The potential of hydrochar for soil improvement and carbon sequestration

Megan J. de Jager

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AG Bodenkunde
Institut für Biologie und Umweltwissenschaften
Fakultät V - Mathematik und Naturwissenschaften
Carl von Ossietzky Universität, Oldenburg

Chapter 1: Introduction

Chapter 2: The influence of hydrochar from biogas digestate on soil improvement and plant growth aspects

Chapter 3: An investigation of the effects of hydrochar application rate on soil amelioration and plant growth in three diverse soils

Chapter 4: The stability of carbon from a maize-derived hydrochar as a function of fractionation and hydrothermal carbonization temperature in a Podzol

Chapter 5: Conclusions and future perspectives

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Chapter 1:

Introduction

Introducing the problems

Exponential world population growth results in:[1,10]

Intensive agriculture, excessive fertilizer use

Enhanced energy production

Land use change

Deforestation, poor agricultural practices

Introducing the problems

Reduced soil quality[1,2]

Increased Greenhouse Gas (GHG) emissions[1,2]

Introducing the problems

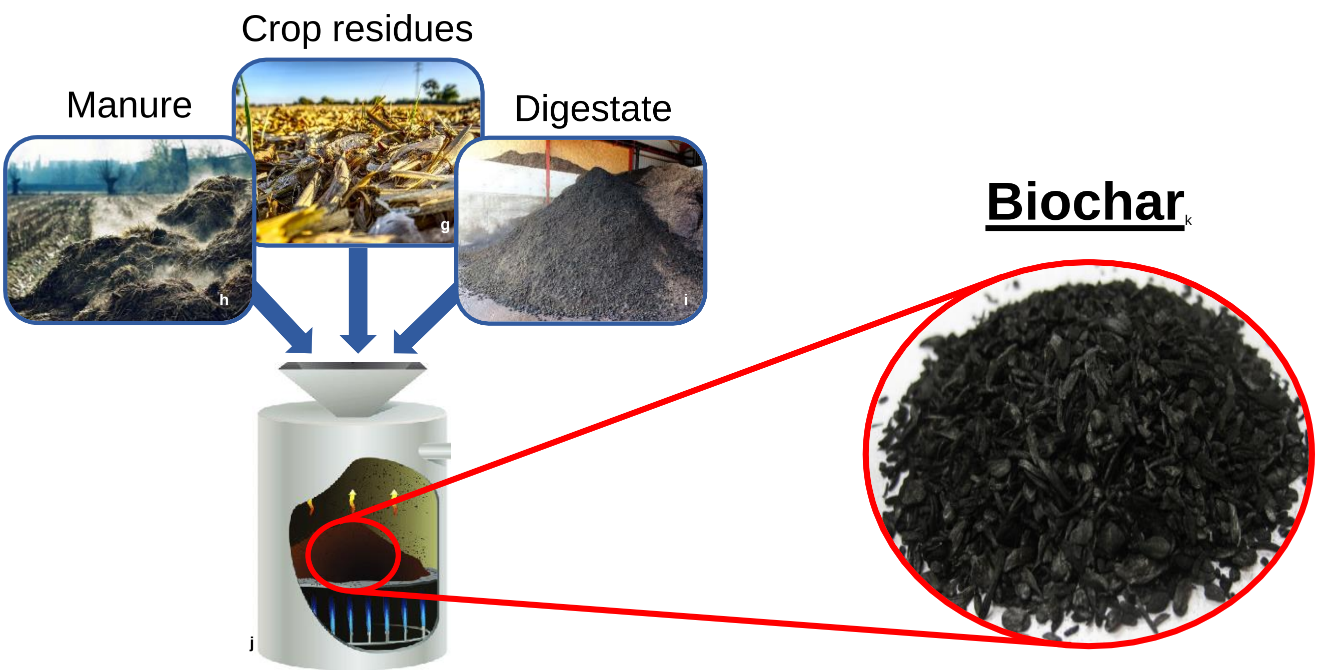
By-products: biomass wastes[2,3]

Crop residues

Manure

Biogas digestate

Solving the problems



Thermochemical conversion:

Pyrolysis[4,5]

Solving the problems

Biochar - Pyrolysis

- **High C sequestration potential**[7,8,9]
  - 50% original C content, recalcitrant[3,6]
- **Soil amendment tool**
  - Nutrient content from feedstock[10,11,33]
  - pH (liming effect)[6,11]
  - Physico-chemical structure[6,11,20,22,23]

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  - Physico-chemical structure[6,11,20,22,23]

Pyrolysis - biochar
Releases GHG's (50% CO_2)[12]
Restricted to dry biomass[13]
Energy for intensive pre-drying[13]

Solving the problems

Biochar - Pyrolysis VS Hydrochar - Hydrothermal Carbonisation

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  - Nutrient content from feedstock[10,11,33]
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- **Thermochemical conversion**[13]
  - Closed, water-saturated system
  - 180 – 260˚C, ca. 20 bar
  - Variable reaction times (mins – days)
  - 60-84% original C content[15]
  - Different physico-chemical structure[16]

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Biochar - Pyrolysis VS Hydrochar - Hydrothermal Carbonisation

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Hydrochar - Hydrothermal Carbonisation

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  - 180 – 260˚C, ca. 20 bar
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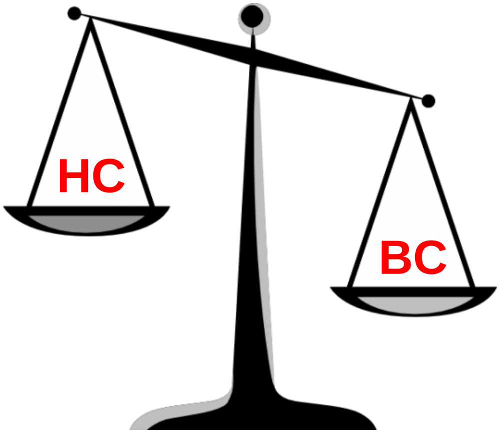
  - Different physico-chemical structure[16]

Pyrolysis - biochar	HTC - hydrochar
Releases GHG's (50% CO_2)[12]	Carbon neutral (ca. 5% CO_2)[14]
Restricted to dry biomass[13]	Converts wet biomass[15]
Energy for intensive pre-drying[13]	Minimal additional energy[15]

Solving the problems

Hydrochar by HTC

- Most research focused on BC
- HC is also suitable for:
  - ✓ Soil amelioration
  - ✓ C sequestration
  - ✓ Reduced GHG emissions
  - ✓ Enhanced plant growth
  - ✓ Promotes biological activity



- Conflicting results[16,36,47,60]
- Results vary depending on:[17,18,19,32,34]

Feedstock, process conditions, HC characteristics, soil properties, environmental conditions, plant species and application rate.

Solving the problems

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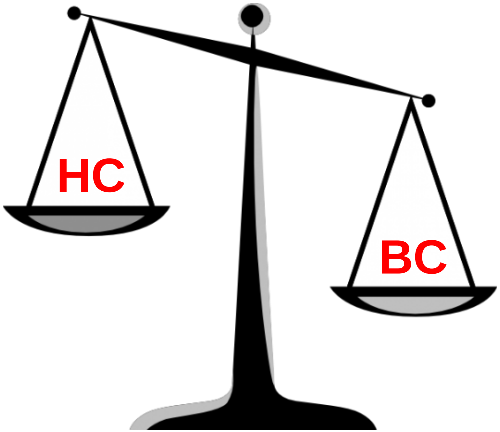

- Conflicting results[16,36,47,60]
- Results vary depending on:[17,18,19,32,34]

Research is lacking

Feedstock, process conditions, HC characteristics, soil properties, environmental conditions, plant species and application rate

Research Objectives

1. Analyse the influence of the **grain size** of hydrochar on soil improvement and germination- and biomass success in three diverse soils **Chapter 2**

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Research Objectives

Interreg North Sea Region BIOCAS European Regional Development Fund EUROPEAN UNION

1. Analyse the influence of the **grain size** of hydrochar on soil improvement and germination- and biomass success in three diverse soils **Chapter 2**

2. Identify the effects of different **application rates** of hydrochar on nutrient availability and physico-chemical properties of three soils, as well as germination success and biomass production **Chapter 3**

3. To investigate the influence of HTC production temperature on the relative **degradability and subsequent fate of HC-C** within the free-, occluded within aggregates- and organo-mineral SOM fractions **Chapter 4**

Chapter 3:

An investigation of the effects of hydrochar application rate on soil amelioration and plant growth in three diverse soils

The influence of HC application rate

Biochar
https://doi.org/10.1007/s42773-021-00089-z

ORIGINAL RESEARCH

An investigation of the effects of hydrochar application rate on soil amelioration and plant growth in three diverse soils

