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ORIGINAL PAPER

Biochar and Hydrochar from Organic Side-Streams Induce Species-Specific Responses in Plants

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Abstract

Biochar (BC) and hydrochar (HC) have gained attention as multipurpose materials for soil improvement, plant growth promotion, carbon removal and waste reduction – key components of the circular economy. Heterogeneous side-stream and waste biomasses together with thermochemical processes produce variable char products whose effects on soil properties and plants may be divergent and dependent on the environmental context. We produced BC and HC from demolition wood, tomato leaves and biogas digestate and characterized chemical and physical properties of feedstock materials and char products. Growth chamber experiments were established to evaluate the phytotoxicity of the char products and their effects on seedling emergence, biomass and nutrient concentrations in three crop indicator species (barley, radish and rape) grown in a boreal soil. We found that both slow pyrolysis and hydrothermal carbonization (HTC) produce mostly good-quality char products within the limits of the EU Fertilising Products Regulation (FPR) 2019/1009. The effects of BC and HC applications on soil properties reflected the characteristics of the char products and application rates. In general, all char treatments increased soil pH, carbon content and organic matter. Effects of char products on emergence and growth depended on the plant species, sowing time, char treatment and application rate, with many interactive effects of treatments. Immediate phytotoxicity was shown by the highest application rate (50 t ha^{-1}) of tomato BC which reduced emergence in all species. Overall, char application had explicit positive effects on biomass in barley only. Our results suggest that pyrolysis and HTC are valuable methods in processing different side-stream and waste materials into char products that are potential soil amendments. Harmful effects of char application are rare with high-quality products, but the observed patterns of short-term plant responses emphasize the need for environment- and species-specific testing of soil amendments.

Highlights

- Various organic side-streams can be used as feedstock material for bio-/hydrochars.
- Feedstock chemical properties were reflected in chars, amended soils and plants.
- Plant species varied in responses to chars, their application rate and sowing time.
- Only a high dose of tomato-based biochar had immediate phytotoxicity on plants.

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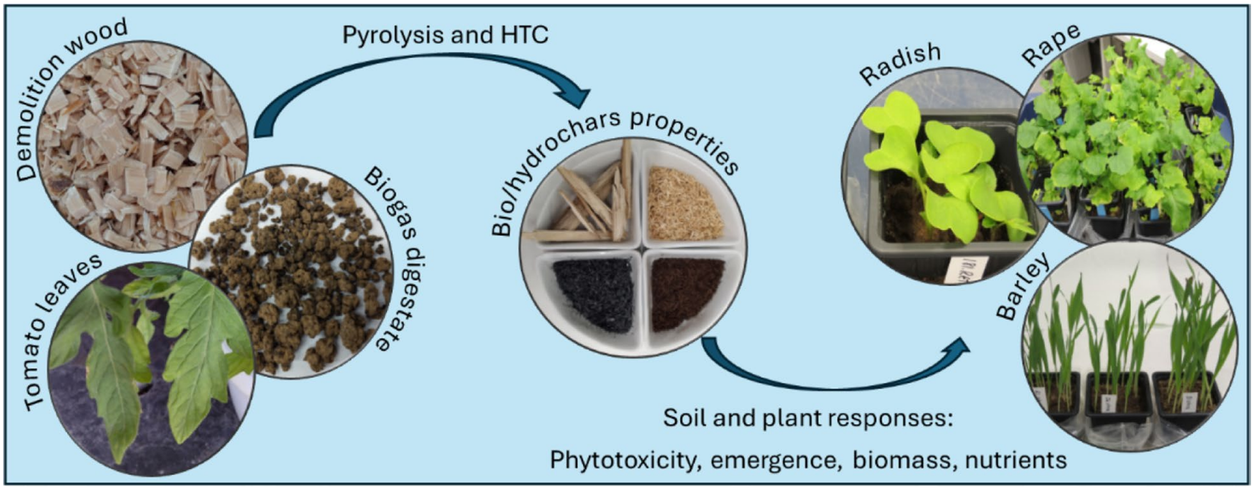
Graphical Abstract



Keywords Circular economy · Hydrothermal carbonization · Slow pyrolysis · Soil amendment · Thermochemical conversion

1 Introduction

Climate change, largely caused by increased CO_2 concentration in the atmosphere, threatens the environment and sustainability of the world. One way to remove atmospheric CO_2 via photosynthesis into a long-lasting reservoir relies on thermochemical decomposition of various biomasses into stable carbon-rich materials (Hu et al. 2021; Oleszczuk et al. 2013; Padhye et al. 2022; Roberts et al. 2010; Woolf et al. 2016). Especially biochar (BC)—a charcoal-like carbon-rich substance usually produced by the pyrolysis of dry plant material under low-oxygen conditions—has gained attention in the environmental sector both as a carbon sink and a soil amendment. Carbon-rich material may also be generated by hydrothermal carbonization (HTC) in which wet and liquid-phase biomass is converted into hydrochar (HC) at relatively mild reaction temperatures (Kambo and Dutta 2015; Padhye et al. 2022). Before various char products become widely applicable in soil improvement to boost CO_2 sequestration, climate goals and circular economy (Bolan et al. 2021; Lehmann and Joseph 2009; Matrapazi and Zabaniotou 2020; Padhye et al. 2022), it is necessary to understand the environmental conditions under which beneficial consequences of char application on soil properties and crop yield arise.

The aim of a circular bioeconomy is to preserve the value of products, materials and resources in the economy for as long as possible and to minimize the generation of end waste (European Commission 2015). In the EU, for example, the increasing biogas digestate production reached 31 Mt (dry matter) in 2022 (EBA 2023), the production of tomatoes alone is ca. 35 Mt per year and that of its side streams and waste fractions several times higher (Løvdal et al. 2019), and 51 Mt of demolition and construction wood is generated annually (Borzęcka 2018). A high proportion of these side-steams and waste fractions can be utilized in applications of a circular bioeconomy: for example, biogas digestate can be used as feedstock for fertilizers or polyhydroxyalkanoates (PHAs), and non-hazardous demolition waste can be recycled in new construction or packing materials (Holden et al. 2023; Malhotra et al. 2022). However, part of side streams and waste fractions may require further processing. For example, the presence of heavy metals, pathogens, and high loads of nitrogen in the digestate limits its land application as such (Bonetta et al. 2014, Monlau et al. 2016). Thus, huge quantities of feedstock materials such as biogas digestate, crop residues from vegetable production and demolition wood could be further processed for BC and HC in Europe (Ghodake et al. 2021; Løvdal et al. 2019).

In addition to boosting soil carbon stocks, BC can affect various soil physical, chemical and biological properties, e.g., by increasing soil pH and microbial activity, improving nutrient and water availability, and immobilizing heavy metals (e.g., Joseph et al. 2021). Such changes can promote plant performance in short and long term. Yet soil-applied BC and HC from organic side streams and waste materials have been shown to have positive, neutral and negative effects on plant growth and yield (e.g., Adjuik et al. 2020; Álvarez et al. 2017; Bargmann et al. 2014; Suarez et al. 2023), indicating strong context-dependence determined by crop species, environmental conditions and char type, including potential pre-treatments and co-amendments (Biederman and Harpole 2013; Jeffery et al. 2011, 2017; Liu et al. 2013; Premalatha et al. 2023; Schmidt et al. 2021; Xu et al. 2025). On a global scale, positive yield effects of char application are associated with acidic and infertile soils in the tropics, whereas in temperate regions, where soils tend to be more fertile and managed, no effect or potentially a negative effect on yield has been reported (Jeffery et al. 2017). The number of studies from high-latitude environments is still limited, and it is not known what the typical responses to chars are in soils that experience pronounced annual temperature fluctuations and that have a high carbon content relative to tropical soils (Kalu et al. 2021). The highly variable patterns of plant responses underline the need for interdisciplinary research that incorporates the potential physical, chemical and biological sources of variation in the outcomes of char application.

Different physicochemical properties of BC and HC significantly affect their potential applications. Chemical and physical qualities of BC and HC depend on the used feedstock material and processing conditions such as temperature, holding time and duration of the process (Ghodake et al. 2021; Nzediegwu et al. 2021; Yaashikaa et al. 2020; Yang et al. 2019). In general, HC exhibits higher O/C and H/C ratios than BC (Wang et al. 2021a, b). Compared to BC, HC results in lower aromaticity and poorer stability when added to the soil and is degraded at a faster rate. Consequently, BC has a higher potential in long term carbon sequestration than HC (Masoumi et al. 2021). A large proportion of feedstock nutrients may end up in the char product and be available for plants when applied to the soil (Ding et al. 2016). Depending on the feedstock material and process conditions, BC and HC may also contain polycyclic aromatic hydrocarbons (PAHs) and other potentially toxic elements (PTE) like heavy metals and volatile organic compounds such as furfural, organic acids, phenols, and dibenzofurans (Busch et al. 2013; Karatas et al. 2022; Lyu et al. 2016; Zhang et al. 2019a, b). Using highly heterogeneous side-stream and waste biomasses such as biogas digestate, greenhouse vegetable wastes and demolition wood together with different conditions of thermochemical processes inevitably leads to highly diverse BC and HC products whose suitability to soil application must be ensured. In comparison to BC, little information is available on the application of HC for soil improvement.

