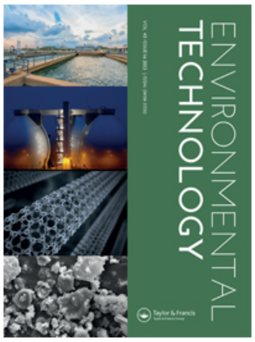

Environmental Technology

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tent20

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To cite this article: Simon Weldon, Pierre-Adrien Rivier, Erik J. Joner, Claire Coutris & Alice Budai (2022): Co-composting of digestate and garden waste with biochar: effect on greenhouse gas production and fertilizer value of the matured compost, Environmental Technology, DOI: 10.1080/09593330.2022.2089057

To link to this article: https://doi.org/10.1080/09593330.2022.2089057

Published online: 22 Jun 2022.

ENVIRONMENTAL TECHNOLOGY
https://doi.org/10.1080/09593330.2022.2089057

Co-composting of digestate and garden waste with biochar: effect on greenhouse gas production and fertilizer value of the matured compost

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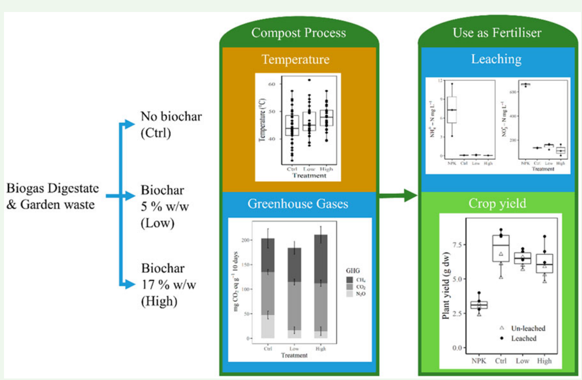
ABSTRACT

Biogas digestate is a nitrogen (N) rich waste product that has potential for application to soil as a fertilizer. Composting of digestate is recognized as an effective step to reduce potentially negative consequences of digestate application to soils. However, the structure of the digestate and the high N content can hinder effective composting. Biochar, which can be produced through the pyrolysis of waste biomass, has shown the potential to improve compost structure and increase N retention in soils. We studied how a high-temperature wood biochar affects the composting process, including greenhouse gas emissions, and the fertilizer value of the compost product including nutrient content, leachability and plant growth. The high Biochar dose (17% w/w) had a significantly positive effect on the maximum temperature (5°C increase vs. no biochar) and appeared to improve temperature stability during composting with less variability between replicates. Biochar addition reduced cumulative N_2O emission by 65–70%, but had no significant effect on CO_2 and CH_4 emission. Biochar did not contribute to greater retention of nitrogen (N) contained in the digestate, but had a dilution effect on both N content and mineral nutrients. Fertilization with compost enhanced plant growth and nutrient retention in soil compared to mineral fertilization (NPK), but biochar had no additional effects on these parameters. Our results show that biochar improves the composting of digestate with no subsequent negative effects on plants.



ARTICLE HISTORY
Received 6 April 2022
Accepted 1 June 2022

KEYWORDS
Biochar fertilizer; nutrient leaching; nutrient availability; carbon storage; methane

1. Introduction

Recycling of organic wastes using anaerobic digestion is an increasingly important strategy to derive energy and organic products from resources that are otherwise underutilized [1,2]. One of the key challenges with anaerobic digestion is the production of digestate, which is a nitrogen (N) rich waste product. Direct application of digestate to land can be problematic because it may contain phytotoxic compounds, has a strong odour and may require sterilization [3–6]. For this reason, dewatering and composting have been proposed as a method to treat digestate prior to use as a fertilizer [4]. However, composting of dewatered digestate is difficult due to the physical properties of the digestate, which can result in anaerobic conditions with enhanced emissions of greenhouse gases (GHG) and a slow composting process [3].

A solution to mitigate this effect of poor feedstock structure is to add a bulking agent [7]. Traditionally

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/09593330.2022.2089057

this would include products such as wood chip, which would provide structure and porosity to the compost. In recent years there has been increasing interest in the application of biochar to the composting process. Biochar is produced by the pyrolysis of organic feedstocks and is a highly stable carbon form with high porosity and relatively high surface area [8,9]. The resistance of biochar to decomposition in soil, and its potential value as a C mitigation tool is the primary reason for the significant interest biochar has attracted over the last two decades [10]. During that time, biochar research has also identified co-benefits of biochar that make it suited for application to soils to increase plant yield [11], reduce GHG emissions and improve soil quality and nutrient retention [12]. These properties have also raised interest in the application of biochar as an additive to compost [13–16].

Biochar has been shown to improve the composting process through reductions in GHG emissions [17], reductions in maturation time and increasing temperature development and stability [18–20]. Biochar addition has also been shown to have a direct impact on both microbial abundance and diversity [21]. The mechanisms proposed to explain this effect range from pH effects [22], increased oxygen infiltration [23,24], facilitation of redox processes [17] and sorption of substrates as either nutrients [25] or gas [26]. There is also evidence that biochar can have a positive effect on the final compost product, increasing its value as a fertilizer through positive effects on plant yields and nutrient retention [27]. However, across the literature, results are variable with both positive, neutral and negative effects of compost biochar mixes on the yield effect of the final product (reviewed by Wang, Villamil [28]). Previous studies have suggested that high applications of biochar (>10% w/v) can have negative consequences on composting process, leading to increased water loss and heat dissipation [24]. Others have argued that application rates above 20% (both w/w and w/v) are generally harmful to the composting process [13,24].

