

Effect of Hydrothermally Carbonized Hemp Dust on the Soil Emissions of CO₂ and N₂O

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The impact on carbon dioxide (CO₂) and nitrous oxide (N₂O) emissions when applying hydrothermally carbonized (HTC) char to soil was investigated in a laboratory experiment with two HTC chars made from hemp (*Cannabis sativa* L.) dust and incubated for 131 d. Two fractions of hemp dust were collected during fiber processing (from fractionation and suction) and were carbonized at 230 °C for 6 h in water. Non-treated and water-washed HTC chars were used in incubation experiments, doubling the carbon concentration of the soil. As a result of adding HTC char to soil, CO₂ emissions increased significantly in all cases compared to the control treatment. Washing the HTC chars easily removed dissolvable carbon (C) compounds, which significantly decreased CO₂ emissions. Nitrous oxide emissions, following the incorporation of HTC char, did not differ from those of the control sample; however, washed HTC char treatments tended to emit less N₂O than the corresponding unwashed samples. Hydrothermally carbonized char obtained from the suction of dust may play a greater role as a soil conditioner than HTC char from dust by fractionation because dust from suction accumulates to a larger degree during hemp fiber processing.

Keywords: Fiber residues; Biochar; Hydrochar; Hydrothermal carbonization; Carbon dioxide; Nitrous oxide

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INTRODUCTION

The organic matter in soil plays an important role in maintaining soil fertility, especially in sandy soil. In sandy soil, organic matter increases the proportion of small and medium sized pores, which enables it to retain water more efficiently (Scheffer *et al.* 2010). All across Europe, a loss of carbon (C) has been observed in agricultural soils, which in turn may lead to a reduction in soil fertility even when following good practice guidelines (Kutsch *et al.* 2010). In order to maintain and increase soil fertility, it is suggested that a stable organic matter fraction (*e.g.*, biochar) be applied to soils (Atkinson *et al.* 2010). Biochar is the solid, carbon-rich product of pyrolysis that persists in soil over longer periods than other organic matter fractions (Lehmann 2007).

The most common procedure for obtaining biochar is dry pyrolysis, which is defined as the thermal decomposition of organic matter under low-oxygen to anaerobic conditions (Libra *et al.* 2011). However, pyrolysis is mostly used for dry feedstock, since dehydration of wet material is energy-consuming. Therefore, the hydrothermal carbonization (HTC) procedure is suggested as an appropriate carbonization technique, because it can be employed with wet feedstock (*e.g.*, spent grains and digestates). The HTC process is an exothermic, thermo-chemical conversion operation, coupled with elimination of water and carbon dioxide (CO₂) (Kruse *et al.* 2012). Substrates covered by water are exposed to relatively low temperatures, ranging from 180 to 250 °C, and elevated pressures (Funke and Ziegler 2010). The HTC process yields a solid, coal-like organic substrate with higher C concentrations than those present in the biomass input (Libra *et al.* 2011). The process is considered to be usable particularly for materials with poor fuel properties (Funke and Ziegler 2010).

It has been suggested that applying biochar to less fertile soils can potentially mitigate climate change (Woolf *et al.* 2010; Bian *et al.* 2014). However, only a few studies have examined the effects of incorporating HTC char into soils on greenhouse gas emissions (Gajic *et al.* 2011; Kammann *et al.* 2012; Malghani *et al.* 2013). Increased emissions of CO₂ after HTC char incorporation, compared with levels from untreated soils, were observed by Gajic *et al.* (2011) and Kammann *et al.* (2012). On the other hand, nitrous oxide (N₂O) emissions decreased after HTC char was applied to soil (Kammann *et al.* 2012; Malghani *et al.* 2013), then increased after the application of nitrogen (N) fertilizer (Kammann *et al.* 2012). Consequently, the general effects on greenhouse gas emissions of applying HTC chars to soils are not fully understood, and therefore, general conclusions cannot yet be drawn. A possible reason for this is that HTC char is characterized by disordered carbon (Titirici *et al.* 2007), small aromatic clusters (Sevilla *et al.* 2011), and a furan-rich core (Falco *et al.* 2011). These fractions will make for relatively stable organic material. However, HTC char may also contain labile organic matter fractions (*e.g.*, carbohydrates), which can easily be decomposed after application to soil, leading to an increase in initial CO₂ emissions (Qayyum *et al.* 2012). It is hypothesized that such degradable HTC fractions might be removed *via* a washing procedure before the char is applied to the soil.