In this study, we used a factorial experimental design with char products that enables an examination of how different types of char treatments − feedstock material, char application rate and sowing time − affect traits in differing plant species and whether different aspects of char application have independent or interactive effects on plant growth. We produced BC and HC from biogas digestate, tomato leaves and demolition wood, and chemical and physical properties of both feedstock materials and char products were comprehensively characterized. We then established growth chamber experiments to evaluate the possible phytotoxicity of char products and to examine their effects on seedling emergence, biomass and nutrient concentrations in three divergent crop indicator species. We hypothesized that **1)** chemical and physical characteristics of the raw materials are reflected in the final char products, **2)** both processing technologies – pyrolysis and HTC – can produce good-quality char products according to the EU Fertilising Products Regulation from waste biomass to be applied on arable soil. Further, we assumed that **3)** immediately after mixing with soil, HCs especially might be phytotoxic to plants, but the effect will diminish after a stabilization period prior to sowing. We also predicted that **4)** after the stabilization period, application of both BC and HC products will improve growth in the indicator species, but the exact effects will depend on the plant species along with the chemical characteristics and application rates of the char products.

2 Materials and Methods

2.1 Feedstock Materials

Feedstock materials used were demolition wood (Class A) from regional waste management company Kiertokaari Oy (Oulu, Finland), tomato leaves from tomato producers' co-operative Österbottens Svenska Producentförbund rf (Närpiö, Finland), and biogas digestate produced from household biowaste by regional waste management company Stormossen (Mustasaari, Finland). The materials were cut or ground to a particle size of 1–5 mm and dried in an oven at 80 °C for 24 h to the moisture content of $< 10\%$ prior to pyrolysis. The feedstock materials were not dried prior to hydrothermal carbonization.

2.2 Pyrolysis and Hydrothermal Carbonization

Pyrolysis conditions depend on the biomass quality. Especially green waste, such as tomato leaves, cannot be pyrolyzed at high temperatures since the weight to volume ratio of the biomass is low, pyrolysis occurs faster, and the yield of BC will eventually become too low. The pyrolysis temperatures and retention times were selected based on literature (Doyle et al. 2016; Islam et al. 2021) and our earlier (unpublished) experiments. BC was produced by slow pyrolysis under a nitrogen flow of 2 L min^{-1} in a custom-made reactor including an Entech furnace. The furnace was heated from room temperature to pyrolysis temperature at heating rate of 5 °C min^{-1} for tomato leaves and digestate, and at 10 °C min^{-1} for demolition wood. Pyrolysis temperature was

300 °C for digestate, 450 °C for tomato leaves and 500 °C for demolition wood. Retention time was 1 h for demolition wood and 30 min for the other materials.. After pyrolysis, the furnace was allowed to cool down freely to room temperature. BC yield was calculated by weighing the raw material and product before and after processing.

Hydrothermal carbonization (HTC) was done with two high-pressure Parr reactors (4575/76 HP/HT Pressure Reactors, USA and the 4520-bench top reactor, USA) one with a volume of 0.4 L and another with 0.78 L. Raw materials (demolition wood, tomato plants and biogas digestate) were placed in the reactor, followed by an addition of distilled water to reach approximately a 1:5 biomass to water ratio. The temperature and pressure were continuously controlled using the 4848-reactor controller. The HTC process was carried out at 200 °C under 15–20 bars for 6 h. Cooling water was used to prevent the reactor from overheating. Vacuum filtration was used to separate the char product from the liquid phase after the system was naturally cooled down. Finally, the wet product was dried in an oven at 80 °C for 24 h. The pH of the batches was measured before carbonization and at the end of the process (Table 1).

2.3 Analyses of Chemical and Physical Characteristics of Materials

The crystalline structure of the samples was analyzed by an X-ray diffractometer (XRD) PANanalytical X'Pert PRO (PANanalytical B.V., Almeno, The Netherlands) using CuKα radiation ($\lambda = 1.54056$ Å) produced at 45 kV/40 mA. The data were collected in a range of $2\theta = 5°–80°$ with a step size of 0.0167°. N_2 physisorption at −196°C was used to calculate specific surface areas, pore sizes, and pore volumes of the samples (Micrometrics ASAP 2020, Norcross, GA, USA). The method of Brunauer–Emmet–Teller (BET) was used for calculating specific surface areas of carbon materials. The pore sizes and total pore volumes were analyzed by the Barrett–Joyner–Halenda (BJH) method. Prior to the analysis, carbon materials were pretreated first at 80 °C for 30 min and then at 105 °C for 14 h. The morphology of raw materials, BCs and HCs, was characterized by a Zeiss Ultra Plus (FESEM, Germany) equipped with an EDS analyzer (FESEM). Prior to the elemental analyses, samples were dried at 80 °C for 24 h. The elemental analysis was done using a PANanalytical® AXIOS mAX 4 kW X-ray fluorescence spectrometer (XRF, Malvern, UK) using the loose powder method under an He atmosphere (XRF). Elemental composition of the chars was analyzed by a PANanalytical Axios Max XRF WDS analyzer with Omnian standardless method and a LECO CS-200 carbon–sulphur analyzer. A Perkin Elmer spectrum 400 Fourier transform infra-red spectrometer with an attenuated total reflectance (§) accessory (ATR-FTIR) was used to study the functional groups of the BCs and HCs. The measurement was carried out from 600 cm^{-1} to 4000 cm^{-1}.

Table 1 pH of the feedstock batches from side-stream and waste materials and the corresponding char products after pyrolysis (BC = biochar) and hydrotermal carbonization (HC = hydrochar), *n* = 3

	pH		
Feedstock	Before processing	BC	HC
Demolition wood	4.44	7.88	3.25
Biogas digestate	7.61	7.30	6.70
Tomato plants	6.12	10.06	7.09[a]
Reference (spruce)	n.d	9.21	n.d

[a]not used in growth chamber experiments

n.d. not determined

2.4 Effects of Char Treatment on Plants: Growth Chamber Experiments

To evaluate the potential phytotoxity and effects of the char products on plant growth in a controlled environment, three distinct indicator plant species were selected for the experiments: barley (*Hordeum vulgare,* cultivar Aukusti), radish (*Raphanus raphanistrum* subsp. *sativus,* cultivar National 2) and rape (*Brassica rapa* subsp. *oleifera*, cultivar Synthia). For the growth medium, topsoil (0 − 20 cm depth, fine sand, organic matter content 1.7%, pH 6, Supplementary material Table S3) was collected from a barley field (64°50′21.7"N, 25°08′16.1"E) with a history of potato cultivation. The effects of six BCs/HCs that were tested were prepared from demolition wood (BC and HC; referred hereafter as demolitionBC and demolitionHC), biogas digestate (BC and HC; referred as digestateBC and digestateHC) or tomato leaves (BC; referred as tomatoBC). A commercially available BC product made from spruce (referred as refBC) was included in the experiments as a reference material (EBC-certified BC, pyrolysis temperature ~ 650 °C, pyrolysis time < 10 min, water holding capacity 318%, bulk density 86 kg m^{-3}, surface area (BET) 398.6 m^2 g^{-1}, total carbon 95%, data obtained from Carbofex Oy, Finland, see also Supplementary material Table S2) and the soil without char amendment as an untreated control.

Three application rates for each char product were used, corresponding to 5, 10 or 50 t ha^{-1} in field settings (0.6, 1.2 and 6.0 g/0.3 L of soil, respectively; based on the assumption that char is applied to the top 25 cm of soil in the field and that 1 ha = 2500 m^3 of soil). The highest application rate was chosen to show potential adverse effects of char application during a short-term study. The char products were ground and mixed with the soil, and the mix was sampled for soil analyses before the addition of a fertilizer. The fertilizer

(Yara Mila Y3, NPK 23–3–8, Yara Finland) was used at 348 kg ha^{-1} for barley, at 435 kg ha^{-1} for rape, and at 478 kg ha^{-1} for radish, corresponding to 80, 100 and 110 kg N ha^{-1}, respectively. Soil moisture was adjusted to 10% (w/w) before mixing the chars and the fertilizer into the soil.

To determine whether the char products have immediate phytotoxicity, seeds were sown on half of the pots (8 cm × 8 cm × 8 cm, filled with 0.3 L of soil) immediately after mixing the chars with the soil. The other half of the pots was sown after a three-week stabilization period to allow for the degradation of potential phytotoxins. For both sowings, each combination of char treatment and application rate had five replicate pots. Four (radish), five (rape) or 16 (barley) seeds were sown per pot at the depth of 1 cm for rape and radish, and at 2 cm for barley, and covered with soil. The pots were divided into five spatial blocks (trays), with one replicate pot per application rate in each, and the trays were covered with a polyethene film until emergence. The pots were sprayed with tap water 7 days after sowing, after which they were bottom-watered three times a week with a 0.1% (w/v) liquid fertilizer (YARA Tern Kristalon NPK 14–9–23 + 3,3 MgO + micronutrients, Yara Finland) and the same volume per pot. The experiments were executed in controlled growth chambers (Fitotron, Weiss Technik, Germany) with a 16-h photoperiod (10 000 lx), 18 °C in light/15°C in dark, and relative humidity of 60%. For the experimental layout and timeline of the experiments, see Supplementary material Table S1 and Figure S4.