To our knowledge, no one has yet assessed the effect of biochar amendment on both the composting process with digestate and the function of the final product as a fertilizer. Such studies are important in order to identify potential synergies and trade-offs. We examined the effect of biochar amendments at two contrasting application rates both low (5 % w/w) and high (17 % w/w). We used a closed batch composting system consisting of modified consumer-grade composting tumblers. The set-up allowed for headspace sampling for quantification of GHG and treatment-dependent generation of heat in the individual chambers, mimicking the natural temperature progression encountered when composting larger volumes. We tested the fertilizer properties of the final composts (without and with biochar) against a NPK mineral fertilizer treatment in a plant growth experiment with spring onions, using a loamy soil with low soil organic carbon. Due to the low carbon content of the soil, we also tested the impact of a leaching event on both plant yield and the loss of nutrients.

We hypothesized that (1) Biochar addition to composting would improve the key measurables of the composting process, increasing maximum temperature and reducing GHG production. (2) Co-composting with biochar would result in a product that has higher nutrient content. (3) Biochar amendment would further improve the retention of the nutrients in the compost product after addition to soil. (4) Nutrients stabilized by biochar are plant available, and the presence of biochar does not reduce plant yield. And (5) The effects on composting process and fertilizer value of the final product would depend on biochar application rate.

2. Materials and methods

2.1. Input materials for composting

Biogas digestate, garden waste and biochar were used in the composting experiment. Dewatered biogas digestate (dry matter content 29%) was collected from a biogas plant at Vormsund, Norway, using food waste as substrate for biogas production. The digestate was used in the experiment the day following its sampling at the biogas plant. Characteristics of the digestate are presented in Table 1. Fresh garden waste was collected at a municipal waste facility at Bølstad, Southern Norway, where it had been coarsely ground and sieved to remove large twigs and branches. This material was used immediately after collection to avoid spontaneous composting prior to mixing of test materials. The garden waste had a dry matter content of 50%. Biochar used in this experiment was made from mixed wood and pyrolyzed by Novo Carbo using Pyreg technology at 550°C Highest Heating Temperature (HTT) (detailed characterization in Table S1). It had a dry matter content of 58% upon addition to the experiment.

Table 1. Key properties of biogas digestate and biochar.

	Digestate	Biochar
pH (H_2O)	8.9	8.0
Loss on ignition (%)	71.1	83.9
Density (g L^{-1})	n/a	262
Dry matter content (%)	27	58
Total Nitrogen (g kg^{-1} dw)	49.6	1.2
Phosphorus (P-AL) (mg 100 g^{-1} dw)	710	200
Potassium (K-AL) (mg 100 g^{-1} dw)	384	800

Each experimental unit (compost chamber) received a mixture of garden waste, digestate and biochar, in the following proportions: 40 L freshly ground garden waste (9 kg fresh weight (fw), 4.5 kg dry weight (dw)), 20 L biogas digestate (12.5 kg fw, 3.6 kg dw), and either 5% (0.70 kg fw, to 0.41 kg dw) or 17% (2.79 kg fw, 1.62 kg dw) biochar by dry weight. A control without biochar was also included in the experiment.

2.2. Experimental set-up of the composting experiment

The composting experiment was conducted in rotating composting units (tumblers), each consisting of two separate 135 L chambers with insulated walls (Joraform 270, Sweden). The chamber side walls each had two sections of 10 cm^2 aeration holes. Three replicate chambers were used for the 5% and 17% biochar treatments, and four replicate chambers for the control treatment without biochar, using in total 10 chambers from 5 tumblers. The reason for the additional control chamber was to avoid having a tumbler with only one filled chamber, and potentially different neighbour effects.

The experiment was started on 20th June 2019 (day 0), when ambient temperatures varied from 14 to 22°C, and temperatures inside the chambers were continuously recorded using Decagon's ECH2O dataloggers. Greenhouse gases were monitored daily for 10 days. After the initial GHG measurement period, composts were left to mature for four months in the tumblers, turning them once every second week during the whole period for mixing and aeration. At the end of the maturation phase, composts were individually homogenized, sieved at 4 mm to remove any remaining twigs, and representative samples of each compost were analyzed for physical and chemical parameters by a commercial analytical laboratory (ALS Global) using ISO methods. The mature composts were then stored at 4°C in the dark for 5 months until used in the plant growth experiment.