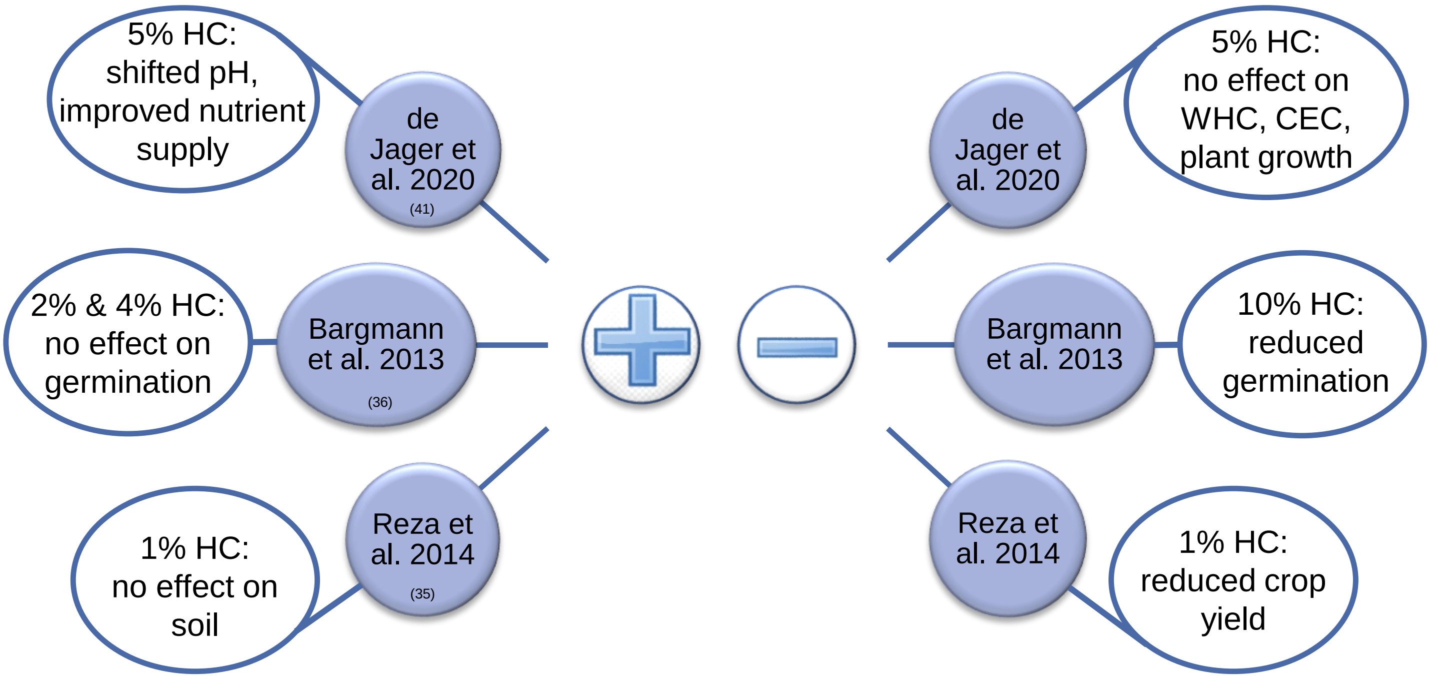
Megan de Jager[1] · Luise Giani[1]

Received: 28 September 2020 / Accepted: 22 January 2021

Abstract
The hydrothermal carbonization (HTC) of biogas digestate alters the raw materials inherent characteristics to produce a carbon (C)-rich hydrochar (HC), with an improved suitability for soil amelioration. Numerous studies report conflicting impacts of various HC application rates on soil properties and plant growth. In this study, the influence of HC application rate on soil improvement and plant growth aspects was investigated in three diverse soils (Chernozem, Podzol, and Gleysol). Pot trials were conducted in which all soils were amended with 5, 10, 20 and 30% (w/w) HC in quintuplicate, with two controls of pure soil (with and without plants, respectively) also included. Prior to potting, soil samples were collected from all HC-amended soils and controls and analyzed for soil pH, plant available nutrients (PO_4-P and K), and microbial activity using standard laboratory and statistical methods. Immediately after potting, a 6-week seed germination experiment using Chinese cabbage was conducted to determine germination success, followed by a plant growth experiment of equal duration and plant species to determine biomass success. At the end of the study (after a total plant growth period of 12 weeks), each pot was sampled and comparatively analyzed for the same soil properties as at the beginning of the study. Soil pH shifted toward the pH of the HC (6.6) in all soils over the course of the study, but was most expressed in the 20% and 30% application rates, confirming the well-documented liming effect of HC. The addition of HC increased the PO_4-P and K contents, particularly with 20% and 30% HC amendments. These results are proposedly due to the large labile C fraction of the HC, which is easily degradable by microorganisms. The rapid decomposition of this C fraction prompted the quick release of the HCs inherently high PO_4-P and K content into the soil, and in turn, further stimulated microbial activity, until this fraction was essentially depleted. HC addition did not inhibit seed germination at any rate, presumably due to a lack of phytotoxic compounds in the HC from aging and microbial processes, and furthermore, showed no significant impact (positive or negative) on plant growth in any soil, despite improved soil conditions. In conclusion, although less pronounced, soil improvements were still achievable and maintainable at lower application rates (5% and 10%), whereas higher rates did not ensure greater benefits for plant growth. While the addition of high rates of HC did not detrimentally effect soil quality or plant growth, it could lead to leaching if the nutrient supply exceeds plant requirements and the soil's nutrient retention capacity. Therefore, this study validates the previous study in the effectiveness of the biogas digestate HC for soil amelioration and suggests that smaller regularly repeated HC applications may be recommendable for soil improvement.

Keywords Biogas digestate · Hydrochar application rate · Soil improvement · Nutrient availability · Microbial activity

Conflicting results on application rate



No generally accepted consensus

Research hypotheses:

Higher HC application rates will result in:

1) Greater pH changes

2) Increased nutrient content (PO_4-P and K) and microbial activity

3) Germination inhibition and reduced plant growth

Materials

Hydrochar:

- Digestate feedstock (crop residues and beef and swine manure)
- ~ 200 ˚C, 18-20 bar,
- ~ 3 hr residence time,
- ~ 1.5 hr heating and cooling rate

Soils:

- Three soil types (dissimilar properties and agricultural value)
- Pot experiments
- Homogenously mixed with hydrochar
- Controls (no hydrochar)

Soil type	Sand (%)	Silt (%)	Clay (%)	Texture (FAO, 2006)
Chernozem	16	43	41	Silty clay
Podzol	66	21	13	Sandy loam
Gleysol	1	6	93	Clay

Methodology

t_0

Controls (pure soil)

t_1

Shortly after HC addition

t_2

End of experiment

Beginning of experiment

Methodology

Hydrochar application rates:

- **5, 10, 20 and 30 % (w/w)**
- C,H,N,S,O and ash content

Methodology:

- Standard pedological methods
- Euro Elemental Analyzer
- Kruskal-Wallis H Test and Mann-Whitney U test (SPSS, ver. 26)

Soil properties:

- pH (H_2O)
- plant available nutrients (phosphate (PO_4-P) and potassium (K))
- microbial respiration rate
- seed germination and biomass success

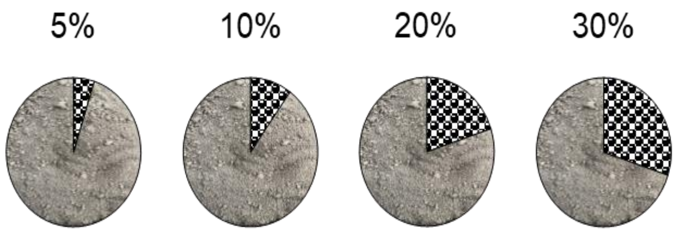
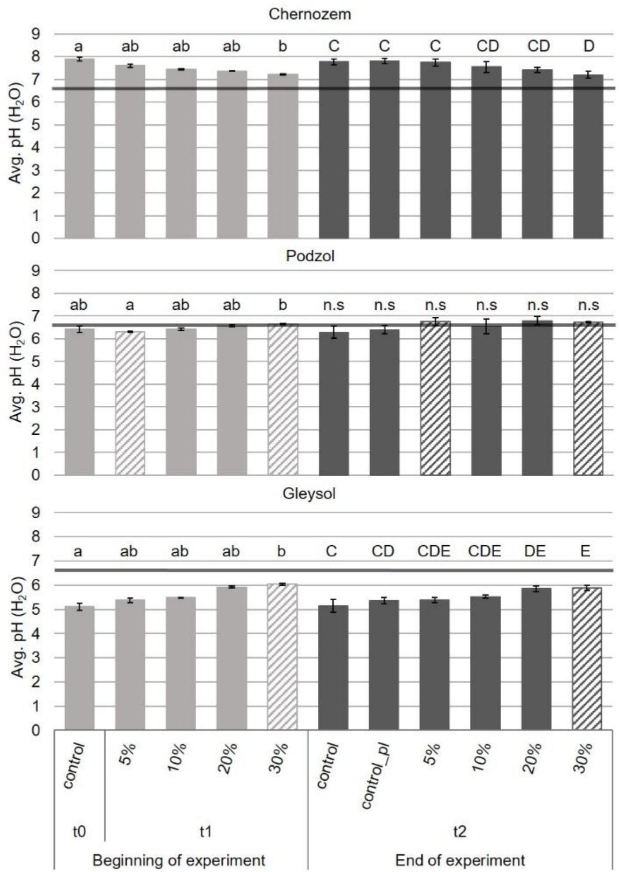


Table 1 The ash content, elemental composition (CHNS and O), and resultant molar element ratios of the hydrochar derived from biogas digestate

Ash content (wt %)	Elemental composition (wt %)					Molar element ratio		
	C	H	N	S	O	H/C	C/N	O/C
47.2	35.2	3.8	2.7	0.9	10.2	1.3	15.2	0.2

Results and discussion: pH



The addition of the acidic hydrochar (6.6) shifted the soil pH to the pH of the hydrochar