In Germany, about 250 million tons per year, *i.e.*, 44% of total organic residues (Schuchardt and Vorlop 2010), could be considered for HTC processing. Parts of these residues might come from by-products of hemp-fiber production. Pecenka *et al.* (2010) reported that the recent increase in the use of wood as a source of energy has created a demand for raw cellulose material. One available feedstock is hemp (*Cannabis sativa* L.), an annual fiber crop, which can contribute considerably to satisfying this demand. Some of the largest hemp-producing areas are Europe (approx. 8,000 ha/year in 2011), Canada (approx. 16,000 ha/year in 2011), and China (more than 80,000 ha/year in 2008) (Müssig 2010; Kruse 2012). The natural fibers produced from hemp are used for insulation materials, for fiber fleece, and by the composite industry (Hesch *et al.* 1996). Shives, a by-product of hemp straw-processing, are used not only for small animal or horse bedding, but also for particle boards (Hesch *et al.* 1996). However, hemp dust, another by-product of hemp processing, accounts for 20 to 25% of the bulk hemp biomass. Hemp dust has not yet been considered as a potentially revenue-generating material (Fig. 1).

The aim of this experiment was to test two different HTC chars made of hemp dust with respect to their effects on CO₂ and N₂O emissions when applied to sandy soil. Additionally, the effects of washing the HTC chars with water after carbonization and prior to application to soil were investigated. It was hypothesized that the presence of HTC char would initially result in higher CO₂ emissions, compared with the non-amended soil. This would potentially occur because easily dissolvable organic C compounds in the HTC chars would be removed by washing both types of hemp char. Analyzing the effects of HTC chars on N₂O emissions should provide information about what kind of feedstock and char treatment is most efficient for greenhouse gas mitigation.

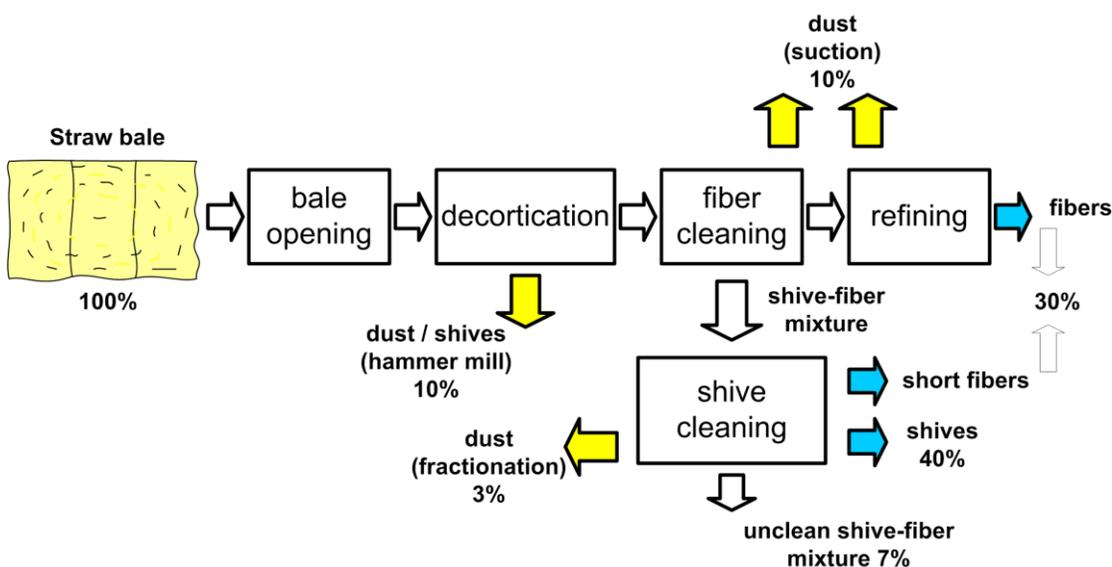


Fig. 1. Hemp fiber processing, hemp dust from fractionation (used for char-1), and hemp dust obtained by suction (used for char-2) were used for carbonization.

EXPERIMENTAL

Materials

Soil samples

Soil samples were taken in May 2011 from the A-horizon (0 to 20 cm) of a short-rotation coppice planted with willow (*Salix viminalis* clone Inger) in north-east Germany (52°26'N, 13°00'E). The soil was classified as loamy sand, which consisted of 83.6% sand, 13.3% silt, and 3.1% clay.

Sampling took place at three different sites, and samples were mixed thoroughly. Dry weights were determined by drying subsamples at 105 °C for 24 h. After sieving (mesh size 2 mm), the air-dried soil samples were analyzed for total C and N concentrations using an elemental analyzer (Vario EL III, Elementar, Germany).