2.3. GHG measurement

Based on the results of a preliminary experiment, gas sampling was optimized to achieve a representative and reproducible sampling of the compost chambers. First, temperature sensors were removed, and all tumblers rotated five times, before opening them and aerating the headspace with a fan for 30 s. Then chambers were made airtight, and a syringe was used through a sampling port to collect gas samples from the headspace at intervals of 10 min over a period of 30 min. Samples were stored in evacuated glass vials for analysis within 1 week of the end of the sampling period. Carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) concentrations were determined by gas chromatography (GC Agilent 7890A, Agilent Technologies, Germany), using a thermal conductivity detector (TCD) for CO_2 and N_2O concentrations above 4 ppm, a flame ionization detector (FID) for CH_4, and an electron capture detector (ECD) for N_2O concentrations below 4 ppm. Two standard gas mixes with certified CO_2, CH_4 and N_2O concentrations were analyzed every 8 samples, to enable the conversion of peak areas into ppm. The low standard contained 398.6 ppm CO_2, 1.96 ppm CH_4, and 0.549 ppm N_2O, and the high standard 2004.8 ppm CO_2, 99.5 ppm CH_4, and 4.9 ppm N_2O.

2.4. Plant growth experiment with compost

A loamy sand soil collected on a farm in Southern Norway (Skjærgaarden, N59.3540, E010.4469) was air dried, sieved at 4 mm, and homogenized before use in the plant growth experiment. Soil chemical and physical characteristics, analyzed by a commercial analytical laboratory (ALS Global) using ISO methods, are presented in Table 2. The main production on this farm, spring onion (*Allium fistulosum*), was the plant species chosen for the experiment. Spring onion seeds were sown in seedling palettes using a potting mix containing peat and transplanted to the experimental pots after 6 weeks. Each pot received 2.7 kg dw equivalent soil and three seedlings. Pots were watered at 65% of the soil maximum water holding capacity (WHC_{max}). WHC_{max}, calculated following Margesin and Schinner [29], was 410 mL per kg soil dw. The application of the compost treatments was based on their N content in order to achieve 300 mg total N per kg soil dw. A treatment with mineral fertilizer (NPK 18-3-15), added to achieve 200 mg kg^{-1} total N, was added to the experimental set-up, and referred to as NPK control. A higher fertilization level was used in pots amended with compost compared to those amended with mineral fertilizer, because

Table 2. Key properties of the potting soil used in the pot experiment. P-AL and K-AL correspond to plant available P and K extracted using ammonium lactate.

	Soil
pH (H_2O)	5.8
Sand (%)	76
Silt (%)	14
Clay (%)	10
Loss on ignition (%)	5.6
C:N	14
Density (g L^{-1})	1400
Total Nitrogen (g 100 g^{-1} dw)	0.18
Phosphorus (P-AL) (mg 100 g^{-1} dw)	13
Potassium (K-AL) (mg 100 g^{-1} dw)	11

Table 3. Physical and chemical properties of the matured composts (Ctrl: without biochar, Low: 5% biochar, High: 17% biochar). P-AL, K-AL, Mg-AL, Ca-AL and Na-AL correspond to plant available P, K, Mg, Ca and Na extracted using ammonium lactate. Results are provided as mean and standard error in parentheses ($n = 4$ for Ctrl, $n = 3$ for Low and High). Means with different letters are statistically different (Tukey, $p < 0.05$).

	Ctrl	Low	High
pH (H_2O)	8.1 (0.2)a	8.0 (0.3)a	8.5 (0.3)a
C/N	7.8 (0.3)a	8.3 (0.48)a	13.4 (0.43)b
Total N (g 100 g^{-1} dw)	3.4 (0.1)b	3.4 (0.14)b	2.6 (0.14)a
NH_4-N (mg kg^{-1} dw)	9.9 (2.2)a	12.7 (3.1)a	7.9 (3.1)a
NO_x-N (mg kg^{-1} dw)	2233 (366)a	1733 (517)a	983 (517)a
Total Organic C (% dw)	26 (1.0)a	27 (1.4)a	35 (1.4)b
P-AL (mg 100 g^{-1} dw)	550 (19)b	503 (27)ab	443 (27)a
Total P (g 100 g^{-1} dw)	1.2 (0.04)b	1.1 (0.06)b	0.8 (0.06)a
K-AL (mg 100 g^{-1} dw)	393 (17)a	387 (24)a	403 (24)a
Mg-AL (mg 100 g^{-1} dw)	193 (6)b	173 (8)b	147 (8)a
Ca-AL (mg 100 g^{-1} dw)	4600 (193)b	3933 (274)ab	3667 (274)a
Na-AL (mg 100 g^{-1} dw)	160 (4)c	140 (5)b	113 (5)a
Dry matter content (g L^{-1})	171 (4)a	173 (6)a	163 (6)a
Dry matter content (%)	37.4 (1.8)a	38.6 (2.6)a	33.6 (2.6)a
Ash content (% dw)	39.5 (0.9)b	37.1 (1.2)ab	34.5 (1.2)a
Loss on ignition (% dw)	60.5 (0.9)a	62.9 (1.2)ab	(1.2)b

the fraction of the total N available to plants is lower in compost than in mineral fertilizer [30]. We had four treatments (NPK control, compost control, compost with 5% biochar, compost with 17% biochar) and six replicates per treatment. Plants were watered every third day the first three weeks, and every second day the following three weeks as plants were getting bigger and evapotranspiration higher. Temperatures in the greenhouse were set at 22°C during daytime (6 AM-8 PM) and 15°C at night (8 PM-6 AM) to mimic Norwegian summer conditions. Plants were harvested at maturity, and the fresh and dry (60°C overnight) weight of the edible part (stem and bulb without roots) were recorded. The physical and chemical characteristics of the various compost mixes were analyzed by a commercial analytical laboratory (ALS Global) using ISO methods. It included plant available P, K, Ca, Mg and Na extracted using ammonium lactate [31] and reported as –AL in Tables 2 and 3.