Greatest change at higher application rates

Stabilization of pH over time

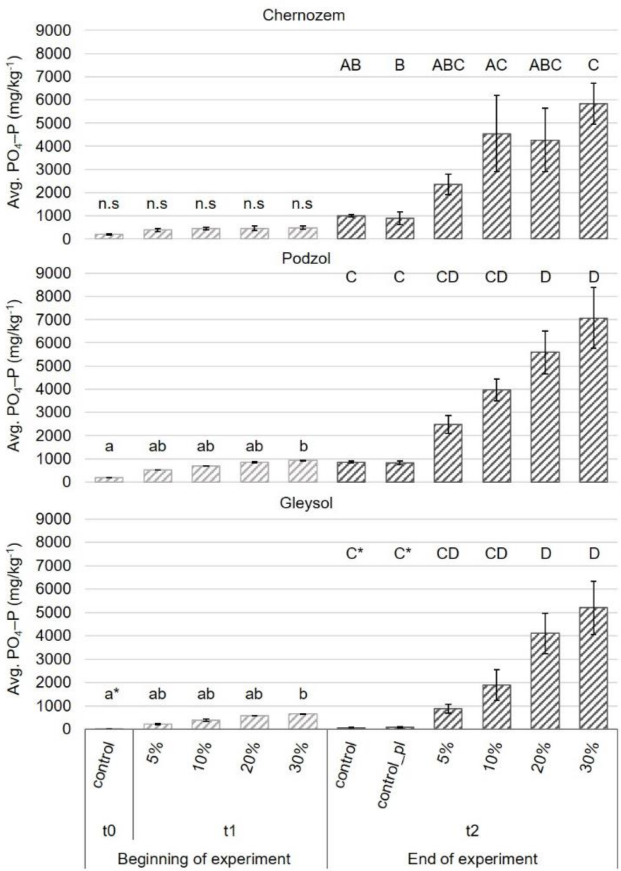
Liming effect due to:[25]

- High ash content[24]
- Contribution of major cations and exchange processes[25,26]
- pH response is dependent on initial soil and HC pH[27]

Repeated application for sustainable effect

Significant differences between means ($p \leq 0.05$) are indicated by different letters. Not Significant (n.s) Significant Hydrochar pH (6.6)

Results and discussion: Phosphate (PO_4-P)



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Hydrochar PO_4-P = 6544,3 mg kg^{-1}

Direct contribution of PO_4-P

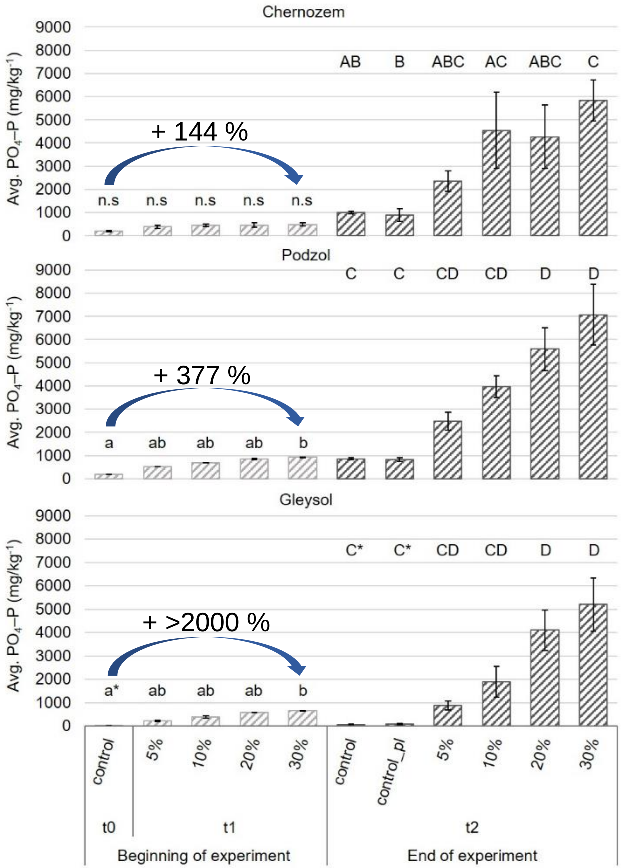
Increased with increasing application rate

Increased from $t_1 - t_2$
= contradicts previous findings

- Inherently high P content of feedstock[28]
- Less resistant to decomposition[6,30,42]
- Liberation of P from Fe-, Al- and Ca phosphates[18,29,38]
  - pH-dependent change
- Plant uptake and microbial biomass incorporation[32] reached maximum
- Excess may be harmful to plant growth[43]

Repeated smaller applications recommended

Results and discussion: Phosphate (PO_4-P)



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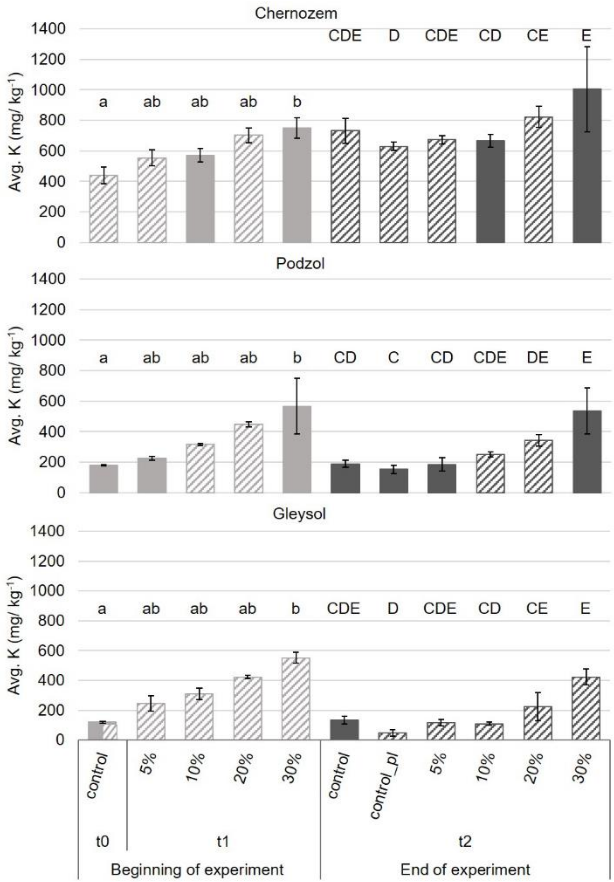
Results and discussion: Potassium (K)



Significant differences between means ($p \leq 0.05$) are indicated by different letters. ■ Not significant (n.s) ▨ Significant difference

Hydrochar K = 2384 mg kg^{-1}

Direct contribution of K

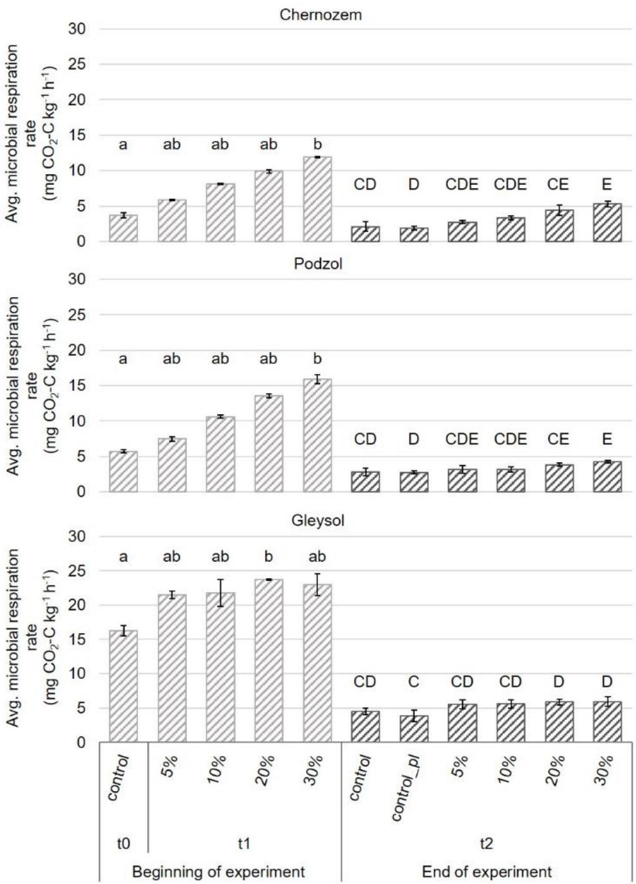
Increased with increasing application rate

Greater increase in low K content soils

- Relatively easily degradable HC fraction[30,31]
- Plant and microbial uptake/ leaching
- Risk of enhanced leaching, especially in sandy soils[27]

Sustainable supply of K at higher application rates

Results and discussion: Microbial Respiration



Significant differences between means ($p \leq 0.05$) are indicated by different letters. Not significant (n.s) Significant difference

Initial stimulus

Higher activity at higher application rates

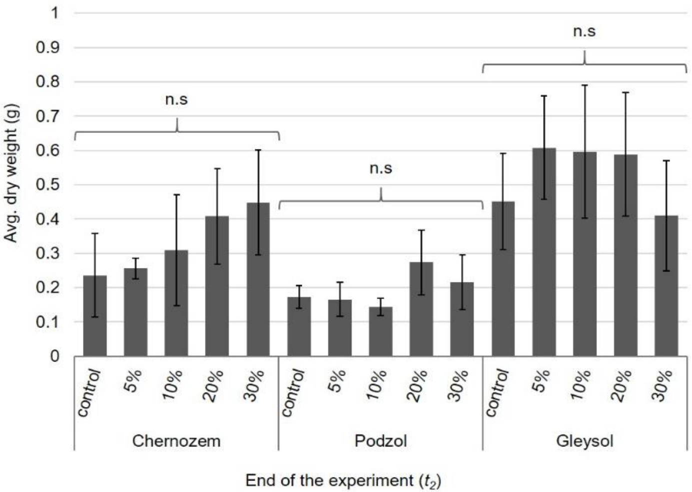
Decreased activity over time

- **Initial stimulus** due to:
  - Labile C fraction of HC[44,45]
  - Response to pH change[46]
- Reduced respiration rate at t_2:
  - **Limited C source**[47,48]
  - Competition from plants
- Mediated respiration rate
  - **Improved biological soil status**

Results and discussion:
Seed germination and biomass success

Average percent germinated seeds for the controls and HC-amended soils over two rounds of the germination experiment.