Soils were analyzed at the start of the experiment for soil type (visual), organic matter (OM) (SFS-EN 13039, SFS-EN 13040), pH (H_2O 1:2.5), electrical conductivity (EC) (H_2O 1:2.5), cation exchange capacity (CEC) (calculated by bases), water soluble N (M KCL extraction/Spectrophotometry), total N (SFS-EN 13654–2:2002), water soluble Ca, Mg, K, S, Na (HAAc extraction, pH 4.65, extraction ratio 1:10/ICP-OES), water soluble P (HAAc extraction, pH 4.65, extraction ratio 1:10/Molybdenum blue method/Gallery) and total organic carbon (TOC) (SFS-EN 15936). At the end of the experiment, the soils were analyzed from the later sowing of barley and the early sowing of radish (excluding TOC and OM). Soil nutrient analyses were done on three replicates per each application rate and the untreated control and carried out by a commercial soil testing lab (SeiLab Oy, Seinäjoki, Finland). The pots were monitored for seedling emergence seven days after sowing. Emergence was recorded as the number of plants appearing above the surface of the soil in each pot. At five weeks aboveground biomass in the pots was measured after drying samples in an oven (70°C, 26 h). Above- and below-ground biomass of radish was combined in each pot. Plant biomass from the later sowing for barley and the early sowing for radish was analyzed for the content of 11 nutrients [N (SFS-EN 13654–2:2002) K, Ca, Mg, Cu, Mn, Zn, P, B, S, Fe (Microwave digestion/ICP-OES)]. For nutrient concentrations, three replicates per char treatment and application rate were analyzed in barley, while in radish the number of replicates per treatment ranged from three to five.

2.5 Statistical Analyses

2.5.1 Correlated Variation Among Soil Variables

The principal component analysis (PCA) was used to identify groups of correlated soil variables at the beginning of the growth chamber experiments and to outline soil variation among the char treatments at different application rates. The analysis was based on a correlation matrix, and the Varimax rotation was used to strengthen the loadings of different variables on one PC only. Components that had eigenvalues above one were retained.

2.5.2 Treatment Effects on Plant Traits

Variation in emergence at day 7 (%, the proportion of emerging seedlings) and biomass at 5 weeks (g) was analyzed using the analysis of variance (ANOVA) with fixed and random effects. Each plant species was analyzed individually. The statistical model tested for the effects sowing time (S; early vs. later; fixed), char treatment (C; seven treatments; fixed), application rate (A; four levels; fixed), S × C interaction, S × A interaction, C × A interaction, S × C × A interaction and block (five blocks; random).

Plant nutrients were analyzed in the later sowing for barley or the early sowing for radish, thus sowing time was excluded from the statistical models for the two species. Analyzing the 11 nutrients both as a single group and individually, multivariate analyses of variance (MANOVA) were carried out, with all factors considered fixed. All multivariate tests that examine factor effects on all nutrients simultaneously produced similar results, and those based on Pillai´s Trace are reported. To test whether the untreated control differed from the specific char treatments and application rates, additional Bonferroni post hoc tests were performed. All statistical analyses were carried out with IBM SPSS Statistics Version 29.

3 Results

3.1 Chemical and Physical Properties of the Feedstock Materials and Char Products

Based on XRF measurements (Table 2), K, Ca, Mn, and Zn and P were found in all raw materials (> LOQ), except for P in demolition wood. Ca contents were significantly higher

Table 2 Elemental contents (%, w/w dry matter; XRF) in different feedstocks (FT) of side-stream and waste materials and the corresponding biochars (BC) and hydrochars (HC). A commercial BC product (refBC) made from spruce was included in the tests as a reference (*n* = 1)

Element	Elemental concentration (%)								
	Demolition			Tomato		Digestate			Ref
	FT	BC	HC	FT	BC	FT	BC	HC	BC
Na	-	-	-	-	-	0.30	0.27	0.15	-
Mg	-	0.060	0.02	0.34	0.45	0.31	0.29	0.40	0.06
Al	-	0.020	0.009	0.006	0.005	0.63	0.50	0.95	0.010
Si	-	0.060	0.023	0.093	0.14	2.2	1.8	3.4	0.045
P	-	0.15	0.21	1.0	1.3	1.6	1.4	2.3	0.15
Cl	-	0.023	0.04	0.35	1.4	0.53	0.54	0.20	0.007
K	0.10	0.22	0.05	9.9	8.2	0.84	0.84	0.50	0.24
Ca	0.36	0.46	0.21	9.6	12.9	5.4	5.5	6.6	0.78
Ti	-	-	-	-	-	0.093	0.081	0.10	-
Cr	-	-	-	-	-	-	0.004	0.006	-
Mn	0.27	0.40	0.10	0.10	0.18	0.083	0.075	0.090	0.060
Fe	-	0.016	0.009	0.030	0.050	1.4	1.3	1.2	0.020
Ni	0.097	0.12	0.024	-	-	-	0.005	0.004	-
Cu	-	0.022	-	-	0.005	0.022	0.017	0.015	-
Zn	0.21	0.46	0.12	0.013	0.015	0.055	0.05	0.050	-
Sr	-	-	-	0.043	0.050	0.014	0.017	0.010	-

- = Concentration below detection level

in tomato plants and biogas digestate compared to demolition wood. Fe and Si contents were several times higher in digestate feedstock and char products than other materials. Additionally, pyrolysis led to an increase in the relative Ca and K content in demolitionBC.

The specific surface area (S_{BET}) of refBC (174 $m^2 g^{-1}$) was higher than that of others (Supplementary material Table S2). The BET surface area of demolitionHC was 2.5 $m^2 g^{-1}$, while it increased to 57 $m^2 g^{-1}$ for demolitionBC. The BET surface area of tomatoBC was significantly lower (4.0 $m^2 g^{-1}$) than that of the other plant based BC materials, and the results were supported by FESEM images. Regarding the digestateBC, the BET surface area could not be measured due to its negligible value.

The carbon, hydrogen, nitrogen, sulfur, and oxygen contents of the samples are presented in Table 3, accompanied by their respective C/N, H/C, and O/C atomic ratios. The samples from HTC and pyrolysis have increased carbon and reduced oxygen contents. Also, the H/C and O/C atomic ratios decreased after the HTC and pyrolysis processes.

The XRD results related to HCs (Fig. 1a) showed that demolitionHC was more carbonized than digestateHC. XRD patterns of demolitionHC had peaks at around $2\theta = 15.8°$ (101), 22.3° (002), and 34.3° (040) that could be

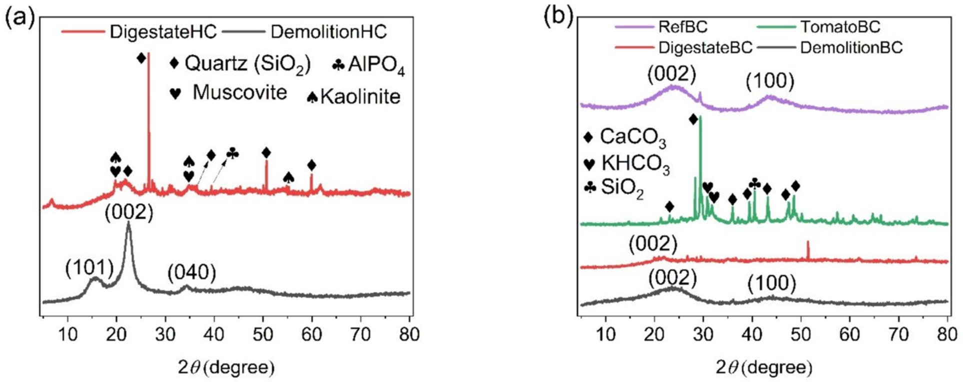
Table 3 Carbon (C), hydrogen (H), nitrogen (N), oxygen (O) and sulfur (S) concentrations (%) in different feedstock materials (FT) and the corresponding biochars (BC) and hydrochars (HC), *n* = 3

Element	CHNOS concentration (%)								
	Demolition			Tomato		Digestate			Ref
	FT	BC	HC	FT	BC	FT	BC	HC	BC
C	51	85	56	31	34	42	46	41	86
H	6.2	3.0	5.7	4.5	1.0	5.8	5.0	5.0	1.0
N	< 0.01	< 0.01	< 0.01	5.0	2.4	4.8	4.8	3.0	0.3
O	39	6.5	33	32	22	22	15	16	3.6
S	< 0.01	< 0.01	< 0.01	2.0	0.1	0.6	0.4	0.4	< 0.01
C/N*	n.d	n.d	n.d	7	17	10	11	16	334
H/C*	1.5	0.4	1.2	1.7	0.4	1.7	1.3	1.5	0.1
O/C*	0.6	0.1	0.4	0.8	0.5	0.4	0.2	0.3	0.03

n.d. not determined as N below detection limit (< 0.01)

*Atomic ratio

Fig. 1 XRD (X-ray diffractometer) results of **a** hydrochars (HC) and **b** biochars (BC) produced from different feedstock materials. A commercial BC product made from spruce was included in the tests as a reference (refBC), *n* = 1



attributed to the polysaccharide crystals from hydrolysis of hemicellulose and cellulose during the hydrothermal carbonization process (Hou et al. 2019; Liu et al. 2022a, b). DigestateHC contained the highest amounts of Si among all the samples, which is visible also in XRD by the SiO_2 peaks appearing at around 2θ = 21.9°, 26.6°, 36.4°, 50.7°, and 59.9°. The presence of P and Al resulted in a peak at around 39.5° that can originate from aluminum phosphate (Wang et al. 2017; Zhang et al. 2021).

Regarding the BCs (Fig. 1b), we observed two wide peaks at 2θ = 22.3° (002) and 44° (100), indicating turbostratic carbon material (Huang et al. 2019). The (002) plane at 15.8° can give a rough estimate on the carbonization degree of the material, and the broad peak at 44° can be assigned to diffractions of graphitic carbons (Yan et al. 2021). DemolitionBC and refBC were more carbonized than tomatoBC and digestateBC. TomatoBC appeared less carbonized, since the XRD diffractogram did not indicate the features related to (turbostratic) carbon. The presence of Ca, K, and Si species was also observed. TomatoBC had some sharp peaks related to $CaCO_3$ at around 2θ = 23.1°, 29.4°, 36.0°, 39.5°, 43.2°, 47.5°, and 48.5° (Liu et al. 2020; Wu et al. 2021). It also had kalicinite related peaks at around 2θ = 30.8° and 31.7° (Karim et al. 2017). TomatoBC had the highest amount of Ca and K among all the materials based on the XRF results. The residual crystalline material was visible also in refBC. DigestateBC did not show clear carbon-related peaks, nor possible raw-material related peaks indicating a non-crystalline composition of the BC (Fig. 1b).

