting to observe that they all had a similar and low NH_4^+-N concentrations at 60 DAI compared with the coir-based growing media that had a constant and low initial value (Fig. 1). The lower initial NH_4^+-N concentration of peat amended with biochar compared with peat alone or amended with vermicompost is in agreement with a previous greenhouse study using cabbage and lettuce as test crops (Messiga et al. 2020). These results are also in line with previous studies showing that biochar owing to its large surface area, surface charge, and cation exchange capacity can fix NH_4^+-N, thus reducing potential risk of inorganic N leaching. For example, Teutscherova et al. (2018) showed that holm oak biochar produced at 600 °C increased NH_4^+-N sorption in a sandy Acrisol. Lehmann et al. (2003) reported that reduced N leaching through soils amended with biochar was partly explained by NH_4^+-N sorption due to the higher CEC and increased water-holding capacity. The substitution of peat with softwood biochar for soilless marigold growth also resulted into reduced extractable NH_4^+-N as well as for organic tomato greenhouse crops (Dorais et al. 2017; Margenot et al. 2018). It is also interesting to observe that lower NH_4^+-N concentrations in peat amended with biochar compared with the other peat-based growing media mixtures occurred only at the beginning of the incubation experiment indicating a rapid NH_4^+-N sorption process. This could be explained by the fine particle size of biochar allowing better mixing conditions with peat. It is also possible that biochar altered the hydrophobicity or water repellency of peat by enhancing water infiltration and retention (Lehmann et al. 2003), thus removing the NH_4^+-N from the ammoniated peat and transferring it onto biochar.

Coir-based growing media mixtures had low NH_4^+-N concentrations throughout the incubation period showing that neither the carbon-rich material nor the two amendments, biochar and vermicompost, were sources of NH_4^+-N (Fig. 1). On the other hand, coir and peat amended with vermicompost had high initial NO_3^--N concentrations compared with the other growing media mixtures indicating that vermicompost was the source of NO_3^--N (Fig. 2). The sharp increase in NO_3^--N concentrations obtained between 18 and 32 DAI for peat amended with vermicompost, and 18 and 46 DAI for coir amended with vermicompost (Fig. 2), suggests favorable conditions for the nitrification process. The amount of vermicompost was 12.9 g in coir + vermicompost but 8.61 g in peat + vermicompost (Messiga et al. 2020). The difference was due to the bulk densities of coir (258 $kg \cdot m^{-3}$) and peat (228 $kg \cdot m^{-3}$) (Table 1). The additional 4.29 g of vermicompost (0.082 mg NH_4^+-N per pot) could have extended the nitrification process in coir + vermicompost mixture up to 46 DAI. Studies showed that nitrification is a dominant process associated with the decomposition of organic N during vermicomposting (Lv et al. 2019). Burrowing and shuttling activities of earthworms during vermicomposting improve aerobic conditions and resulting in high nitrification rates (Cáceres et al. 2018). The initial NO_3^--N concentration observed prior to 18 DAI could be explained by the immobilization of NO_3^--N during vermicomposting in the earthworm's tissues and cells and microbial biomass or sorption onto vermicompost materials. The NO_3^--N or its precursors such as nitrites immobilized during the vermicomposting process could represent a transient phase that leads to nitrification once favorable conditions prevail. Among the favorable conditions that trigger the reactivation of microbial activity are the cycles of drying and rewetting (Chen et al. 2014) as well as mixing of coir or peat with vermicompost before and during the incubation. The nitrification proceeded over a long period (18–46 DAI) under coir amended with vermicompost owing to the physical properties of the growing media mixture (Fig. 2). Coir is a loose and fluffy material compared with peat, and therefore, the mixture between coir and vermicompost had more pores available for water and gas exchanges, conditions favorable for the nitrification process. The prolonged nitrification process favored N supply and supported higher leafy vegetable yields obtained under coir amended with vermicompost compared with peat amended with vermicompost growing media during the greenhouse experiment (Messiga et al. 2020).

CO_2-C and N_2O-N emissions and microbial biomass C and N

The large cumulative CO_2-C and N_2O-N emissions obtained under peat amended with biochar is in line with several studies (Liu et al. 2016; Wang et al. 2020), but in contrast with others (Dorais et al. 2017). The increase in CO_2 emission with biochar is generally associated with the labile C contained in biochar itself (Lévesque et al. 2020*b*). High NH_4^+-N content associated with peat may have enhanced the mineralization of labile C of biochar. Thus, the association between NH_4^+-N from peat and labile C from biochar was favorable for CO_2 emission in peat amended with biochar. Studies conducted on soils with varying properties showed that fluxes of CO_2 and N_2O with biochar addition increased with N fertilizer rates (Fang et al. 2016; Wang et al. 2020). In the other hand, Lévesque et al. (2020*b*) found that addition of compost decreased CO_2 emissions probably due to the low priming effect on native soil C decomposition. In stark contrast with peat, coir amended with biochar did not impact CO_2 and N_2O emissions (Figs. 3 and 4). This could be explained by differences in coir and peat characteristics that may have inhibited the mineralization of labile C contained in biochar resulting in sharper plateau after 18 DAI and lower MBC at 60 DAI (Table 1). The total N and NH_4^+-N concentrations were lower in coir compare with peat which may have limited the mineralization of labile C associated with biochar when mixed with coir, resulting in a lower MBC after 60 DAI. The pH of coir was greater than peat (6.08 vs. 4.03), and studies have shown that biochar may increase net emissions in acidic environments (Sheng et al. 2016).