Soil	Chernozem	Podzol	Gleysol
		Avg. %	
Control	87	54	91
5 %	79	80	89
10 %	84	77	87
20 %	76	89	94
30 %	92	81	93



No seed germination inhibition

Higher application rates did not reduce biomass production

Fresh HC can contain organic contaminants[36,37,39] – not evident here

Adverse HC impacts reduced by:

- HTC process conditions (temp. & reaction time)[35]
- Free gas exchange at soil-atmosphere interface[36]
- Microbial decomposition of phytotoxic compounds[37]
- Age and storage time of HC[36]

Significant differences between means ($p \leq 0.05$) are indicated by different letters. Not significant (n.s)

Conclusions

Hypotheses:

Higher HC application rates will result in:

1) Greater pH changes ✓

- Shifted the pH of the soil toward the pH of the hydrochar – stabilized over time
- Most pronounced at higher application rates

2) Increased nutrient content (PO_4-P and K) and microbial activity ✓

- PO_4-P content increased with increasing application rates – surplus remains
- K content increased with application rate – sustained at higher rates
- Microbial activity initially increased – stimulus limited to labile C availability

3) Germination inhibition and reduced plant growth ✗

- No seed germination inhibition at any application rate
- Supported plant growth, especially at higher application rates

HC from biogas digestate is suitable for soil amelioration, preferably in smaller regular applications

Chapter 4:

The stability of carbon from a maize-derived hydrochar as a function of fractionation and hydrothermal carbonization temperature in a Podzol

Background

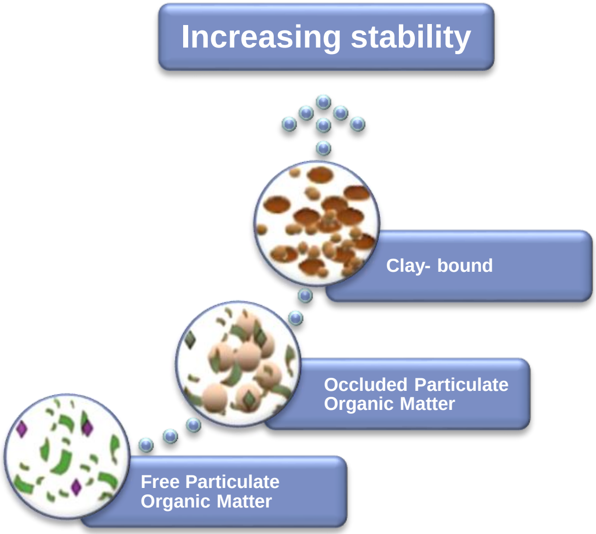
HC less effective tool for C sequestration

- Higher H:C and O:C ratios[49,50]
- Labile C fraction[15,51]

<u>Dependent on HTC conditions and feedstock</u>[19]

Means to improve HC effectiveness

- Higher HTC production temperatures[13]
  - Condensed C structure → recalcitrant[8,52]
- Interactions and association with primary soil organic matter (SOM)
  - Protection against degradation[53,54]
  - Increased stability

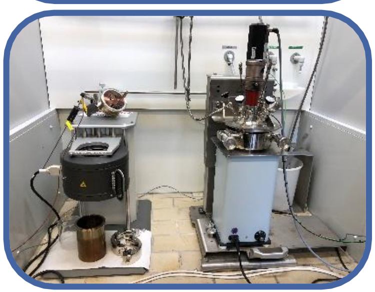


Limited knowledge available about HC – SOM interactions

Methodology

Hydrochar:

- Maize silage feedstock
- **190, 210 and 230 ˚C**
- 5 % application rate
- C,H,N,S,O and ash content



Methodology:

- Density fractionation procedure[55]
- Flash 2000 Elemental CN Analyzer coupled via a ConFlo III Interface to a Delta V Advantage IRMS[56]
- Euro Elemental Analyzer
- Kruskal-Wallis H Test (SPSS, ver. 26)

Soils:

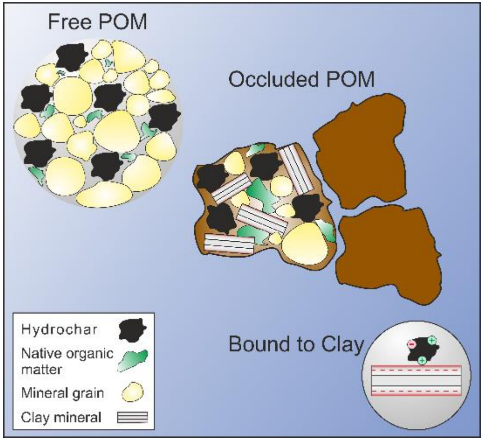
- Podzol (sandy loam)
- Pot experiments for ~ 1 year
- Homogenously mixed with hydrochars
- Control (no HC)

Methodology

Measured parameters:

- Weight proportions of:
  - Initial free particulate organic matter (iPOM$_F$) – at the beginning
  - Free particulate organic matter (POM$_F$)
  - Occluded particulate organic matter (POM$_O$)
  - Organic matter bound to clays (OM$_{Cl}$)

  (POM$_F$, POM$_O$, OM$_{Cl}$) after ~ 1 year



- C and N – accumulated OC, TOC
- δ ^{13}C (‰) – % HC-derived C in SOM fractions[57,58]
  - Distinct δ ^{13}C signatures of different plants tissues[62]

$$C_{HC-derived}\,[\%] = ((\delta^{13}C_{sample} - \delta^{13}C_{control})/(\delta^{13}C_{HC} - \delta^{13}C_{control})) \times 100$$

- Share of HC-C and native SOC per fraction

(ca.) **– 28 ‰**

Podzol: C_3 plant cultivation

(ca.) **– 13 ‰**

Hydrochars: C_4 plant feedstock

Research questions

1) How much HC-C is lost (decomposed) from the free-POM fraction of the soil after approx. 1 year (i.e. how stable is the HC-C in its initial free-POM form)?

2) Is the level of HC-C decomposition from the free-POM fraction controlled by the HTC production temperature?

3) Do the remaining products of HC decomposition become incorporated within the relatively stable SOM structures of the occluded-POM fraction and organic matter bound to clay particles?

4) Are the interactions and associations of the HC decomposition products with the relatively stable SOM fractions (POM_O and OM_{Cl}) controlled by the HTC production temperature?

Results and discussion: HC properties

Table 4.1: The elemental composition (CHNS, O), ash content and calculated atomic ratios of the hydrochars produced at increasing HTC temperatures.

Hydrochars	C	H	N	S	O	Ash content	Atomic ratio		
				wt %			C/N	H/C	O/C
190 °C HC	57.9	7.1	1.2	n.d	31.1	2.7	56.3	1.5	0.4
210 °C HC	60.7	7.3	1.7	n.d	26.2	4.1	41.6	1.4	0.3
230 °C HC	70.5	6.9	2.5	n.d	15.3	4.8	39.2	1.2	0.2

n.d: not detected

Increasing stability

- **Increased C and decreased O with HTC temperature**[59]
- **Increased degradability of HC = high H/C (≥ 0.6) and O/C (≥ 0.4) ratio**[19,40,60]

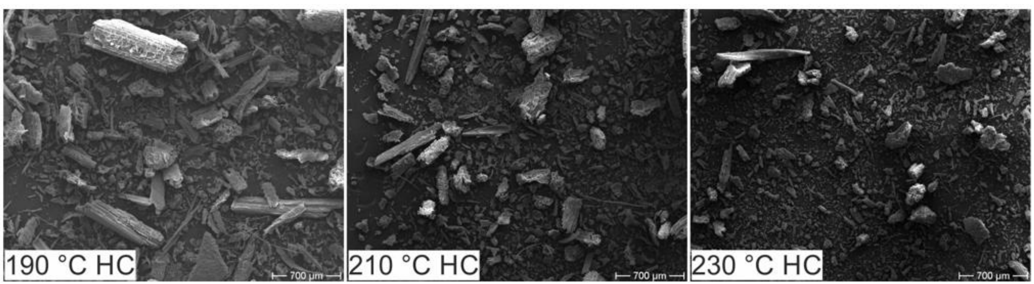


Figure 4.1: Scanning electron microscope (SEM) high resolution micrographs of the hydrochars produced at increasing HTC temperatures.