Demolition wood feedstock exhibited a fiber-like morphology because of lignocellulosic biomass, while HC produced from it showed a rough and irregular surface with some pores after hydrothermal carbonization (Supplementary material Fig. S1). This raw material was maybe the most homogeneous, as shown also by the FESEM images. In general, porosity of tomatoBC (Supplementary material Fig. S2) and digestateBC (Supplementary material Fig. S3) was low. HC surfaces were rougher than those of BCs.

3.2 ATR-FTIR Spectroscopy

The infrared spectrum (Fig. 2) revealed distinct bands corresponding to various functional groups within the sample. The wide band at above ~3000cm^{-1} in the case of HCs and raw materials originates from O–H vibration related to moisture content in the samples. Aliphatic C-H bands observed at 2835–2990 cm^{-1} are observed for digestateBC/HC as well as demolitionHC (Guo et al. 2024). These may originate from methyl- or methylene functional groups. The C = O band at 1732 cm^{-1} may originate from carboxylic acid, ester, ketone and aldehyde groups only observed for raw materials (Reza et al. 2020; Zhang et al. 2019a, b). Based on the absence of shoulder-like features near aliphatic alkyl C-H stretching vibrations and the observed C = O band location, this vibration is most likely related to carboxylic acids. The aromatic C–C stretching of hemicellulose appears at approximately 1610–1560 cm^{-1}. Based on the pH measurements, the HCs are acidic that would support the presence of carboxylic acids. From the BCs, digestateBC is closest to neutral while others are more basic, especially tomatoBC having pH ~ 10. The band at about 1400–1450 cm^{-1} that was seen for digestateHC, digestateBC, and tomatoBC can be ascribed to tensile vibration of the carboxyl (O = C–O) (Guo et al. 2024). Further analysis unveiled bands indicative of ether or ester in cellulose and hemicellulose, detected at 1034 cm^{-1} (C-O), 1055 cm^{-1} (C-O), 1107 cm^{-1} (C-O group of ether or alcohol), and 1161 cm^{-1}, respectively (Gale et al. 2021). Peaks observed below 1500 cm^{-1} predominantly stemmed from vibrational stretching of esters, carboxylic acids, and aldehyde groups coming from cellulose or lignin (Taskin et al. 2019; Zhu et al. 2023). The exact identification of the peaks is complicated by the inorganic contents of digestateHC and tomatoBC that vibrations appear also somewhat above 1000 cm^{-1}. For example, wide digestateHC peak appearing at around 1030 cm^{-1} may originate also from Si–OH vibration, since digestate contained significant amount of Si (XRF) and SiO_2 was observed in XRD (Tran et al. 2013).

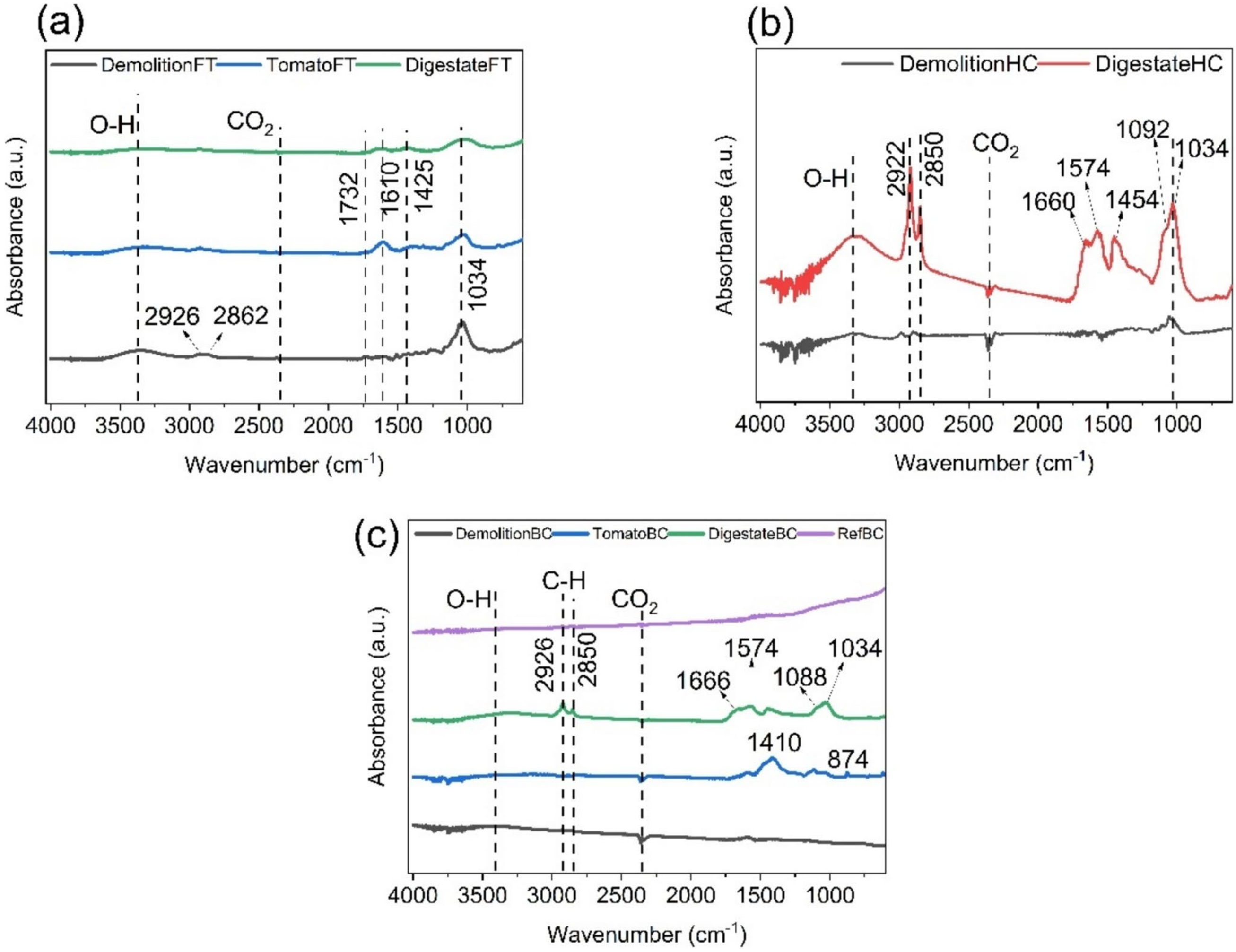


Fig. 2 FTIR (Fourier-transform infrared) spectroscopy results of the **a** feedstock materials (FT) and the corresponding **b** hydrochars (HC) and **c** biochars (BC). A commercial BC product made from spruce was included in the tests as a reference (refBC)

3.3 Characteristics of Char-Applied Soils

OM (%) increased in parallel with the carbon content of soil-applied BC and HC products and with the application rate, being 1.7% in the untreated control soil, 1.3–3.4% in char treatments with application rate 5 t ha^{-1}, 2.0–3.5% at 10 t ha^{-1} and 2.3–4.4% at 50 t ha^{-1} (Supplementary material Table S3). At the start of the experiment, pH of the untreated control soil was 6.0. Application of all BC products and digestateHC increased soil pH, the effect of tomatoBC being the greatest (pH 8.3 at 50 t ha^{-1}). Only the highest application rate of demolitionHC decreased the soil pH. Wood-originating BCs (demolition wood and reference) had no large effect on soil EC and CEC, whereas the BCs and HCs made of tomato and digestate increased EC and CEC remarkably. Elemental concentrations of BC and HC products were parallelly seen in soil characteristics (Supplementary material Table S3). For example, high concentration of K, P and Zn in feedstock materials were also observed in the corresponding chars, i.e., K in tomatoBC, Zn in demolitionBC/HC, and P in tomatoBC and digestateBC/HC. DigestateBC/HC increased soil S concentration several-fold: in soil amended with tomatoBC at 50 t ha^{-1} the increase was 164-fold. Ca concentration was also higher in the soils with tomatoBC and digestateBC/HC than in the untreated control soil and in soils amended with chars produced from wood biomass.

During the experiment soil pH remained at a similar level or was reduced slightly (Supplementary material Table S3). EC increased ca. 2–sevenfold in all treatments. S concentration of the soil was several times higher in all treatments at the end of the experiment, except in those amended with digestateBC or tomatoBC which had high S concentrations already in the beginning of the experiment. Otherwise, no big changes in the elemental concentrations in soils were seen during the experiment.

PCA identified three groups of correlated variables with eigenvalues above one among the soil characteristics in the beginning of the experiment (Table 4). Soil-PC1, explaining over 50% of total variation, was strongly and positively associated, for instance, with S, K, EC, CEC and pH. For Soil-PC1, all char treatments had higher values than the control, and the most distinct treatment was tomatoBC that yielded substantially higher values than any other treatment (Fig. 3a, d). For demolitionBC, digestateHC and refBC the highest application rate especially increased soil-PC1 values. Soil-PC2 exhibited strong and positive associations only with Na and total N, and most char treatments and application rates exhibited similar or lower values than the untreated control (Fig. 3b). For Na, digestateBC and digestateHC had higher overall values than the control especially at the highest application rate (Fig. 3e). Soil-PC3 was positively correlated with TOC, C/N and OM, with higher values in the char treatments than in the untreated control particularly at the highest application rate (Fig. 3c, f). Soluble N loaded similarly on soil-PC1 and soil-PC2, suggesting its variation among char treatments was not as distinct as, for instance, that of EC or CEC.