The pH value was measured at 1:5 in deionized water before the experiment and at the end in the mixtures. Prior to use, the air-dried soil samples were stored at room temperature.

Feedstock

Hemp dust is a by-product of hemp fiber production. During hemp fiber processing, different fractions accumulate (Fig. 1). Two fractions of hemp dust were used for carbonization. One sample, obtained during the process of separating/fractionating the shive-fiber mixture, corresponded to char-1, and the other, that accumulated while cleaning the fibers by suction, corresponded to char-2. Hemp dust from fractionation contained 38.6% C, and hemp dust from suction contained 44.9% C on a dry matter basis.

Methods

Carbonization

The hemp dust was carbonized at 230 °C for 6 h in distilled water in a 1-L stirred-pressure reactor (Parr, USA) with internal sensors for temperature and pressure and an external resistance heater. The two fractions differed in density; therefore, the initial C in the reactor was 35.4 g for hemp dust from fractionation with a substrate to water ratio of 1:5 and for hemp dust from suction the initial C was 15.0 g with a substrate to water ratio of 1:12. After carbonization, the HTC char was filtered with a folded paper filter (Roth filter: type 113P) to separate the HTC char from the liquid. After separation, about one half of each of the two hemp chars (still in the filter paper) were washed with half a liter of distilled water to remove easily dissolvable organic C fractions. The washing took place at room temperature and removed water-soluble particles smaller than 5 to 8 μm (area of retention of filter paper). It took around 15 min for each HTC char sample. Subsequently, all HTC chars were dried at 60 °C, and subsamples were analyzed with an elemental analyzer for total C and N concentrations. The C recovery rate was calculated by multiplying the amount of solid HTC-char-C by 100 and dividing by the amount of C added to the reactor. The dry matter content was determined by drying a subsample at 105 °C to achieve constant weight, which was after 12 h. The loss on ignition method was used to determine the ash content. Samples were ignited at 550 °C for 4.5 h. The pH was measured at 1:10 in distilled water.

Fourier-Transform-Infrared analysis

Hydrothermally carbonized char samples were analyzed by Fourier Transform Infrared (FTIR) spectroscopy, using the KBr technique with a BioRad® FTS 135 (Massachusetts, US), as described in Ellerbrock *et al.* (2005). In brief, 0.5 mg of HTC char was mixed with 80 mg KBr. The mixture was finely ground in an agate mortar, dried over silica gel, and analyzed using 16 scans with a resolution of 1 cm^{-1} per spectrum.

The FTIR spectra were quantitatively analyzed for the intensity of absorption bands at (i) the 2960 to 2850 cm^{-1} region attributed to hydrophobic methyl (CH-) groups (combined to one absorption band A), (ii) 1740 and 1580 cm^{-1} , attributed to hydrophilic (C=O) groups (combined to one absorption band B), (iii) approx. 1500 cm^{-1} , attributed to lignin and lignin-like substances (absorption band L), and (iv) 1080 cm^{-1} , attributed to stretching vibrations of C-O-C groups (absorption band C). Band C was used as an internal standard to facilitate comparisons between spectra of different samples. The intensity of absorption band A relative to that of absorption band B (A/B- ratio), could be used as an indicator of potential wettability; values close to zero pointed to an easily wettable sample. The ratio between the intensity of absorption band A and that of band C (A/C-ratio) in the

FTIR spectra provided information about the relative proportion of hydrophobic groups in the sample. The infrared band assignment was performed according to Ellerbrock *et al.* (2005), Hesse *et al.* (2002), and Steinbeiss *et al.* (2009).

Incubation experiment

Bulk soil, along with mixtures of soil and HTC char, were incubated in 125 mL bottles and screwed shut with gas-tight butyl rubber stoppers. Five replicates were used per treatment. The treatments were: Loamy sand without hemp HTC char additions (control), soil hemp-char mixtures with unwashed HTC char from either fractionation (char-1) or suction (char-2), and the water-washed HTC char fractions (char-1-washed and char-2-washed), respectively. Five grams of soil and a corresponding amount of the oven-dried (60 °C) HTC char was added. In order to increase the C concentration in the bottles with the HTC chars to 2% C for each treatment, between 83 to 278 mg of HTC char was added. This doubling of the C concentration in the HTC-treatments, corresponded to an application rate of 21 t C ha⁻¹ (calculated with a bulk density of 1.4 g cm⁻³ and an incorporation depth of 15 cm). Water was added to reach approximately 70% of the maximum water-holding capacity. To the control, 1.30 mL of water was added. For the HTC char treatments, between 1.32 and 1.37 mL of water was added, depending on the amount of HTC char present. The maximum water-holding capacity of the soil was determined according to Öhlinger (1996). The bottles were incubated in the dark under laboratory conditions at 22 °C ± 1 °C.