2.5. Nutrient availability

Three out of six replicates per treatment were submitted to a leaching event corresponding to 400 mL water above the WHC_{max}, (equivalent to 10 mm of precipitation). Pots that were not subjected to leaching were watered the same day to 95% of the WHC_{max} so that the plants experienced comparable soil oxygen levels. These leaching events occurred two weeks prior to harvest, at the beginning of a sunny day to minimize any potential stress due to excess watering. Leachates were collected from each pot, filtered at 0.45 µm and stored at −22°C until analysis. Ammonium (NH_4-N) and nitrate (NO_3-N) concentrations were measured by spectrophotometric methods using a SEAL analyzer, with a limit of detection of 0.01 mg N L^{-1}.

2.6. Statistical analysis

Comparisons of treatments were undertaken using an ANOVA, followed by *post hoc* Tukey test for pairwise examination of treatments. In order to understand the relationship between the biochar effect on temperature and GHG production, linear regression using a generalized linear model (GLM) was used to examine the relationship between temperature measured in the chambers and GHG production. We chose a GLM to address the highly skewed nature of the GHG response variables and specified a Gaussian distribution with a log link function (R core team, 2019).

3. Results and discussion

3.1. Effects of biochar addition on composting dynamics

3.1.1. Composting temperature

In all compost treatments there was a rapid onset of compost heating, with peak temperatures observed after only 4 days (Figure 1). This is comparable to other studies that observed the onset of thermophilic composting after only 1 day of composting (e.g. Chen, Huang [25]). The high biochar addition significantly increased the maximum temperature reached over the course of the measurement period of 10 days compared with control (Fig.1d, ANOVA: $F = 3.13$, $p = 0.048$), but there was no significant difference between either the high and low treatments or the low treatments and the control. There appeared to be a higher degree of variability in the max temperature between replicates in both the control and low biochar treatment compared with the control (Figure 1(a–c)). Biochar addition to compost has been shown to increase microbial respiration [32] and compost temperatures, resulting in an acceleration of the composting process [18]. This has been explained by biochar effects on compost physical properties such as aeration [33], and reductions of anaerobic clump formation [34]. In our study, visual observations suggested that Biochar reduced clump formation observed as digestate adhering to the more structured garden waste in the control treatment.

3.1.2. Greenhouse gas emissions

Both CO_2 and CH_4 were initially high in all treatments with a peak from day 1 of the measurements (Figure 2 (a,c)). Peak CO_2 emissions measured on day 1 likely

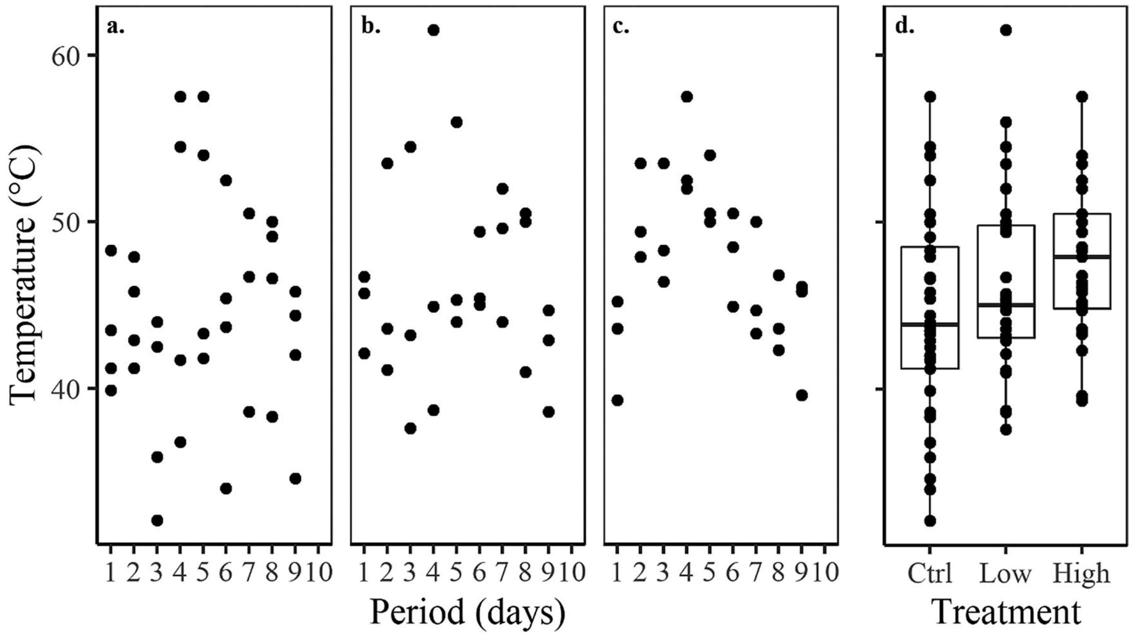

Figure 1. Point plots showing daily maximum temperature prior to GHG measurement in each tumbler in (a) Compost control (Ctrl, $n = 4$); (b) Compost with 5% biochar (Low, $n = 3$); (c) Compost with 17% biochar (High, $n = 3$). Plot (d) is a boxplot of max temperatures summarizing differences between treatments.