3.4 Effects of Char Treatments on Indicator Plants

3.4.1 Main Effects of Treatments

Effects of the treatments on the three plant species and two responses, emergence at day 7 and biomass at 5 weeks, varied (Fig. 4 – 5, Table 5ab). Treatment effects were either positive, negative or non-significant depending on the species. The main effect of sowing time on emergence was statistically significant in barley and radish: the average effect of the early sowing relative to the later sowing was negative in barley (−4.75% points) and positive (+ 42.4% points) in radish (Fig. 4). Sowing time affected biomass in all three species, with early sowing decreasing biomass in barley (−0.059 g) and increasing it in radish (+ 0.662 g) and rape (+ 0.304 g) relative to the later sowing (Fig. 5).

The main effect of char treatment was significant for both emergence and biomass in barley and rape, but in radish char treatment did not affect biomass (Table 5ab). The average effect of the tomatoBC on emergence was negative in barley and rape (Fig. 4a, c, f), but for biomass the effect was not consistent (Fig. 5a, c, f). Barley exhibited more striking responses relative to the control (Fig. 5a).

The main effect of application rate was significant for emergence in barley and rape, and for biomass in radish and rape (Table 5ab). The average effect of the highest application rate was negative for emergence in barley and rape (Fig. 4a, c, f), but for biomass, the highest application rate tended to increase biomass in barley (Fig. 5a, d) and reduce it in rape (Fig. 5c, f).

3.4.2 Interaction Effects of Treatments

Various treatment interactions were statistically significant particularly in barley and rape (Table 5ab). The occurrence of both significant main effects and interactions indicates that while different individual treatments had consistent effects on plant traits, their joint effects were not independent of each other. Giving rise to sowing time × treatment/

Table 4 Principal component analysis (PCA) that was used to identify correlated characteristics in a set of 14 soil variables measured in char treatments applied to field soil. The table presents Pearson´s correlation coefficients between the individual soil variables and three principal components (Soil-PC1/PC2/PC3), with strong correlations (−0.7 > *r* > 0.7) underlined. All PCs had eigenvalues above one (a common threshold for which PCs to keep), and together they explained 89.3% of total variation among soil variables

	Component		
	Soil-PC1	Soil-PC2	Soil-PC3
Eigenvalue	7.28	2.80	2.42
Variance explained	52.0%	20.0%	17.3%
Soil variables:			
pH	0.886	0.321	0
Electrical conductivity (EC; 10 × mScm^{-1})	0.963	0.0505	−0.0314
Ca (mg L^{-1})	0.938	0.323	−0.0674
K (mg L^{-1})	0.990	0.0491	−0.0638
Mg (mg L^{-1})	0.879	0.421	−0.0900
P (mg L^{-1})	0.733	0.580	−0.0160
S (mg L^{-1})	0.991	0.0180	−0.0785
Na (mg L^{-1})	−0.0008	0.848	0.102
Organic matter (OM; %)	−0.106	0.358	0.794
Total organic carbon (TOC; %)	0.0510	0.162	0.952
Soluble N (mg kg^{-1})	0.503	0.664	0.154
Total N (mg kg^{-1})	0.461	0.770	0.00098
Cation exchange capacity (CEC; cmol L^{-1})	0.959	0.260	−0.0720
C/N	−0.146	−0.320	0.908

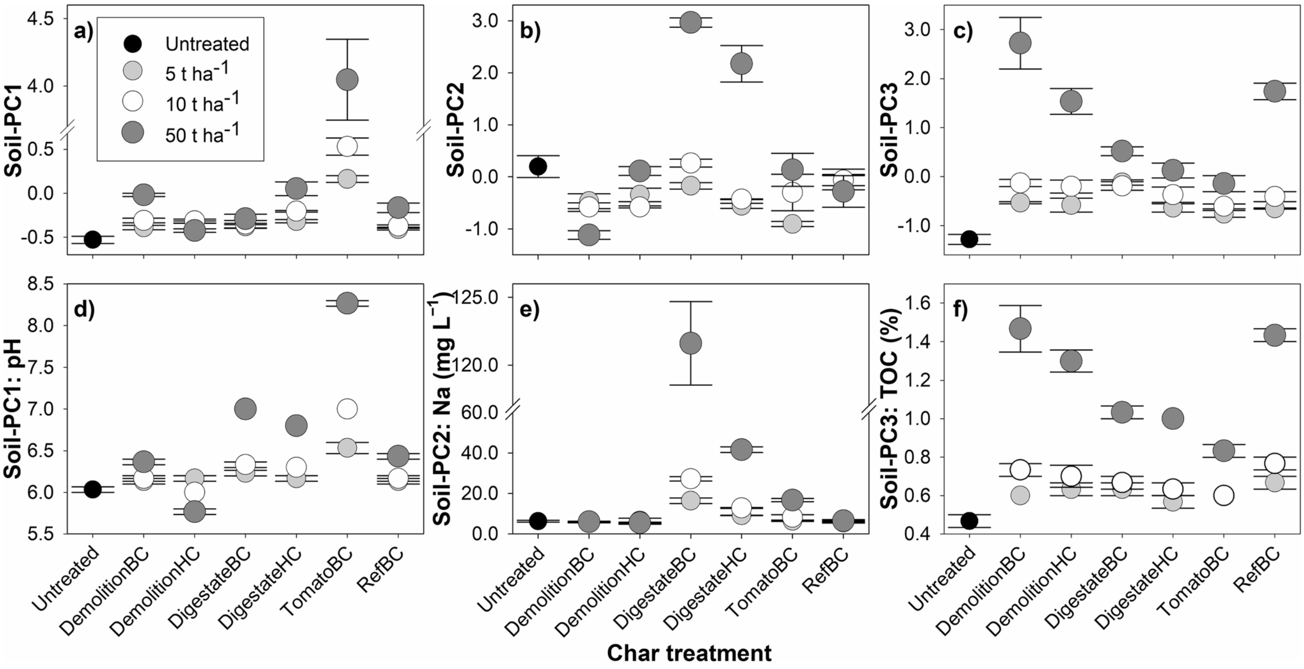


Fig. 3 Soil characteristics of char treatments with different application rates, described by treatment averages of three principal components that were estimated using 14 individual soil variables (see Table 4 for details): **a** soil-PC1, **b** soil-PC2, and **c** soil-PC3. One representative characteristic per PC is shown: **d** pH for soil-PC1, **e** Na for soil-PC2, and **f** total organic carbon (TOC) for soil-PC3. Error bars represent standard errors of the mean based on three technical replicates of soil analyses. In addition to organic waste-originating char, the experiment contained an untreated control without applications and a commercial biochar (refBC) produced from spruce

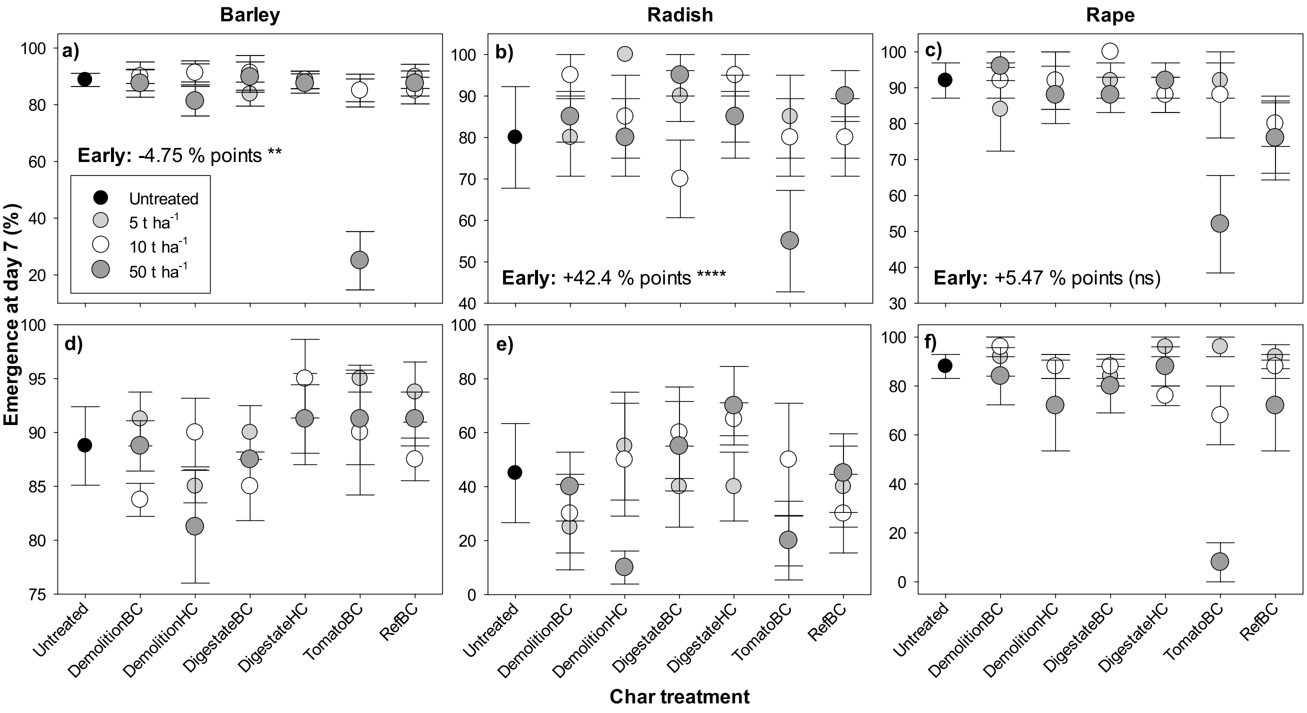


Fig. 4 Char treatment averages at different application rates for emergence at day 7 in three indicator species: **a**, **d** barley, **b**, **e** radish, and **c**, **f** rape, with data for the early sowing in the top panel (a – c) and data for the later sowing in the lower panel (d – f). The species-specific average effect of early planting on emergence relative to the later sowing is shown in the top panel. Error bars represent standard errors of the mean