Gas chromatography (GC)

On days 1, 2, 6, 13, 23, 34, 51, 72, 99, and 131 the amount of CO₂ and N₂O produced between the sampling dates (*i.e.*, the amount accumulated in the bottle headspace) was determined *via* GC (Varian CP-3800). The oven temperature was set to 50 °C. Gas samples passed a 2 m long packed column (Porapak QS 80/100 2 m x 1/8" SS) for the flame ionization detector (FID) and a 2 m long packed column (Hayesep D 80/100 2 m x 1/8" SS) for the electron capture detector (ECD). Nitrous oxide was determined with a ⁶³Ni ECD (15 mCi), operating at 360 °C. The pure nitrogen flux was 22 mL min⁻¹. Carbon dioxide, after methanisation, was detected with a FID, operating at 300 °C. For the measurements, a 5 mL gas sample was thoroughly mixed in the headspace, removed from the bottles with a syringe, and inserted into the GC. All measurements were calibrated with external calibration curves, using standard gases. After the measurements, the bottles were unscrewed and aired for 2 hours.

The amount of gas produced per bottle (m_{gas} in µg) was calculated as follows (Eq. 1),

$$m_{\text{gas}} = W \cdot V_{\text{headspace}} \cdot \frac{MM}{MV} \quad (1)$$

where $V_{\text{headspace}} = 0.12$ L, $MV = 24.47$ L mol⁻¹ is the molar volume of a gas at 20 °C and standard pressure, $MM = 44$ g mol⁻¹, is the molar mass of the gas of interest (CO₂ or N₂O),

and W = the concentration of gas produced in $\mu\text{mol mol}^{-1}$. Background concentrations were subtracted from the data obtained before the calculation.

Statistical analyses

Statistical analyses were performed using SAS (SAS 9.2, North Carolina, USA). Single and cumulative emissions were analyzed by running a variance analysis (ANOVA), which applied the PROC MIXED procedure with treatment as a fixed effect. Significance was accepted at $P < 0.05$, p-values and confidence limits were adjusted accordingly with the SIMULATE option.

RESULTS AND DISCUSSION

Characteristics of Soil and Hemp Char

The soil C and HTC char C concentrations are presented in Table 1. Washing the HTC chars with water reduced the C concentration by 30% and 2% for char-1 and char-2, respectively (Table 1).

The pH values of the hemp char were acidic and ranged between 5.1 and 6.1 (Table 1). The pH of the soil was 7.7 at the beginning of the incubation period (Table 1). The hemp char did not affect the pH of the soil/HTC char mixtures, except for char-1. At the end of the incubation, the pH of treatments with hemp char was 7.7, except in the case of char-1 unwashed, which had a pH value of 7.8 and differed significantly ($P < 0.05$) from the other treatments.

Table 1. Properties of Soil (control) and HTC Products from Fractionation of Fibers and Shives (Char-1) and from Suction of Fibers (Char-2) before Incubation

Characteristics	Soil	Char-1		Char-2	
		unwashed	washed	unwashed	washed
Total C (g kg^{-1} dm)	9.8	259.4	180.9	603.7	592.1
Total N (g kg^{-1} dm)	0.9	19.5	8.1	19.6	19.2
C:N ratio	11.4	13.3	22.3	30.8	30.8
pH	7.7	6.1	5.8	5.1	5.6
Dry matter / g kg^{-1}	989.9	987.6	992	970.7	971.6
Ash content (g kg^{-1})	977.7	492.9	786.3	177.9	159.6
A/B-ratio	nd	0.476	0.433	0.377	0.365
A/C-ratio	nd	0.619	0.454	0.641	0.602

(dm: dry matter, nd: not determined) Washing medium = distilled water.

Additionally, char-1 had a high ash content, corresponding with low C contents of the washed and unwashed char (Table 1). During the carbonization, 31% of feedstock C was recovered in char-1, while in the case of char-2, 50% of the feedstock C was carbonized. The residual C remained in the liquid and gaseous phase of HTC.