correlate with the relative abundance of easily degradable organic matter at the start of the composting process [35]. Variability in this initial flux between treatments is largely responsible for the visible differences in cumulative emissions of CO_2 and CH_4 between the treatments (Figure 2(c,d)). CH_4 production was especially high at the second sampling point in the high biochar treatment, further contributing to the high cumulative CH_4 emission of this treatment (Figure 2(f)). Both CO_2 and CH_4 emissions were positively correlated with maximum temperature, except on the first day of the 10-day composting period (Table S2). The shift from the early mesophilic to thermophilic phase, which generally occurs after the first day of composting, results in a variable response of microbial turnover to compost temperature [35]. We saw no significant effect of treatment on either CO_2 or CH_4 emission despite the effect of treatment on temperature development. Sanchez-Garcia, Alburquerque [34] also saw a significant effect of temperature and a non-significant effect of biochar treatment on CO_2 emissions in a poultry manure compost although they also reported a higher CH_4 emission from biochar amended compost. Studies of biochar and compost mixes have shown contradictory effects of biochar addition on both CO_2 and CH_4 with both higher [34,36] and lower emissions following biochar addition [33,37,38]. For example, increases in CH_4 emission are most often explained by the increases in compost rates and the positive correlation between composting temperature and both CO_2 and CH_4 which we also see in this study. Meanwhile, lower CH_4 emission potentials are attributed to the greater oxygen availability supported by the porous biochar addition [33] and lower CO_2 emissions are explained by abiotic mechanisms [37]. Explanations for the contrasting results for CH_4 mitigation potential of biochar in compost may be related to the texture of the composting mixture and the composting method used, which would also modify oxygen availability in the compost.

There was a clear and significant effect of biochar addition on N_2O emission, with a consistently lower N_2O production in the biochar treatments compared to the control compost (Figure 2(b)). However, there was no evidence of that dose had any effect and there was no correlation with temperature (Table S2). N_2O emission increased towards the end of the measurement period in all treatments, but more strongly in control compost. N_2O production in this study was limited to the period following the peak in heating and the onset of cooling, while others have measured N_2O production during the thermophilic phase [34]. Biochar addition to compost has been shown to have either a negligible effect on N_2O emissions [34] or to reduce these emissions by as much as 98% relative to control [33]. In our study, we saw an average cumulative reduction by 65–70% (Low to High biochar) relative to the control (Figure 3). N_2O emission in the maturation phase of composting may occur through both denitrification and nitrification-mediated pathways [34], and biochar is thought to