Table 5 Analysis of variance (ANOVA) that was used to test which factors (sowing time, char treatment, application rate, their interactions, and block) had statistically significant effects on variation in **a**) emergence at day 7, and on **b**) biomass at 5 weeks in three indicator plant species: barley, radish and rape. df = degrees of freedom, *F* = *F*-ratio

		Barley	Radish	Rape
	df	*F*	*F*	*F*
a) Emergence at day 7 (%)				
Main effects:				
Sowing time (S)	1	8.64 **	109 ****	3.30 ns
Char treatment (C)	5	6.59 ****	2.75 *	6.78 ****
Application rate (A)	2	10.8 ****	0.698 ns	11.1 ****
Block	4	2.46 *	9.30 ****	2.48 *
Interactions:				
S × C	5	11.2 ****	1.12 ns	1.87 ns
S × A	2	7.40 ***	1.10 ns	3.92 *
C × A	10	6.44 ****	2.01 *	5.18 ****
S × C × A	10	6.08 ****	0.968 ns	0.629 ns
b) Biomass at 5 weeks (g)				
Main effects:				
Sowing time (S)	1	9.58 **	266 ****	168 ****
Char treatment (C)	5	18.1 ****	1.02 ns	4.99 ***
Application rate (A)	2	2.78 ns	7.36 ***	17.0 ****
Block	4	11.2 ****	10.5 ****	24.5 ****
Interactions:				
S × C	5	3.37 **	0.144 ns	3.40 **
S × A	2	0.410 ns	1.35 ns	5.23 **
C × A	10	4.24 ****	0.905 ns	2.64 **
S × C × A	10	3.25 ***	0.884 ns	1.96 *

ns = non-significant, $P > 0.05$; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; **** $P < 0.0001$

application rate interactions in emergence in barley, the negative effects of tomatoBC and the highest application rate were specific to the early sowing (Fig. 4a, d). For emergence in rape, the significant sowing time × application rate interaction indicated that the highest application rate in the later sowing resulted in lower emergence (Fig. 4c, f). Further, the significant char treatment × application rate interaction signaled that the effect of char treatment was dependent on application rate, with the combination of tomatoBC and the highest application rate in particular lowering emergence (Fig. 4f).

In barley, char treatments at the highest application rate increased biomass, but for refBC the lowest application rate induced growth most (Fig. 5a), resulting in a char treatment × application rate interaction (Table 5b). In rape the early sowing increased average biomass, but the difference between the sowings varied, being largest for tomatoBC and smallest for the untreated control (sowing time × char treatment interaction; Fig. 5c, f). Further, the early sowing increased the effects of application rates, but less so with the highest application rate (sowing time × application rate interaction). Finally, the highest application rate reduced biomass especially with digestateBC, digestateHC and tomatoBC, resulting in a char treatment × application rate interaction.

3.4.3 Treatment Effects on Plant Nutrients

Overall, nutrient concentrations in barley and radish were affected by char treatment, application rate and the treatment × application rate interaction (Table 6ab, Supplementary material Table S4). Depending on the nutrient, the statistical model explained 15.1 (Fe) – 98.9% (Zn) of total variation in barley, and 10.2 (N) – 98.0% (Zn) of total variation in radish (Table 7ab). Treatment effects were nutrient-specific, with both positive and negative effects relative to the untreated control detected, and for instance in the case of Zn, variation in nutrient content among the char treatments in both barley and radish reflected variation in Zn concentration among the initial char products (Fig. 6a, b, c). The coefficient of determination was high also for Mn (Fig. 6d, e, f). All except two nutrients exhibited a significant char treatment effect in barley, while in radish there were four such nutrients. Generally, the effect of application rate was significant for fewer traits than with char treatment, with many nutrients exhibiting a significant interaction between treatment and application rate. Hence, the combined effects of char treatment and application rate could not be fully estimated by the individual effects of different factor levels.

4 Discussion

We found that feedstock material had a great influence on BC and HC properties, and that chemical and physical characteristics of the raw materials were reflected in the final char products. Both slow pyrolysis and HTC produced from selected waste biomasses yielded good-quality char products that mostly fulfilled the requirements for soil application according to the European BC Certificate (EBC 2024) and the EU Fertilizing Products Regulation (EU 2019/1009). Experiments in controlled growth chamber environments on three indicator plant species showed that responses to sowing time, char treatment and application rate varied among the species and that treatment interactions commonly occurred, with only a combination of tomatoBC and a high application rate systematically slowing down emergence. Positive effects of char application on biomass were clearest in barley.

As expected, BC and HC had different properties depending on the feedstock material and production

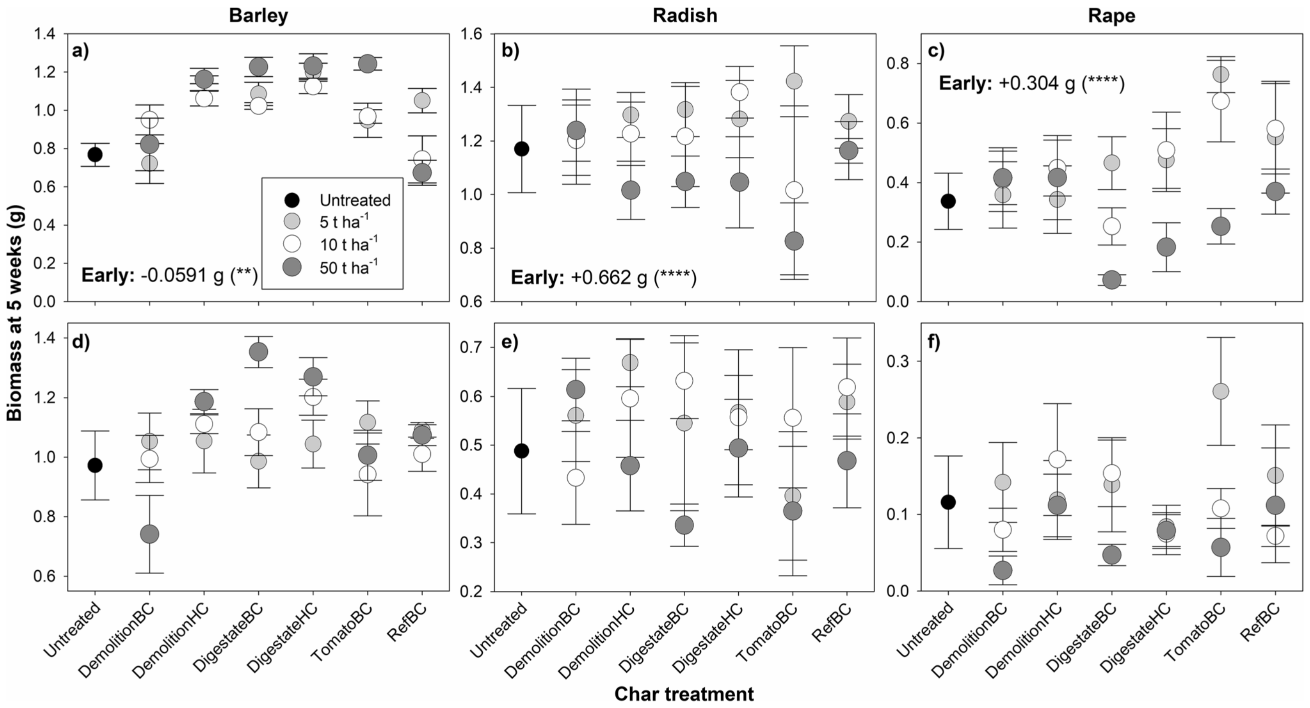


Fig. 5 Char treatment averages at different application rates for biomass at 5 weeks in three indicator species: **a**, **d** barley, **b**, **e** radish, and **c**, **f** rape, with data for the early planting in the top panel (a −c) and data for the late planting in the lower panel (d −f). The species-specific average effect of early sowing on biomass relative to the later sowing is shown in the top panel. Error bars represent standard errors of the mean

Table 6 Multivariate analysis of variance (MANOVA) that was used to test whether char treatment, application rate, their interaction and block had statistically significant and simultaneous effects on concentrations of all 11 nutrients in **a**) barley (later sowing) and **b**) radish (early sowing). Table 7 shows nutrient-specific univariate analyses. df =degree of freedom, *F*=*F*-ratio

	a) Barley			b) Radish		
	df	Pillai's trace	*F*	df	Pillai's trace	*F*
Main effects:						
Char treatment (C)	55, 140	4.3	15.7 ****	55, 165	3.57	7.51 ****
Application rate (A)	22, 50	1.53	7.39 ****	22, 60	1.34	5.56 ****
Block	22, 50	0.947	2.04 *	44, 128	1.81	2.41 ****
Interactions:						
C × A	110, 330	4.83	2.80 ****	110, 380	4.31	2.61 ****