Results and discussion: C stocks of SOM fractions

The total organic carbon (TOC) content of the bulk soil (including sand and silt fractions (data not shown)) in g kg^{-1} at the beginning of the study (shortly after HC addition) and after 1 year of soil incubation, and the percentage (%) lost over the 1 year period.

	Bulk soil TOC*		
	After HC addition	**After 1 year**	**% loss**
	(g kg^{-1})		
Control	18.1	21.2	
HC190	47.1	36.7	22
HC210	48.5	38.5	21
HC230	53.4	40.9	23

*Bulk soil TOC was determined as the sum of accumulated OC of all SOM fractions (including silt and sand).

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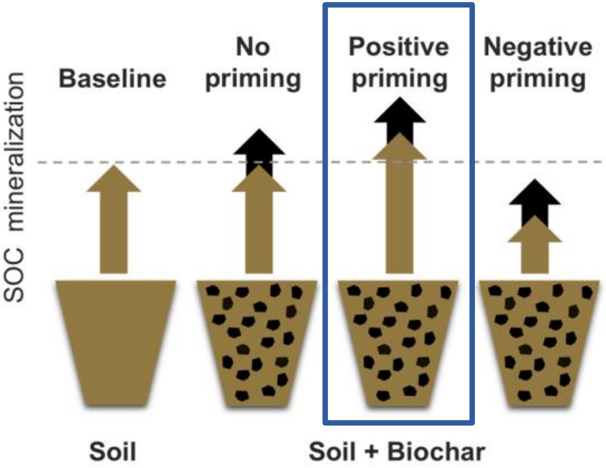
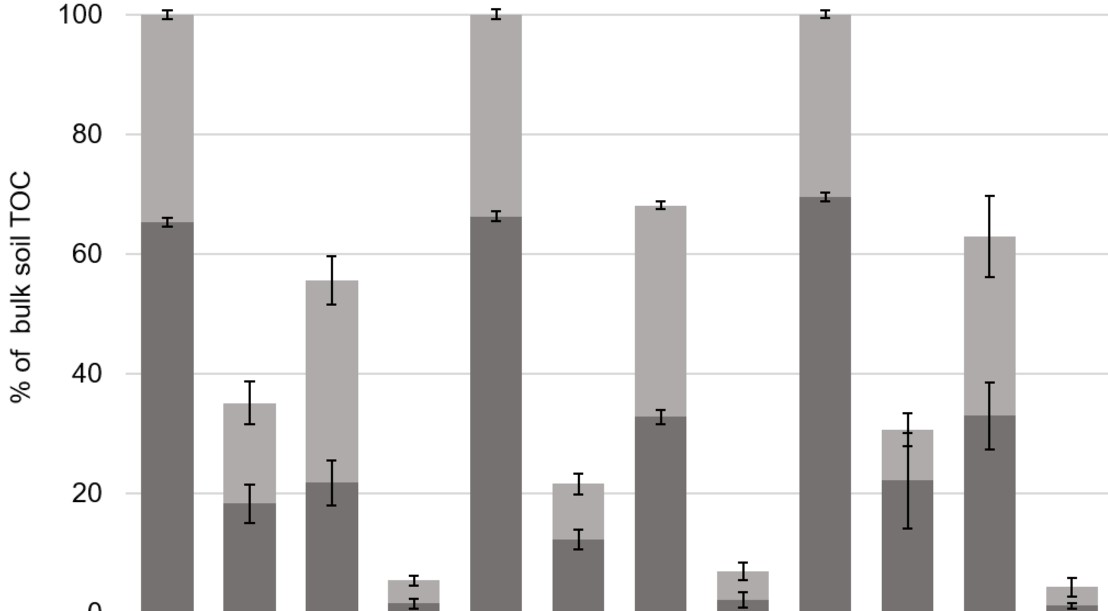


Source: Lehmann 2019[68]

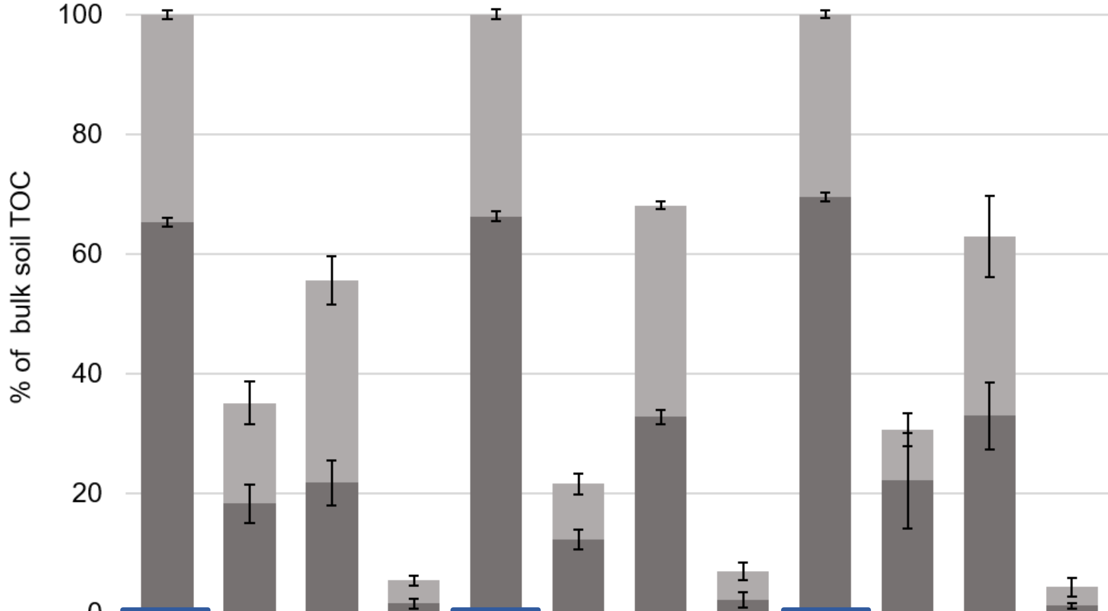
Results and discussion: HC-derived C in SOM fractions



	HC190				HC210				HC230			
	iPOMF	POMF	POMO	OMCl	iPOMF	POMF	POMO	OMCl	iPOMF	POMF	POMO	OMCl
native SOC	34.7	16.8	33.8	3.8	33.7	9.3	35.4	4.7	30.5 a	8.4	30.0	3.1 *
HC-C	65.3 *	18.3	21.7	1.6 *	66.3*	12.3	32.8	2.2 *	69.5 * b	22.1	32.9	1.2 *

The average percent of total organic carbon (TOC) derived from the hydrochars (HC-C) and native soil organic carbon (SOC) at the beginning of the study (as iPOM$_F$), and after approx. 1 year (as POM$_F$, POM$_O$ and OM$_{Cl}$)

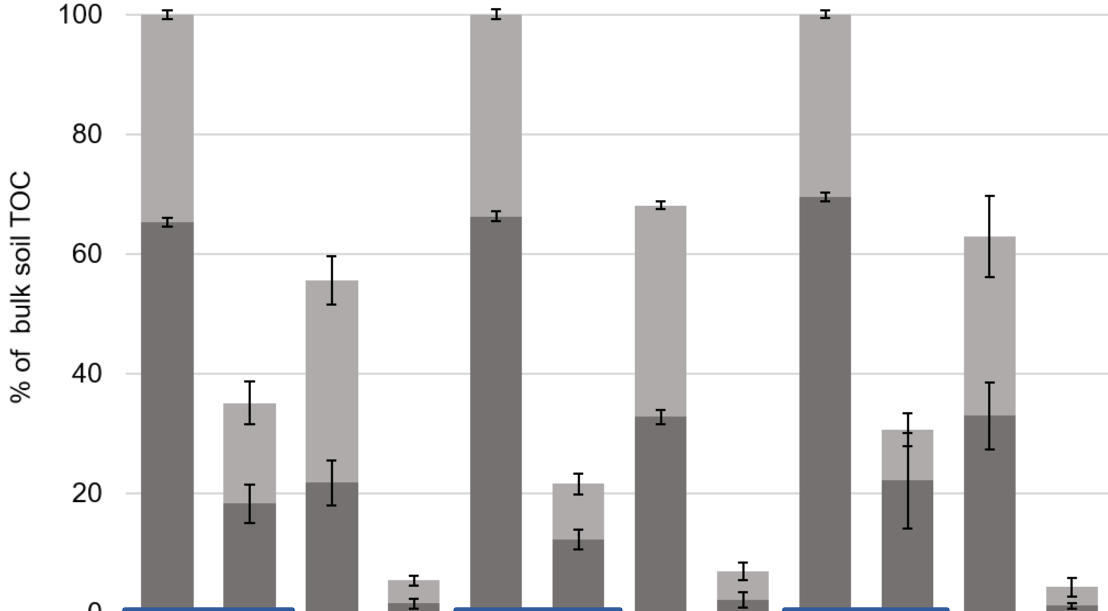
Results and discussion: HC-derived C in SOM fractions



	HC190				HC210				HC230			
	iPOMF	POMF	POMO	OMCI	iPOMF	POMF	POMO	OMCI	iPOMF	POMF	POMO	OMCI
native SOC	34.7	16.8	33.8	3.8	33.7	9.3	35.4	4.7	30.5 a	8.4	30.0	3.1 *
HC-C	65.3 *	18.3	21.7	1.6 *	66.3 *	12.3	32.8	2.2 *	69.5 * b	22.1	32.9	1.2 *