The FTIR spectra of all samples showed similar patterns (Fig. 2), and were comparable to spectra found by Eibisch *et al.* (2013). For char-2, the spectra of washed (Fig. 2 black dashed line) and unwashed (Fig. 2 black solid line) samples were almost identical with respect to the intensity of absorption bands, indicating a similar composition for the washed and unwashed char-2 samples. The FTIR spectra of char-1 samples differed from those of char-2 and was different for washed and unwashed samples, indicating that the composition of the washed sample differed from that of the unwashed sample.

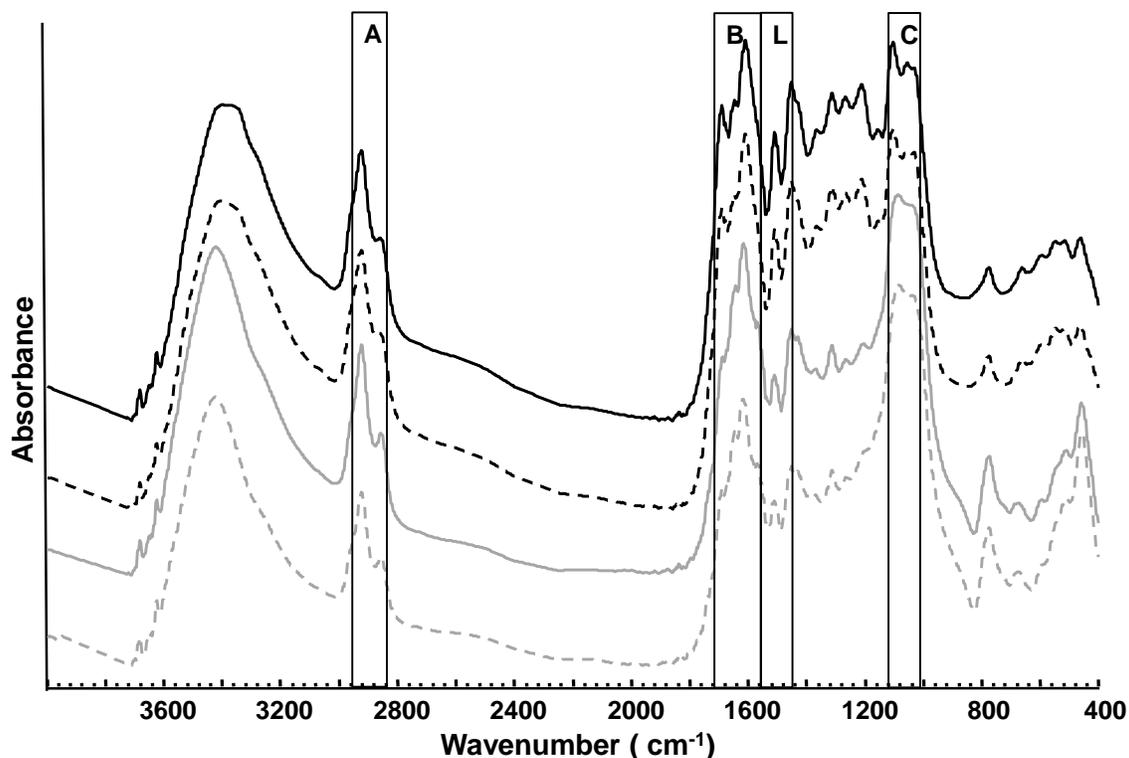


Fig. 2. FTIR-spectra of char-1-unwashed (grey), char-1-washed (grey, dashed), char-2-unwashed (black) and char-2-washed (black, dashed)

For unwashed char-1, the absorption bands A, B, and L in the FTIR spectra were smaller compared with those in the FTIR of char-2. Char-1 samples showed a higher A/B ratio than char-2 samples, although the A/C ratios of both chars are comparable (Table 1). Washing the HTC chars reduced the intensities of absorption bands A and B for char-1 but had hardly any effect on those of char-2. The absorption band L (at 1500 cm^{-1}) was larger in the spectra for washed and unwashed char-2 samples, indicating a higher lignin content than char-1 samples. As a result, washed and unwashed char-1 samples showed a difference in A/C and A/B ratios (Table 1). Such differentiation was not found between washed and unwashed char-2 samples.

Carbon Dioxide Emissions

After 131 days of incubation, all treatment samples emitted significantly more CO_2 than the control ($P < 0.05$), as was hypothesized. This was also reported by others (*e.g.*,

Malghani *et al.* 2013). Overall, the carbon loss ranged between 4.4 and 8.6%, which was comparable to results by Steinbeiss *et al.* (2009). Most of the CO₂ was released during the initial phase of mineralization within the first three weeks.