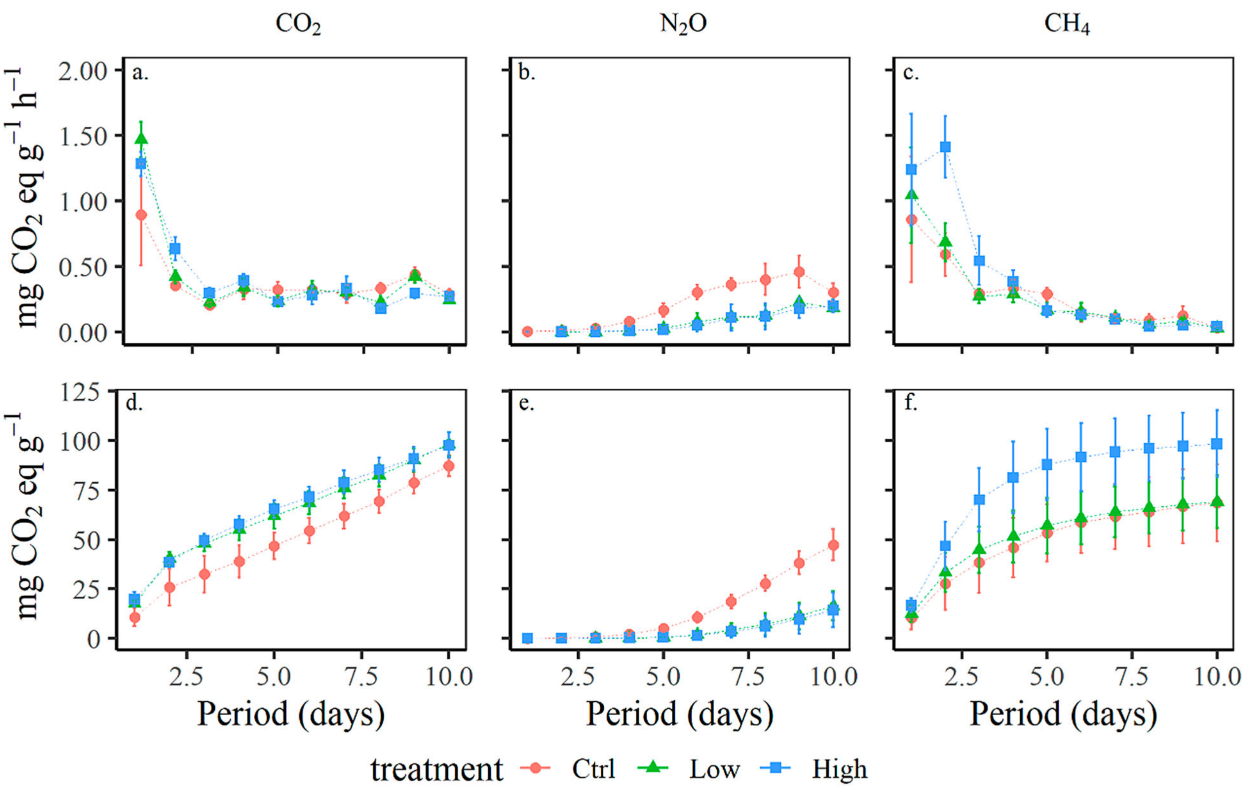

Figure 2. GHG measurements from the composting process throughout the measurement period of 10 days. Top: Mean measured gas flux dynamics of CO_2 (a), N_2O (b), and CH_4 (c). Bottom: Mean cumulative emissions of CO_2 (d), N_2O (e), and CH_4 (f). All values are presented in mg CO_2 equivalents g^{-1} (h^{-1}) based on 100 years using emission factors of 298× for N_2O and 28× for CH_4. Colours and shape represent treatments, bars represent standard error ($n = 4$ Ctrl; $n = 3$ biochar treatments Low and High).

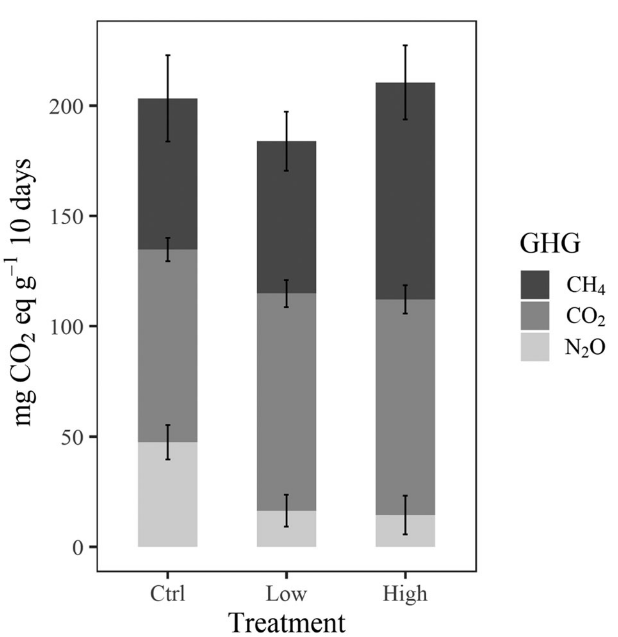

Figure 3. Stacked boxplot of the mean cumulative GHG emissions in CO_2 equivalents (eCO_2). Error bars are standard error (Control compost, $n = 4$; compost with 5 and 17% biochar, $n = 3$).

affect these processes differently. Biochar effects on denitrification mediated N_2O emissions are well documented [12] and due to a reduction in the $N_2O/(N_2O + N_2)$ product ratio [39]. The mechanisms responsible for the biochar effect on nitrification-mediated N_2O emissions are less well studied. He, Yin [40] showed evidence that biochar simultaneously improves denitrification processes through greater N_2O consumption potential and also through a lower ammonium production potential and lower nitrite consumption potential, resulting in lower net N_2O emission. Additionally, the biological response to biochar addition may be mediated by abiotic effects of biochar addition on product accumulation [17,26,41,42]. All of this suggests that the N_2O emission reductions in our study could have been influenced by both compost aeration and by more direct effects of biochar on microbial nitrogen turnover and N_2O emissions. Since the N_2O emissions, unlike the CO_2 and CH_4 emissions, were clearly a function of treatment, this supports the argument that biochar addition was directly impacting the nitrogen turnover rather than simply altering the aeration of the compost.

Differences between treatments in total GHG emission as CO_2 equivalents based on the cumulative values are shown in Figure 3. Biochar addition clearly reduced N_2O emissions by 65–70% for both the low and high biochar dose, while slightly increasing CO_2 emissions by 12–13% relative to the control. The high biochar dose led to the highest increase (44%) in cumulative CH_4 emissions, resulting in this treatment contributing to the highest total cumulative GHG emissions, 3% higher than the control, while the low biochar treatment was 10% lower than the control. However, owing to the high variability in GHG measurements, the total cumulative GHG emissions in CO_2 equivalents were not statistically different across treatments.

Total accumulated GHG emissions in CO_2 equivalents highlight that the N_2O emission reduction is a significant factor governing the total GHG reduction potential of biochar. The lack of a biochar dose effect on N_2O emission combined with the moderate increase in CO_2 and CH_4 in the high biochar treatment suggests that a low biochar amendment is sufficient to achieve a total reduction in GHG emission from green waste and digestate compost.