The average percent of total organic carbon (TOC) derived from the hydrochars (HC-C) and native soil organic carbon (SOC) at the beginning of the study (as iPOM$_F$), and after approx. 1 year (as POM$_F$, POM$_O$ and OM$_{Cl}$)

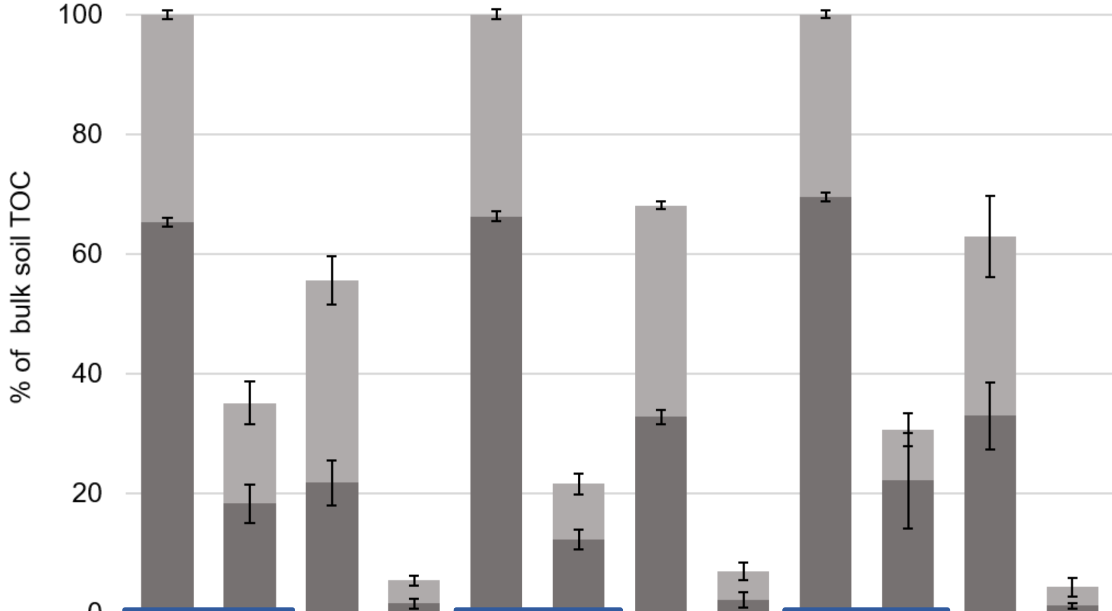
Results and discussion: HC-derived C in SOM fractions



	iPOMF	POMF	POMO	OMCI	iPOMF	POMF	POMO	OMCI	iPOMF	POMF	POMO	OMCI
	HC190				HC210				HC230			
native SOC	34.7	16.8	33.8	3.8	33.7	9.3	35.4	4.7	30.5 a	8.4	30.0	3.1 *
HC-C	65.3 *	18.3	21.7	1.6 *	66.3*	12.3	32.8	2.2 *	69.5 * b	22.1	32.9	1.2 *

68 – 81 % HC-C lost from POM_F

Results and discussion: HC-derived C in SOM fractions



	iPOMF	POMF	POMO	OMCI	iPOMF	POMF	POMO	OMCI	iPOMF	POMF	POMO	OMCI
	HC190				HC210				HC230			
native SOC	34.7	16.8	33.8	3.8	33.7	9.3	35.4	4.7	30.5 a	8.4	30.0	3.1 *
HC-C	65.3 *	18.3	21.7	1.6 *	66.3 *	12.3	32.8	2.2 *	69.5 * b	22.1	32.9	1.2 *

51 – 72 % SOC lost from POM_F

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Results and discussion: HC-derived C in SOM fractions

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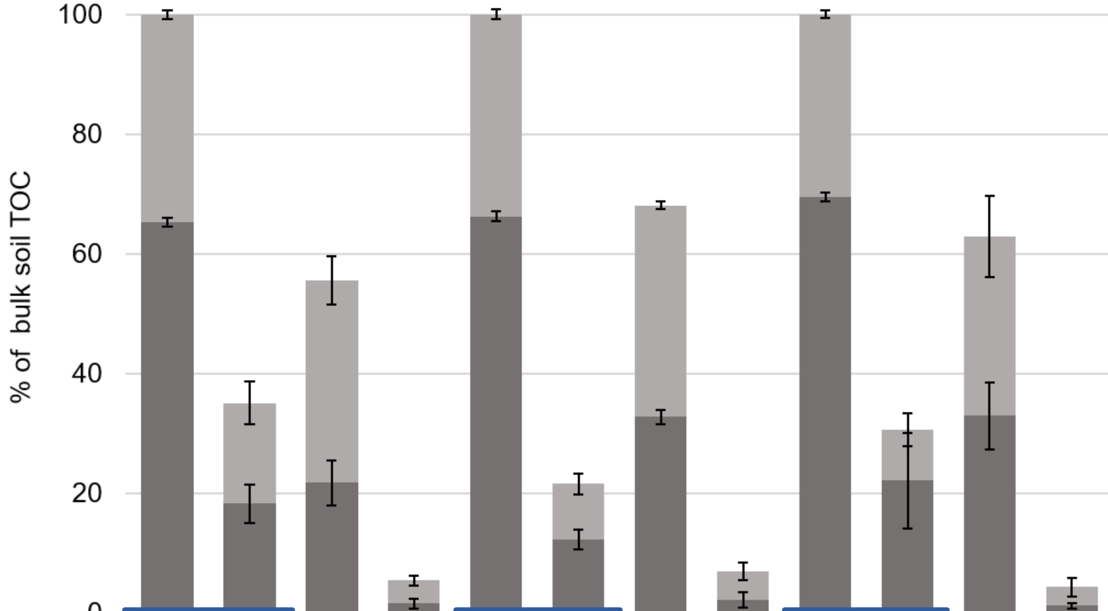
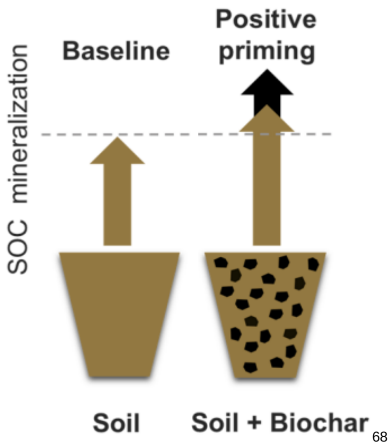


	HC190				HC210				HC230			
	iPOMF	POMF	POMO	OMCI	iPOMF	POMF	POMO	OMCI	iPOMF	POMF	POMO	OMCI
native SOC	34.7	16.8	33.8	3.8	33.7	9.3	35.4	4.7	30.5 a	8.4	30.0	3.1 *
HC-C	65.3 *	18.3	21.7	1.6 *	66.3 *	12.3	32.8	2.2 *	69.5 * b	22.1	32.9	1.2 *

Positive Priming Effect

30,47,54

Results and discussion: HC-derived C in SOM fractions



[68]

Hydrochars	Atomic ratio		
	C/N	H/C	O/C
190 °C HC	56.3	1.5	0.4
210 °C HC	41.6	1.4	0.3
230 °C HC	39.2	1.2	0.2

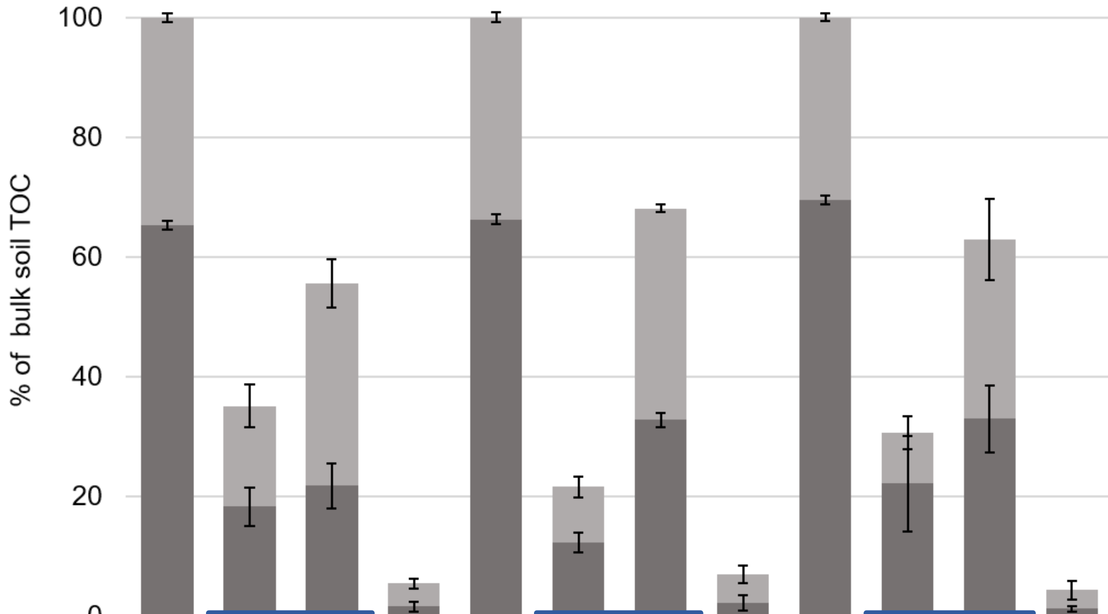
H/C ≥ 0.6: higher degradability[19,60]