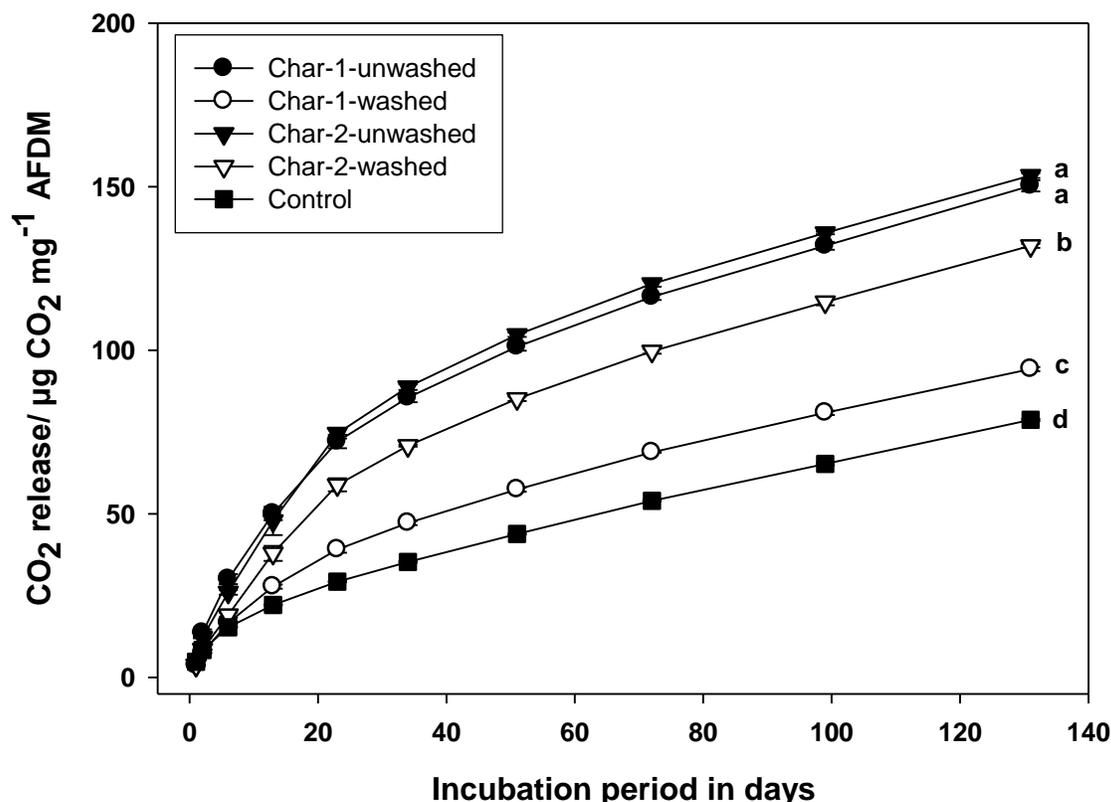


Fig. 3. Cumulative emissions of CO₂. Symbols and error bars represent mean \pm SD (n=5). Treatments were HTC char from fractionation, char-1-washed, char-1-unwashed, HTC char from suction, char-2-washed, char-2-unwashed, and without any amendment (control). Letters show significant differences after 131 days ($P < 0.05$) (AFDM: ash free dry matter).

Large CO₂ emissions at the beginning of the incubation may be explained by the presence of easily degradable C and the decomposition of carbohydrates, as reported by Qayyum *et al.* (2012). The CO₂ losses from their HTC chars, however, were much lower compared with most of our HTC chars. After one year of incubation, only about 2 to 6% of applied C had been mineralized, even though the HTC char was produced under less severe conditions (200 °C). According to general observations, the amount of CO₂ released depends not only on the process conditions, but also on the feedstock (Zimmerman *et al.* 2011; Singh *et al.* 2012). Different stabilities between the original feedstock and the corresponding char products from HTC can be observed (Eibisch *et al.* 2013). This may explain the differences between this study and the study of Qayyum *et al.* (2012), who did not use dusty materials for carbonization, but instead used bark, a material which under

natural conditions is less readily degradable by microbes, because of the well-preserving nature of cork material (Pereira 2007).

Besides the processing conditions and the feedstock, it could be shown that a treatment like washing of the charred hemp residues controlled their emission of CO₂ as was also found by Jones *et al.* (2011) for biochars. Water-washed treatment samples emitted significantly less CO₂ than their unwashed counterparts ($P < 0.05$, Fig. 3). Washing char-1 lowered the CO₂ emissions by 49% ($P < 0.05$), and those of char-2 by 14% ($P < 0.05$). This difference in CO₂ emissions was also supported by the chemical properties and the FTIR spectra of the chars (Table 1, Fig. 2). Therefore, the effects of washing seemed to differ due to the kind of feedstock.