* $P < 0.05$; **** $P < 0.0001$

process. In general, BCs showed a higher pH, porosity and lower mineral element content compared to HC, as found by Taskin et al. (2019) among others. The EBC states that the required molar H/C ratio for good-quality BC should be less than 0.7 and O/C ratio below 0.4 (EBC 2024). O/C ratio of each BC and HC product was below the limit value of 0.4. Instead, H/C ratios for HCs produced from biogas digestate and demolition waste and BC made from biogas digestate were above 0.7. This is due to the lower temperature in the HTC process than in the pyrolysis, resulting in lower carbonization and higher atomic H/C and O/C ratios than plant-based BCs (e.g., Libra et al. 2011; Masoumi et al. 2021). The higher H/C ratio of digestateBC may be impacted by the inorganic minerals present in the feedstock material. Also, the carbonization of the HCs was less complete than that of the BCs. Carbon content of tomatoBC (34%) was slightly below the recommendation (35–95%) by EBC (2024), most probably due to a lower pyrolysis temperature and processing time used to increase the product yield to an adequate level. Furthermore, tomato-/digestateBCs were less carbonized than demolitionBC and refBC. In addition, tomatoBC had

Table 7 Univariate analyses of variance (ANOVA) that were used to test how different factors influenced variation in individual nutrients in **a**) barley (later sowing) and **b**) radish (early sowing). *F*-ratios are shown for different factors: C = char treatment, A = application rate, B = block, C × A = char treatment × application rate interaction (degrees of freedom shown in parentheses); R^2 = coefficient of determination, showing how much of total variation is explained by the statistical model. Control vs. C indicates which char treatments were statistically significantly different from the untreated control, and Control vs. A indicates which application rates (5, 10 or 50 t ha^{-1}) were statistically significantly different from the untreated control

a) Barley

	Main effects			Interactions			
	C (5, 34)	A (2, 34)	B (2, 34)	C × A (10, 34)	R^2	Control vs. C	Control vs. A
N	2.92 *	6.21 **	9.27 ***	2.74 *	51.2%	ns	50
Ca	23.3 ****	0.312 ns	4.33 *	7.47 ****	77.6%	TomatoBC	ns
K	21.5 ****	1.79 ns	9.17 **	6.38 ****	76.0%	TomatoBC	ns
P	21.6 ****	4.42 *	7.59 **	11.8 ****	81.8%	DigestateBC/HC	ns
Mg	9.72 ****	7.04 **	4.85 *	3.22 **	61.9%	TomatoBC	ns
Cu	0.773 ns	1.74 ns	0.507 ns	0.687 ns	26.0%	DemolitionBC/HC, digestateBC/HC, refBC, tomatoBC	5/10/50
Mn	138 ****	80.9 ****	5.36 *	84.5 ****	96.9%	DemolitionHC, digestateBC/HC, tomatoBC	5/10
Zn	558 ****	487 ****	7.02 **	189 ****	98.9%	DemolitionBC/HC	10/50
Fe	3.29 *	0.738 ns	0.944 ns	0.933 ns	15.1%	ns	ns
S	22.2 ****	9.64 ***	4.36 *	2.33 *	72.7%	DemolitionHC	ns
B	1.98 ns	6.81 **	3.40 *	2.16 *	38.3%	ns	ns

b) Radish

	Main effects			Interactions			
	C (5, 39)	A (2, 39)	B (4, 39)	C × A (10, 39)	R^2	Control vs. C	Control vs. A
N	1.44 ns	2.21 ns	2.11 ns	1.04 ns	10.2%	ns	ns
Ca	11.3 ****	1.19 ns	3.34 *	5.49 ****	65.0%	ns	ns
K	6.53 ***	6.51 **	5.37 **	2.86 **	49.5%	TomatoBC	ns
P	14.4 ****	7.34 **	1.78 ns	3.56 **	68.5%	DigestateBC/HC	5/50
Mg	14.3 ****	2.99 ns	3.39 *	1.27 ns	61.7%	TomatoBC	ns
Cu	3.27 *	6.50 **	4.93 **	0.833 ns	31.6%	ns	ns
Mn	103 ****	93.8 ****	3.46 *	72.4 ****	96.4%	DemolitionHC, digestateBC/HC, tomatoBC	5/10
Zn	231 ****	305 ****	3.34 *	106 ****	98.0%	DemolitionBC/HC	50
Fe	2.09 ns	2.95 ns	2.77 *	1.81 ns	21.9%	ns	ns
S	0.963 ns	0.312 ns	5.67 **	1.52 ns	32.1%	ns	ns
B	0.565 ns	0.563 ns	6.12 **	0.958 ns	21.6%	ns	ns

ns = non-significant, $P > 0.05$; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; **** $P < 0.0001$

remarkably high contents of S, Ca and K, as found also by Stylianou et al. (2023). Concentrations of these elements in BC or HC are not restricted by the regulations or standards and do not prevent their use in agriculture. Indeed, processing organic waste from vegetable production into char-rich products and their use in agriculture has great potential.

Secondly, we predicted that both slow pyrolysis and HTC produce good-quality char products from selected waste biomasses that are suitable for soil application. This prediction was partly confirmed in terms of BC characteristics which mostly fulfilled the requirements for soil application according to the EBC (2024). Characteristics of both BCs and HCs were also within the limits of the new EU Fertilizing Products Regulation 2019/1009, except for Ni and Zn in demolitionBC and Ni in the demolitionHC. Elevated concentrations of Zn in demolitionBC have been reported previously (Sørmo et al. 2020). High Zn concentrations in demolition wood are typically explained by the surface treatment technologies and industrial preservatives (Krook et al. 2004). Increased Zn concentrations were further seen in plant tissues (see the next chapters). Although demolition wood used as feedstock contained only class A wood and material to carbonization was carefully selected, small amounts of impurities may have ended up in the process. Thus, when demolition wood is used in BC production, the feedstock materials should be carefully selected and analyzed. Heavy metals have also been mentioned to restrict the soil application of sludge-based BCs (Mohamed et al. 2023). Use of household biowaste-based biogas digestate as feedstock material for BC production is currently restricted by the European fertilizer legislation (EU 2019). In our study,

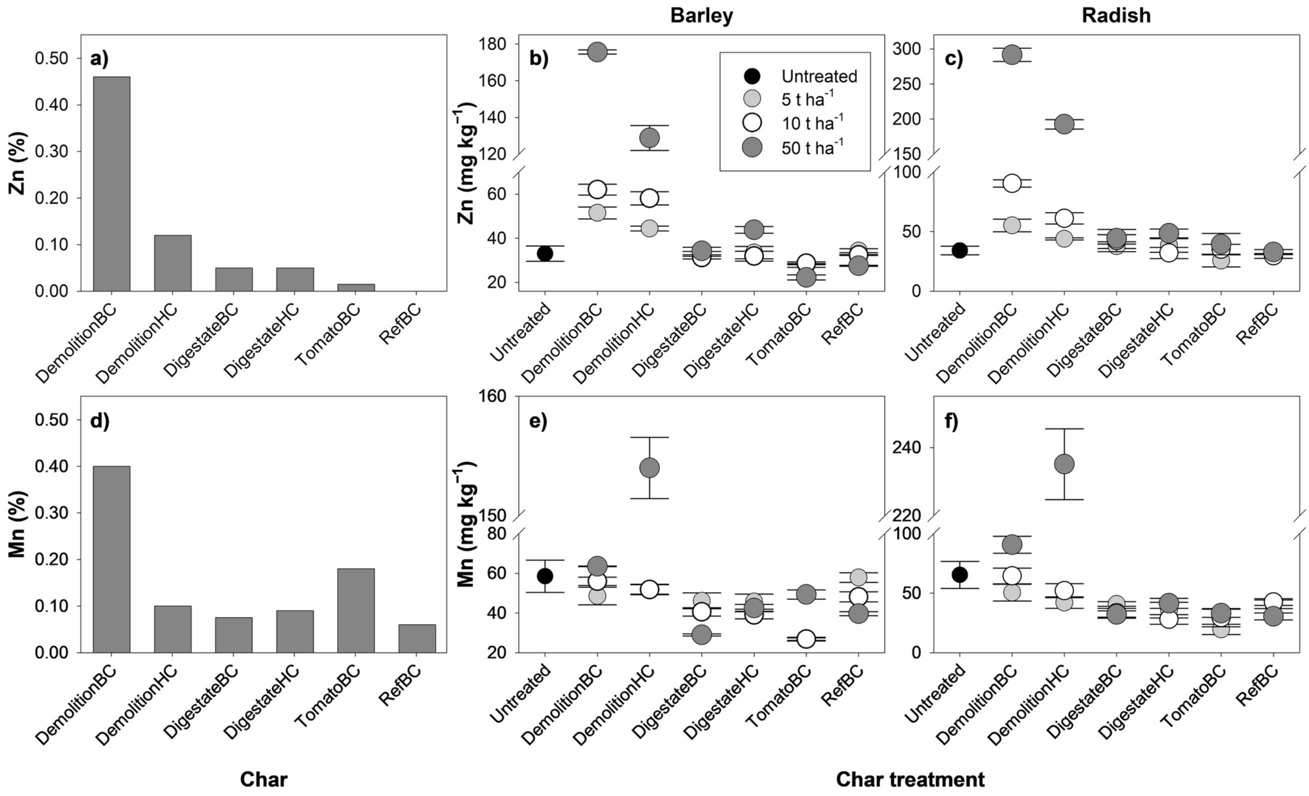


Fig. 6 Concentrations of zinc (Zn) and manganese (Mn) in biochars (BC) and hydrochars (HC) produced from various side streams, also including a commercial reference biochar (refBC), and in barley and radish grown in soils applied with different HC and BC products at various application rates. **a** Zn content of BC and HC products. **b**, **c** Zn content in barley and radish grown in BC and HC treatments. **d** Mn content of BC and HC products. **e**, **f** Mn content in barley and radish grown in BC and HC treatments. Error bars represent standard errors of the mean

concentrations of measured heavy metals in digestateBC and -HC remained below the guidelines, similarly to Monlau et al. (2016). Co-pyrolysis of digestate and sewage sludge with plant-based biomass for stabilizing heavy metals and reducing BC toxicity has recently been suggested to reduce metal concentrations and improve the end-product quality for soil application (Mohamed et al. 2023).