High fluxes of CO_2-C and N_2O-N under peat amended with biochar compared with peat alone did not translate into high concentrations of cumulative MBC and MBN (Figs. 5 and 6), whereas the opposite was observed for peat amended with vermicompost. Microbial biomass under coir amended with biochar was lower (MBC) or similar (MBN) compared with coir alone, which is in line with the trends of CO_2 and N_2O emissions that were not different. Except for peat amended with vermicompost, the limited MBN increase beyond 20 DAI suggests that the pool of labile C, associated with biochar or with the other growing medium materials, that could feed microbial growth was limited (Xu et al. 2016). In a previous experiment, we observed that the growth of young cabbage plants was delayed under peat and coir amended with biochar in the absence of N fertilizer until 2–3 wk after transplanting. We also observed re-growth following this period indicating that N was supplied to the young cabbage plants which is consistent with the increase of MBN (Messiga et al. 2020). It is, therefore, possible that the spike in MBN was re-mineralized into mineral N, which would support the increase in NO_3^--N observed for peat and coir amended with vermicompost after 32 and 46 DAI, respectively (Figs. 1 and 2).

The large cumulative N_2O-N emission obtained with addition of vermicompost in peat and coir compared with their respective control, was induced by the high NO_3^--N content measured between 18 and 46 DAI (Fig. 2). In a previous study, we also found that partial substitution of peat and coir with vermicompost increased NO_3^--N concentrations in the growing media and leachates (Messiga et al. 2020). High N concentrations due to N fertilization tends to exponentially increase N_2O emissions (Shcherbak et al. 2014; Lévesque et al. 2020*b*). Denitrification of NO_3^- could explain part of the increased N_2O emissions particularly under prevailing anaerobic conditions. During vermicomposting, the transit of organic substrates and microorganisms in the gut of earthworms facilitates spore germination which would explain the increasing MBC and MBN in peat amended with vermicompost (Pramanik 2010). Another study also demonstrated that some fungal strains responsible for rapid mineralization of wastes increased after earthworm gut passage (Aira et al. 2005). Vermicompost used in this study was sticky and maintained high moisture content (bulk density of 569.5 $kg \cdot m^{-3}$, dry matter content of 25.15% and coarse particles including 17% >2000 μm and 81% between 2000 and 1000 μm; Table 1) which may have favoured anaerobic conditions and, therefore, increased denitrification after 32 or 46 DAI (Figs. 2, 5, and 6). Studies have shown that N_2O emissions increased dramatically at water-filled pore space >70% (Barton and Schipper 2001). To benefit from the properties of vermicompost including an increased NO_3^--N supply as partial substitute of peat, improved water management would be a key issue. Strategies that avoid or limit anaerobic conditions in the growing media will be needed to reduce denitrification and, therefore, losses of N through N_2O-N emissions. The pH of the growing media could also explain the higher N_2O-N emissions observed under peat amended with vermicompost (Figs. 4*a*, 4*b*). Peat and vermicompost had acidic pH, 4.03 and 4.22, respectively (Table 1). Messiga et al. (2020) observed that the mixture of peat and vermicompost at the end of one cycle of cabbage and lettuce production had an acidic pH suggesting that the pH of the mixture remained acidic throughout the incubation experiment. Several studies have reported increased N_2O emissions with decreasing soil pH in the range of acidic pH (Šimek and Cooper 2002; Sun et al. 2012). Wang et al. (2018) in a regional study in China reported that soil pH is the main factor explaining regional disparities in N_2O emissions. The main mechanism controlling N_2O emissions across the range of acidic pH is the inhibition of a functional N_2O reductase enzyme (Bakken et al. 2012; Liu et al. 2014). It is, therefore, possible that the acidic pH of peat amended with vermicompost growing inhibited the functional N_2O reductase enzyme, thus increasing N_2O emissions. Raising soil pH of acidic soils to neutrality by liming has resulted to decreased soil N_2O emissions (Hénault et al. 2019). Additional management practices including liming to raise the pH of peat amended with vermicompost close to neutrality could be important to decrease the associated N_2O emissions.

Conclusion

Partial substitution of peat with biochar decreased the concentration of NH_4^+-N in the growing media mixture during the incubation study of 60 d. In addition, large CO_2-C and N_2O-N emissions were also associated with peat amended with biochar, although no relationship with MBC and MBN was observed. In contrast to peat, amending coir with biochar did not impact the CO_2-C and N_2O-N emissions, which, similarly to peat amended with biochar, were not related to MBC and MBN. These chemical changes occurring in peat amended with biochar growing media mixture indicate that the high NH_4^+-N from peat enhanced the mineralization of labile C content in biochar, resulting in high CO_2-C and N_2O-N emissions. On the other hand, partial substitution of peat and coir with vermicompost increased the concentration of NO_3^--N during the incubation study, indicating that vermicompost was a significant source of this nutrient. This NO_3^--N concentration increase, however, induced large cumulative N_2O-N emissions as vermicompost maintained a high moisture. Higher N_2O-N emissions of peat amended with vermicompost were associated with higher MBN and MBC, whereas only MBN was related to the cumulative N_2O-N emissions of coir amended with vermicompost. Substituting part of the peat and coir with biochar had a different impact on CO_2-C and N_2O-N emissions, which may affect their environmental footprint. Our results highlight that biochar reduces NH_4^+-N availability in the short term (up to 32 DAI), whereas vermicompost improves NO_3^--N supply through the mid-term (32–46 DAI), which would be an important contribution of high-performing growing media mixtures to plant nutrition through nutrients recycling.

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