Nitrous Oxide Emissions

The washed HTC char samples emitted less N₂O than the unwashed samples and the control, but due to high standard deviation, the differences were not significant ($P > 0.05$, Fig. 4), and in the same range as reported by Dicke *et al.* (2014). Most of the N₂O was emitted at the beginning of the incubation (Fig. 4), which coincided with the CO₂ emissions (Fig. 3). The control treatment emitted larger amounts of N₂O during the first three days, whereas the HTC char treatments displayed a slower increase in cumulative N₂O emissions.

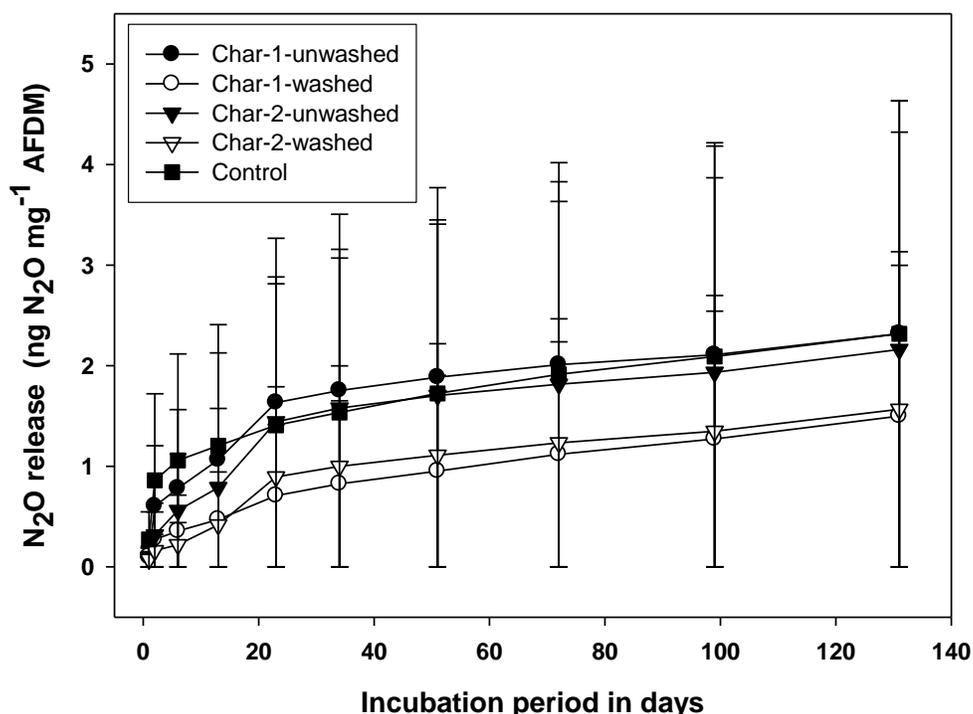


Fig. 4. Cumulative emissions of N₂O. Symbols and error bars represent mean \pm SD (n=5). Treatments were HTC char from fractionation, char-1-washed, char-1-unwashed, HTC char from suction, char-2-washed, char-2-unwashed, and without any amendment (control). (AFDM: ash free dry matter)

The addition of washed HTC chars to the soil samples tended to reduce the N₂O emissions, which can be attributed to the losses of N via washing. With the amendment of HTC char to soil, the N concentration of the soil/HTC-char-mixtures was increased. Even though all HTC char treatments contained more N, the N₂O emissions were not higher compared to the control. An explanation for this could be the inaccessibility of the added N. It has been shown that the majority of N in HTC char is fixed in heterocyclic N (Qayyum *et al.* 2012; Chen *et al.* 2014). So far, N of HTC char has hardly been investigated. In pyrolysis char, organic N is also mainly incorporated as heterocyclic N, which is thought to be more refractory than organic N (Knicker 2007; Koutcheiko *et al.* 2007). Therefore, it is expected that the heterocyclic N of HTC char would behave in a similar way to the pyrolytic heterocyclic N.