In general, all tested soil treatments with BC or HC applications exhibited good characteristics as growing media, except for tomatoBC at the highest application rate most probably due to the increased soil EC. The effects of BC and HC applications on soil properties reflected the characteristics of the char products and application rates. In general, char treatments increased soil TOC, OM and pH. Only highest application rate of demolitionHC decreased soil pH. The extent of the impact was dependent on the characteristics of the char products and their application rates, as suggested also by Dai et al. (2020). Soils applied with wood-originating BCs (demolitionBC and refBC) had slightly lower nutrient concentrations (P, K, Ca, Mg, S) than soils with other char treatments (digestate and tomato-based products). High Ca, K and S content in tomatoBC increased their soil concentrations. Thus, the application rate of tomatoBC in soil should be considerably lower than those of the other tested products. Also, nutrient compositions in digestateBC/HC were reflected in soil nutrient concentrations, but interestingly there were no big differences between the BC and HC. Char products may also affect soil structural properties (Dai et al. 2020), but these were not assessed in this study. To conclude, chemical responses induced by BC and HC in soil were in general comparable to their characteristics of char products.

Our third prediction was that especially HCs exhibit phytotoxicity on plants if sowing is done immediately after mixing the chars in soil, but the effect is decreased after a stabilization period. As expected, BCs and HCs induced some phytotoxicity on three indicator plant species, but while there was some consistency in responses to the treatments within each species, there were differences in how the different species responded to sowing time, char treatment and application rate. Differences among the char treatments were slighter than expected, and a consistent negative effect on plant emergence was only seen at 50 t ha^{-1} of tomatoBC. EC generally determines the level of soil salinization and is closely linked to nutrient availability in the soil (Heiniger et al. 2003) and depends also strongly on the soil type and the method used for the determination of EC (Friedman 2005; Kargas et al. 2020). Soils with EC ≥ 4 dS m^{-1} are classified as saline soils (Munns 2005), and high EC values in the growing medium tend to inhibit plant growth and development (Yadav et al. 2019). In Finnish arable soils typical EC values are below 2.5 and in greenhouse cultivation between 4 and 6, while soils applied with tomatoBC at 50 t ha^{-1} had EC values as high as of 19.8.

Contrary to our expectations, the three-week stabilization period enhanced emergence and growth in barley only. Contrastingly, emergence and biomass of radish and rape were in fact greater when the seeds were sown immediately after char application. Differences in the sensitivity of plant variables is a well-known phenomenon, the response being also highly dependent on soil properties (Suarez et al. 2023). Other studies have also shown species- or crop type-specific differences in plant responses to HC or BC applications (Hagner et al. 2016; Suarez et al. 2023, Xu et al. 2025), indicating that the generalization of results across species and environments is challenging. Indeed, global meta-analyses across environments and species demonstrate that positive effects of BCs are generally associated, e.g., with nutrient-poor and acidic soils in the tropics and subtropics (Jeffery et al. 2011, 2017). Consequently, there is a need for standardized protocol for testing BC and HC products to demonstrate their potential as soil amendment for different crop plants and soil types.

Some studies have connected BC-induced phytotoxicity to BC containing PAHs, hazardous metals and other PTEs (Buss et al. 2015; Hale et al. 2012; Lyu et al. 2016; Zhang et al. 2019a, b). However, in our study, no direct link between BC metal concentrations and measured plant responses were found. Although the concentration of Zn in demolitionBC/HC was above the current restrictions and guidelines (EU 2019; EBC 2024), only the highest application rate of 50 t ha^{-1} increased plant Zn concentrations near to or above (demolitionBC 175–296 mg kg^{-1} and demolitionHC 129–195 mg kg^{-1}) the limit values of the EU for use in feed (EC 2016/1095; limit value $<$ 120–200 mg kg^{-1} depending on the species). Instead, Zn concentrations in the plants grown in the soils treated with demolitionBC/HC at lower rate (5 and 10 t ha^{-1}) were within an acceptable level for feed use. Similarly, demolitionHC in highest application rate increased Mn concentration of both tested plant species above the limit value for feed (EU 2019/962; 100–200 mg kg^{-1}) but at lower application rates the concentrations in plants were below the recommendations. In addition, Ni concentration of demolitionBC/-HC products were above the limit value of current restrictions and guidelines (EU 2019; EBC 2024), but unfortunately Ni concentration of plants was not analysed in our study. Nevertheless, our experiments investigated only short-term effects of fresh BC and HC products in a controlled environment. In agricultural soils these products persist for a long time, and in the long run the functionality of aged products may differ significantly from fresh ones (Purakayastha et al. 2019). Thus, although BC/HC application did not affect the metal concentrations of plants in our study, there might be a risk for leaching and phytoaccumulation in the long run when using BC/HC products with higher heavy metal concentrations and high application rates (Wang et al. 2021a, b).

Further, according to Cavali et al. (2023) and Atallah et al. (2021), the presence of toxic organic compounds such as furfural, furans, organic acids, and phenolic compounds may explain differences in plant responses. Due to the limited amount of char products available for analysis, we were not able to analyze all recommended characteristics of the char products (EU 2019; EBC 2024). Based on the ATR-FTIR analysis, demolitionHC and digestateHC as well as digestateBC and tomatoBC seem to contain some carboxylic acids that could have an impact on plant growth. Undoubtedly, as no major effects on plant emergence or growth were seen, the concentrations of these potentially harmful organic compounds in the products were below the acute phytotoxic levels already in the beginning of the experiment. Due to our char treatments affecting multiple soil characteristics at the same time, it is not possible to isolate the exact individual feature or features that induced responses in plant phenotype.

Finally, we assumed that after the stabilization period both BCs and HCs improve growth, and that the effect depends on the crop plant species, chemical characteristics, and application rate of the char products. Opposite to our hypothesis, BC and HC applications did not systematically increase biomass in all three species, and the most marked biomass gains in response to char treatment were seen in barley. The effects of BC soil applications on plant growth may vary greatly between crop types and species (Liu et al. 2013), and also among genotypes within species (Liu et al. 2022a, b). Improved growth of barley with the digestateBC/HC, tomatoBC and demolitionHC applications might be due to the higher concentrations of plant-available nutrients in these products (de Jager and Giani 2021; Novak et al. 2014). In wood-based BCs nutrients are typically less easily available for plants (Purakayastha et al. 2019). The most probable reason for mainly slight responses in emergence and biomass of plants to various char products in our experiment was a good nutritional status and the quality of used soil, enabling good germination and growth in all treatments. It remains to be tested whether char application yields more recurrent and striking beneficial consequences in those boreal soils that are demonstrably poor in quality, e.g., due to poor crop rotation, low microbial activity or heavy metal pollution.

From an agricultural viewpoint, the most promising char products are those that not only help sequester carbon but also enhance crop yields and plant health. Typically, BC application rates of 5–50 t ha^{-1} have been utilized in field experiments, but there are no specific recommendations for soil application (Premalatha et al. 2023). In our study, if a positive response in plant biomass existed, it was seen already with the lowest char application rate. Based on these results, when the aim is to improve crop yield, 5 t ha^{-1} may be an appropriate application rate, and no benefit is gained by increasing the rate to 10 t ha^{-1}. However, effects of BC on crop biomass, yield and nutrient content in boreal soil may require multiple growing seasons to occur and be slighter than at lower latitudes, as shown previously by Kalu et al (2021). According to our results, digestate and demolition wood-based HCs produced as much as or more plant biomass than the corresponding BC products when used at 5–10 t ha^{-1} application rates. When applied to biomasses characterized by a high water content (> 30%) such as sewage sludge or digestate, the pyrolysis process can be inefficient in terms of costs and a high energy demand (Mani et al. 2006). In some cases, digestate-based HCs may also contain more plant available nutrients such as P than the corresponding BC (Belete et al. 2021). In this context, the HTC process might be a more cost-effective alternative (Wang et al. 2018) to produce char- and nutrient-rich products for soil application but without relevance for long term carbon sequestration.

5 Conclusions

Circular economy principles can be boosted by using waste materials as feedstocks for various thermochemical processes and techniques that generate products suited for broad use across different sectors. Both pyrolysis and hydrothermal carbonization (HTC) can produce good-quality char products from side-stream waste biomasses that fulfill the requirements for soil application according to the European BC Certificate (EBC 2024) and the EU Fertilizing Products Regulation (EU 2019/1009). However, variable plant responses to char treatments highlight the need for longer-term and species-specific testing in environmental settings relevant to each crop. Thus, further studies are needed to make clear recommendations for their agricultural use. Even without systematic beneficial effects on crop yields, soil char application may become important in advancing the circular bioeconomy and carbon sequestration once carbon markets start to function.

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Data Availability Data available on request from the authors.

Declarations

Competing of interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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