	HC190 iPOMF	HC190 POMF	HC210 iPOMF	HC210 POMF	HC230 iPOMF	HC230 POMF
native SOC	34.7	16.8	33.7	9.3	30.5 a	8.4
HC-C	65.3 *	18.3	66.3*	12.3	69.5 * b	22.1

Positive Priming Effect

[30,47,54]

Results and discussion: HC-derived C in SOM fractions

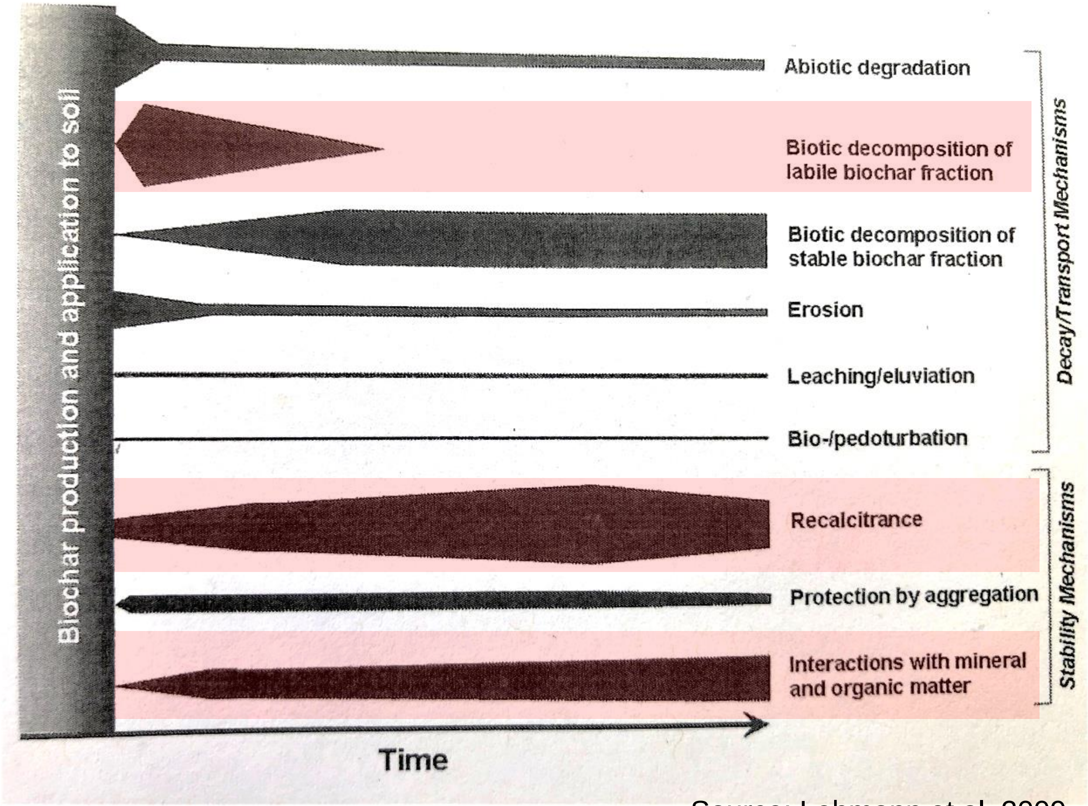


	iPOMF	POMF	POMO	OMCI	iPOMF	POMF	POMO	OMCI	iPOMF	POMF	POMO	OMCI
		HC190				HC210				HC230		
native SOC	34.7	16.8	33.8	3.8	33.7	9.3	35.4	4.7	30.5 a	8.4	30.0	3.1 *
HC-C	65.3 *	18.3	21.7	1.6 *	66.3*	12.3	32.8	2.2 *	69.5 * b	22.1	32.9	1.2 *

HC-C and SOC increased in POM$_O$ fraction

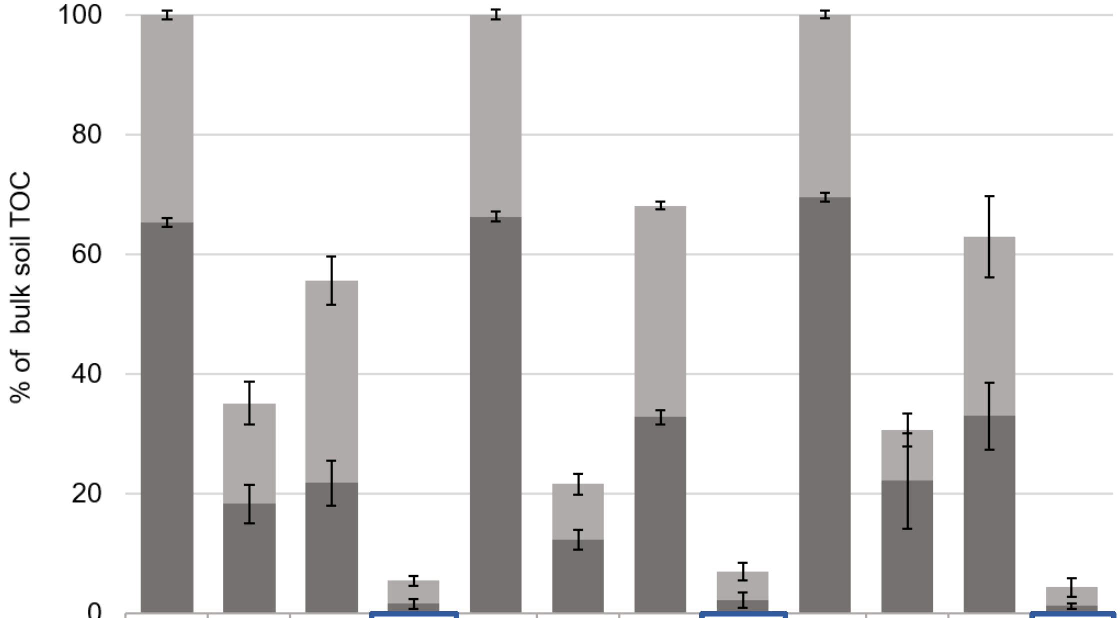
Results and discussion:
HC-derived C in SOM fractions

Factors influencing the stability and decay of biochar, and their importance over time



Source: Lehmann et al. 2009[63]

Results and discussion: HC-derived C in SOM fractions



	HC190				HC210				HC230			
	iPOMF	POMF	POMO	OMCI	iPOMF	POMF	POMO	OMCI	iPOMF	POMF	POMO	OMCI
native SOC	34.7	16.8	33.8	3.8	33.7	9.3	35.4	4.7	30.5 a	8.4	30.0	3.1 *
HC-C	65.3 *	18.3	21.7	1.6 *	66.3*	12.3	32.8	2.2 *	69.5 * b	22.1	32.9	1.2 *

OM_{Cl} fraction – slow reactivity[8,64,65]

Answering the research questions

1) How much HC-C is lost from the POM_F fraction after approx. 1 year?

- 68 – 81 % HC-C and 51 – 72% native SOC was lost from the POM_F fraction
- Positive priming effect was temporary

2) Is the level of HC-C decomposition from the POM_F fraction controlled by the HTC production temperature?

- No significant differences in losses between different temperature HCs

3) Does HC-C incorporate within the relatively stable POM_O and OM_{Cl} fractions?

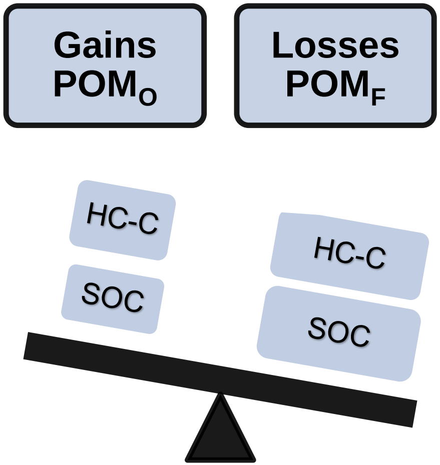
- Yes, HC-C present in POM_O and OM_{Cl} fractions after 1 year

4) Are these interactions controlled by the HTC production temperature?

- Influenced HCs physico-chemical and structural properties
- No significant differences in HC-C content of POM_O and OM_{Cl} fractions

Conclusion

Despite large C contribution from the maize-derived HCs, its effectiveness is reduced by positive priming effect. Therefore, more research is required on reducing initial priming losses and promoting long-term stabilization in stable SOM fractions



Chapter 5:

Major Conclusions and Future Perspectives

Major Conclusions

- **Hydrochar from biogas digestate – effective soil amendment**
    - Repeated addition of finer grained HC at 5 - 10 % application rates

- **Hydrochar from maize silage – low suitability for C stabilization over short-term**
    - Longer-term research required to verify C sequestration potential

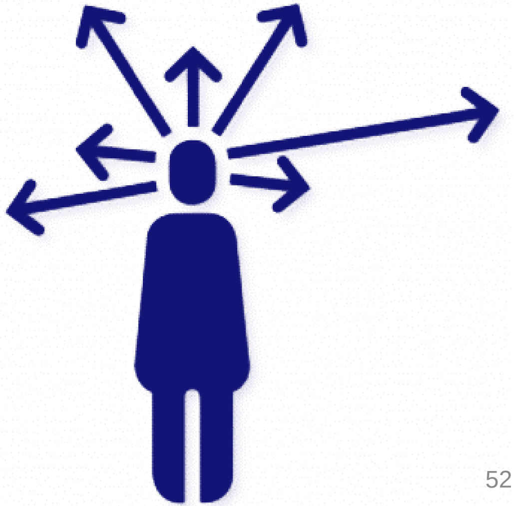
Future perspectives

- Field studies using recommended grain size and application rate

- Influence of recommended HC parameters on other soil properties, e.g. Nmin, Ca, Mg, Al and Fe

- Long-term research (> 2 years) required on C balance in SOM fractions

- More soil types and textures – beneficial HC interactions



Thank you for your attention!