3.2. Fertilization potential of compost and biochar-amended compost

3.2.1. Fertilizer value of the mature composts

We saw no evidence that biochar improved the nutrient retention capacity of the final compost since there were no significant differences between the treatments in NH_4-N content, NO_x-N content and K content (Table 3). Biochar has previously been shown to reduce the loss of mineral N through reduced NH_3 emissions [22,43] and higher NO_3^- and NH_4^+ retention [27,44]. Khan, Clark [45] found that the increase in N retention of co-composted biochar was relative to initial N content of the parent material, with larger retention the lower the initial N content. Sarkhot, Berhe [46] found that biochar could hold 8% N following mixing in manure. The lack of a significant effect of biochar on mineral N retention in our study may be due to the high initial N content of the digestate and the inclusion of garden waste, which may have performed a similar function to biochar as a porous organic media.

The high biochar compost had significantly higher C/N ratio and TOC than the other treatments, reflecting the significantly larger proportion of biochar. There was also a significant dilution effect of the biochar addition in the high biochar treatment, as shown by the lower concentrations of total N, total P, plant available P, Mg, Ca and Na (P-AL, Mg-AL, Ca-AL, Na-AL), and ash (Table 3). Compared to concentrations in control compost, these elements showed 8–14% dilution in the compost with 5% biochar, and 19–29% dilution in the compost with 17% biochar. For most physical and chemical parameters, the low biochar treatment was not significantly different from the control. Dilution effects were accounted for during the fertilization experiment by using compost volumes with similar total N content.

3.2.2. Nutrient leaching and plant yield

A leaching treatment during the plant growth experiment was used to test the hypothesis that biochar would reduce leaching of plant nutrients (Figure 4(a, b)). The addition of biochar to compost did not result in greater retention of either ammonium or nitrate than observed in soil amended with compost without biochar, as similar amounts of NH_4-N ($p = 0.09$) and NO_3-N ($p = 0.44$) were leached in all compost treatments. By contrast, there was significantly more ammonium ($p = 0.006$) and nitrate ($p < 0.001$) leached from the NPK fertilized soil compared to compost-amended treatments.

All compost treatments, including biochar amended compost, resulted in significantly higher yield of spring onion (6.62 ± 1.11 g dw, mean ± SD) than observed with the NPK mineral fertilizer (3.13 ± 0.55 g dw). Yield studies, comparing mineral fertilization to compost addition, have shown inconsistent effects with both positive, negative and neutral effects [47–50]. Variability in crop yield responses to compost addition are likely an interaction between crop type [49] and native soil properties [51]. The soil used in this study was taken from a field in intensive vegetable production. For Norwegian conditions, soil pH was moderately low (pH 5.8) and P concentration was high, which is a consequence of high long-term application of mineral compound fertilizer. As a sandy soil (76% sand) it was expected to have a low capacity for nutrient and moisture retention. Compost addition to soil has been shown to have significant effects on soil's physical and chemical properties. The addition of compost, rich in stabilized organic matter, can increase total SOM content and improve soil bulk density and water holding capacity [52,53]. The effect of increased SOM has been shown to have a positive effect on plant yield due to better access to nutrients and better root development through lower bulk density of the soil [50]. High pH compost like the compost in this study can also have a significant liming effect on soil [51,54] with consequences for nutrient availability and retention. A combination of these effects likely explains why compost amendment had a significant and positive effect on plant yield in our study. This is further supported by the significantly higher leaching losses of both NO_3^- and NH_4^+ in the NPK treatment, which is likely a consequence of the poor nutrient holding capacity of the agricultural soil used. We also observed that the leached pots had