Table 2. Studies that Investigated the Effect of HTC Char Application on the Emission of N₂O

Study	Process condition	Feedstock	Incubation condition	Amount of biochar applied	Soil used	N ₂ O emission compared to control
Kammann <i>et al.</i> 2012	203 °C, 16 Mpa	beet root chip	22 ± 1 °C, 65% MWHC	8% (w/w)	agricultural soil, Luvisol	increase after stirring and N fertilization
Kammann <i>et al.</i> 2012	203 °C, 16 Mpa	bark chip	22 ± 1 °C, 65% MWHC	8% (w/w)	agricultural soil, Luvisol	increase after N fertilization
Malghani <i>et al.</i> 2013	230 °C & 180 °C, 90'	corn silage	20 °C, 70% WHC	1%(w/w)	deciduous forest soil, Cambisol	increase
Malghani <i>et al.</i> 2013	230 °C & 180 °C, 90'	corn silage	20 °C, 70% WHC	1%(w/w)	spruce forest soil, Cambisol	decrease
Malghani <i>et al.</i> 2013	230 °C & 180 °C, 90'	corn silage	20 °C, 70% WHC	1%(w/w)	agricultural soil, sandy loam	decrease, even after N fertilization
Schimmelpfennig <i>et al.</i> 2014	200 +3 °C, 1.6 Mpa, 120'	<i>Miscanthus x giganteus</i>	21 ± 1 °C, 31-37%WHC	14.5 t/ha ~0.7 % (w/w)	grassland soil	no difference
Dicke <i>et al.</i> 2014	230 °C, 6 h	digestate	20 °C, 70% WHC	2 % (w/w)	agricultural soil, topsoil	decrease, even after N fertilization
Dicke <i>et al.</i> 2014	230° C, 6 h	digestate	20 °C, 70% WHC	0.2 % (w/w)	agricultural soil,subsoil	no difference

A comparison of the results of this study with literature reveals that the effects of HTC char application to agricultural soils on the emissions of N₂O are unclear (Table 2). Increased (Kammann *et al.* 2012) and reduced (Malghani *et al.* 2013; Dicke *et al.* 2014) emissions of N₂O after fertilizer application compared with control treatments have been documented; however, cases of no difference between HTC and control treatments have been reported by Schimmelpfennig *et al.* (2014), which accords with our results. Reasons for this could involve the production conditions of HTC, the feedstock, the incubation

conditions, and the soil used. Higher HTC production temperatures seem to influence the emissions of N₂O. At production temperatures of 230 °C, reduced emissions of N₂O were reported (Malghani *et al.* 2013; Dicke *et al.* 2014), whereas lower production temperatures resulted in increased or unchanged emissions, compared with HTC char-free soils (Kammann *et al.* 2012; Schimmelpfennig *et al.* 2014). Not only the temperature, but also the feedstock used influences the emissions of N₂O. The HTC production and incubation conditions used in this study and a previous study (Dicke *et al.* 2014) were nearly identical; only the feedstock differed. Hydrothermally carbonized char made of digestate and wheat straw reduced emissions of N₂O (Dicke *et al.* 2014), whereas emissions after adding HTC char made of hemp dust did not differ significantly from those of the control sample. Furthermore, Schimmelpfennig *et al.* (2014) observed no difference between treatments with or without HTC char and concluded that this was caused by the moisture regimes compared with Kammann *et al.* (2012). In different forest soils, Malghani *et al.* (2013) observed both increased and decreased emissions of N₂O, compared with the HTC char-free soil. This was attributed to the different texture of the soils and the change in HTC char water holding capacity (Malghani *et al.* 2013).

This short literature review shows that HTC char has the potential to reduce N₂O emissions. However, a more systematic approach is needed to elucidate what factors of HTC char application influence the emission of N₂O.

The washing of the chars may result in environmental problems. The wash-waters contain organic C and N whose concentration should be reduced prior to disposal. One possible way of removing the organic compounds of the wash water is to perform anaerobic treatment as is done with the HTC-process liquor (Wirth and Mumme 2013), and methane would be produced concomitantly.

On the basis of this study, an overall greenhouse gas mitigation effect of the HTC char, based on the emission of CO₂ and N₂O, was probably less distinct in comparison with the increase of organic matter resulting from HTC char applied to the soil.

CONCLUSIONS

1. This study investigated a new way to utilize byproducts of hemp processing after hydrothermal carbonization. Under the aspect of C sequestration, char-2 (suction) appeared to be more suitable as a soil amendment than char-1 (fractionation). This was attributed to a low ash, high C content and its high availability, because more of this kind of residue accumulates during hemp fiber processing than hemp dust from fractionation.
2. Washing significantly affected the emission of CO₂, and the effect was mainly visible at the beginning of the incubation period. Washing may not be feasible on a larger scale.
3. Neither of the two tested carbonized hemp dusts were preferable for mitigating emissions of N₂O, and washing did not exert any influence either.

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