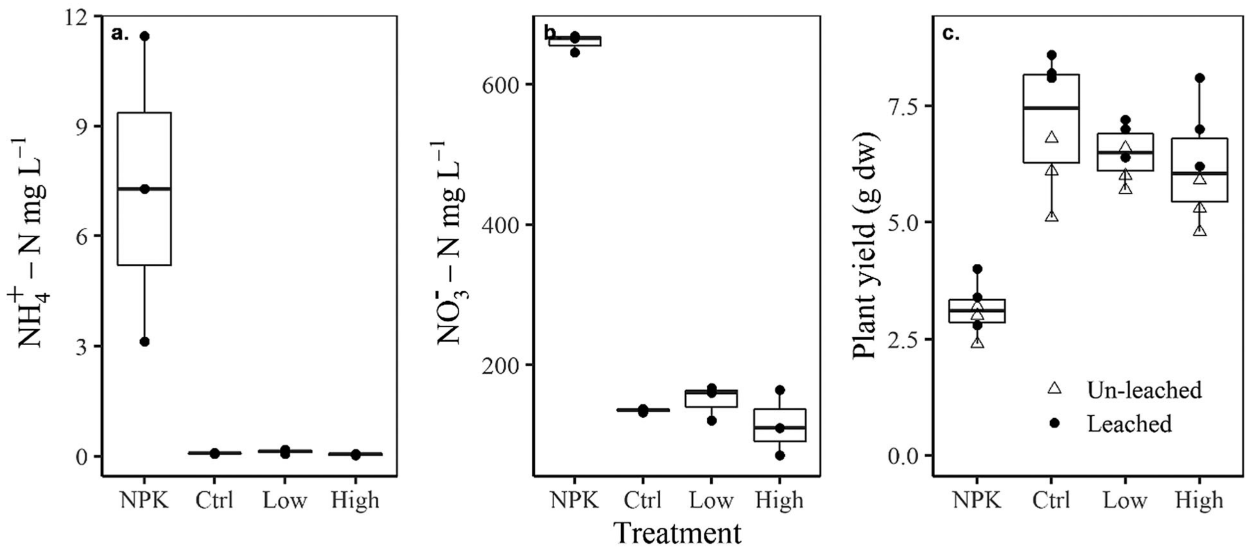

Figure 4. Total leached NH_4-N (a) and NO_3-N (b) following two leaching events. (c) Plant yield at maturity (g dw) showing the results from a leached and un-leached treatment in pots fertilized with mineral fertilizer (NPK), compost without biochar (Ctrl), compost with 5% biochar (Low), and compost with 17% biochar (High).

significantly higher yield than the un-leached pots, suggesting that the leached nutrients were not the primary cause of the observed difference between the yield in the NPK treatment and the compost treatment.

One of our hypotheses was that biochar would improve the fertilization effect of compost mixture and reduce leaching. Our study showed no significant difference in the yield effect of compost addition at any level of biochar addition ($p = 0.35$, Figure 4(c)). Yield effect of biochar addition to soils has been shown to be higher in low pH soils with low SOC [11,55] such as the soil used in this study. However, the dominant effects of biochar in these soils are related to increases in SOC, pH and the application of plant nutrients in the ash fraction [11]. Our analysis of the final compost and biochar mixes confirmed that biochar addition did not result in a significantly higher pH of the final material, and we saw evidence of both mineral and N dilution by the added biochar. Other studies have suggested that biochar additives to compost can influence both pH [18] and the retention of nutrients [27]. Banegas, Moreno [56] showed that bulking agents such as sawdust can result in a significant nutrient dilution effect at high mixing ratios, similar to the effect we see here with the high biochar treatment. It is possible that our enclosed batch composting resulted in reduced nutrient leaching when compared with larger-scale open windrow composting. It is also possible that the dilution effect is more apparent in the composting of high N feedstocks such as digestate [56].

Our results agree with the findings of Wang, Villamil [28] who found that across 14 similar studies, increases in crop yield were best explained by compost addition and that biochar addition to compost had no discernible additive effect on yield. Because of the dilution effect of biochar addition this can be seen as a challenge, due to the higher application requirement at higher biochar mixing ratios to meet the N requirements of the crop. However, it also presents an opportunity through the increased carbon storage potential of the amendment.

Our experimental design, consisting of two contrasting doses, limits conclusions regarding the dose response of biochar in our composting system. For this reason, we are unable to conclude the optimum biochar application rate for our system. Our application of 17% biochar (by weight) with the high biochar treatment is at the higher limit of application that has been seen to have a positive effect on compost properties [13,24], most notably reducing N_2O emissions compared to the control. Despite this, our results show that the final compost product from the 5% biochar treatment, which was more similar to the un-amended compost, did not lead to a significant dilution of nutrients, and resulted in a lower total GHG burden.

4. Conclusions

Our study showed that the addition of a high-temperature wood biochar during composting increased the thermal stability of the composting process and that addition of low amounts of biochar reduced the emissions of N_2O, while emissions of CO_2 and CH_4 were unaffected. Increasing the amount of biochar increased CO_2 and CH_4 emissions due to higher compost temperatures, suggesting a higher microbial turnover. Full maturation of the composts resulted in a dilution effect of the high biochar treatment for both N and mineral nutrients. Biochar addition did not affect nutrient leaching or yield of spring onion, however it benefited the composting process and inputs of stable C to soil. This shows that biochar addition to compost can improve the composting process while not negatively impacting the fertilizer properties of the final product. Long-term studies are needed to understand whether repeated applications of biochar amended compost have positive consequence beyond these immediate effects. Life cycle assessments will also enable us to understand how biochar addition can contribute to the total GHG mitigation effect of this process.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

Author contributions

Simon Weldon: Conceptualization, Experimental plan, Statistical analysis, First draft article, reviewing and editing. Pierre-Adrien Rivier: Conceptualization, Experimental plan, Experimental work, reviewing and editing. Claire Coutris: Experimental plan, Experimental work, reviewing and editing: Erik Joner: Experimental plan, reviewing and editing. Alice Budai: Conceptualization, Experimental plan, reviewing and editing, funding acquisition.

Acknowledgements

This work was supported by the Norwegian research fund for agriculture and food industry (FFL/JA) as part of the project 'KarbonVekst: Reduced greenhouse gas emissions and better agronomy with the use of biochar in fertilisation and composting', 159160. Espen Govasmark from OSLO EGE biogas for providing digestate; Andre Skurdal, from Follo Ren for providing the garden waste, Jan Erik Jacobsen for ammonium and nitrate analysis.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the Norwegian agriculture agency through the Research Fund for Agriculture and Food Industry (FFL/JA) as part of the project 'KarbonVekst: Reduced greenhouse gas emissions and better agronomy with the use of biochar in fertilisation and composting', 159160.

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