Danke für Ihre Aufmerksamkeit!

Questions?

References

1. Jones NF, Pejchar L, Kiesecker JM (2015) The Energy Footprint: How Oil, Natural Gas, and Wind Energy Affect Land for Biodiversity and the Flow of Ecosystem Services. *BioScience, 65*(3), 290-301. http://doi.org/10.1093/biosci/biu224
2. Lilliestråle A (2007) Hydrothermal carbonization of biowaste–a step towards efficient carbon sequestration and sustainable energy production, Unpublished Masters thesis, Uppsala University School of Engineering, Sweden pp 53
3. Lehmann J, Gaunt J, Rondon M (2006) Bio-char sequestration in terrestrial ecosystems – a review. Mitigation Adapt. Strategies Global Change 11:403–427
4. Gwenzi W, Nyambishi TJ, Chaukura N, Mapope N (2018) Synthesis and nutrient release patterns of a biochar-based N–P–K slow-release fertilizer. Int J Environ Sci Technol 15:405–414. https://doi.org/10.1007/s13762-017-1399-7
5. Rafiq MK, Bachmann RT, Rafiq MT, Shang Z, Joseph S, Long R (2016) Influence of Pyrolysis Temperature on Physico-Chemical Properties of Corn Stover (Zea mays L.) Biochar and Feasibility for Carbon Capture and Energy Balance. PLoS ONE 11(6):e0156894. https://doi.org/10.1371/journal.pone.0156894
6. Verheijen FGA, Jeffrey S, Bastos AC, van der Velde M, Diafas I (2009) Biochar application to soils: A critical scientific review of effects on soil properties, processes and functions. EUR 24099 EN, Office for the Official Publications of the European Communities, Luxembourg
7. Fang Y, Singh BP, Nazaries L, Keith A, Tavakkoli E, Wilson N, Singh B (2019) Interactive carbon priming, microbial response and biochar persistence in a Vertisol with varied inputs of biochar and labile organic matter. Eur J Soil Sci 70:960–974. https://doi.org/10.1111/ejss.12808
8. Greenberg I, Kaiser M, Gunina A, Ledesma P, Polifka S, Wiedner K, Mueller CW, Glaser B, Ludwig B (2019) Substitution of mineral fertilizers with biogas digestate plus biochar increases physically stabilized soil carbon but not crop biomass in a field trial. Sci Total Environ 680:181–189
9. Kizito S, Luo H, Lu J, Bah H, Dong R, Wu S (2019) Role of nutrient-enriched biochar as a soil amendment during maize growth: Exploring practical alternatives to recycle agricultural residuals and to reduce chemical fertilizer demand. Sustainability 11:3211. https://doi.org/10.3390/su11113211
10. Gunarathne V, Mayakaduwa S, Vithanage M (2017) Biochar's Influence as a Soil Amendment for Essential Plant Nutrient Uptake, in Naeem M, Ansari AA, Gill SS (ed.). Essential Plant Nutrients: Uptake, Use Efficiency, and Management. Springer International Publishing, pp 47–67. https://doi.org/10.1007/978-3-319-58841-4
11. Marchetti R, Castelli F (2013) Biochar from swine solids and digestate influence nutrient dynamics and carbon dioxide release in soil. J Environ Qual 42:893–901
12. Steiner C, Garcia M, Zech W (2009a) Effects of Charcoal as Slow Release Nutrient Carrier on N-P-K Dynamics and Soil Microbial Population: Pot Experiments with Ferralsol Substrate, in Woods WI, Teixeira WG, Lehmann J, Steiner C, WinklerPrins A, Rebellato L (ed.): Amazonian Dark Earths: Wim Sombroek's Vision. Springer, Dordrecht, pp 325–328
13. Kambo HS, Dutta A (2015) A comparative review of biochar and hydrochar in terms of production, physico-chemical properties and applications. Renew Sust Energ Rev 45:359–378

References

14. Ramke HG, Blöhse D, Lehmann HJ, Fettig J (2009) Hydrothermal carbonization of Organic Waste. In: Cossu R, Diaz LF, Stegmann R (eds) Sardinia 2009: Twelfth International Waste Management and Landfill Symposium, Sardinia, Italy, 05-09 October 2009, Proceedings, CISA Publisher
15. Libra JA, Ro KS, Kammann C, Funke A, Berge ND, Neubauer Y, Titirici M-M, Fühner C, Bens O, Kern J, Emmerich K-H (2011) Hydrothermal carbonisation of biomass residuals: a comparative review of the chemistry, processes and applications of wet and dry pyrolysis. BioFuels 2:71–106
16. Busch D, Glaser B (2015) Stability of co-composted hydrochar and biochar under field conditions in a temperate soil. Soil Use Manage 31:251–258
17. Alburquerque JA, Calero JM, Barrón V, Torrent J, del Campillo MC, Gallardo A, Villar R (2014) Effects of biochars produced from different feedstocks on soil properties and sunflower growth. J Plant Nutr Soil Sci 177:16–25 https://doi.org/10.1002/jpln.201200652
18. Glaser B, Lehr V-I (2019) Biochar effects on phosphorus availability in agricultural soils: A meta-analysis. Scientific Reports 9:9338
19. Dieguez-Alonso A, Funke A, Anca-Couce A, Rombolà AG, Ojeda G, Bachmann J, Behrendt F (2018) Towards biochar and hydrochar engineering-influence of process conditions on surface physical and chemical properties, thermal stability, nutrient availability, toxicity and wettability. Energies 11:496
20. Liu, Z., Dugan, B., Masiello, C.A. and Gonnermann, H.M. 2017. Biochar particle size, shape, and porosity act together to influence soil water properties. *PLoS ONE, 12*(6), 1-19. Doi:10.1371/journal.pone.0179079
21. Blume H-P, Brümmer GW, Fleige H, Horn R, Kandeler E, Kögel-Knabner I, Kretzschmar R, Stahr K, Wilke B-M (2016) Scheffer/Schachtschabel Soil Science. Springer-Verlag, Berlin Heidelberg, pp 186 – 187
22. Brodowski S, Amelung W, Haumaier L, Abetz C, Zech W (2005) Morphological and chemical properties of black carbon in physical soil fractions as revealed by scanning electron microscopy and energy- dispersive X-ray spectroscopy. Geoderma.128:116–129
23. Hammes and Schmidt. 2009. Changes of biochar in soil. In Lehmann and Joseph (ed.) Biochar for environmental management, Science and technology. Earthscan, London. Pp. 169-182.
24. Domingues RR, Trugilho PF, Silva CA, de Melo ICNA, Melo LCA, Magriotis ZM, Sánchez-Monedero MA (2017) Properties of biochar derived from wood and high-nutrient biomasses with the aim of agronomic and environmental benefits. PLoS ONE 12:e0176884
25. DeLuca TH, MacKenzie MD, Gundale MJ (2009) Biochar effects on soil nutrient transformations. In: Lehmann J, Joseph S (ed) Biochar for environmental management: science and technology. Earthscan, London, pp 251–270
26. Hailegnaw NS, Mercl F, Pračke K, Száková J, Tlustoš P (2019) Mutual relationships of biochar and soil pH, CEC, and exchangeable base cations in a model laboratory experiment. J Soils Sediments 19:2405–2416
27. Biederman LA, Harpole SW (2013) Biochar and its effects on plant productivity and nutrient cycling: A meta-analysis. GCB Bioenergy 5:202–214
28. Alling V, Hale SE, Martinsen V, Mulder J, Smebye A, Breedveld GD, Cornelissen G (2014) The role of biochar in retaining nutrients in amended tropical soils. J Plant Nutr Soil Sci 177:671–680

References

29. Marmiroli M, Bonas U, Imperiale D, Lencioni G, Mussi F, Marmiroli N, Maestri E (2018) Structural and functional features of chars from different biomasses as potential plant amendments. Front Plant Sci 9:1119
30. Gronwald M, Don A, Tiemeyer B, Halfrich M (2015) Effects of fresh and aged chars from pyrolysis and hydrothermal carbonization on nutrient sorption in agricultural soils. SOIL 1:475–489
31. Buss W, Assavavittayanon K, Shepherd JG, Heal KV, Sohi S (2018) Biochar phosphorous release is limited by high pH and excess calcium. J Environ. Qual 47:1298–1303
32. Zhang X, Zhang L, Li A (2017) Hydrothermal co-carbonization of sewage sludge and pinewood sawdust for nutrient-rich hydrochar production: Synergistic effects and products characterization. J Environ Manage 201:52–62
33. Tambone F, Adani F (2017) Nitrogen mineralization from digestate in comparison to sewage sludge, compost and urea in a laboratory incubated soil experiment. J Plant Nutr Soil Sci 180:335–365
34. Hagemann N, Harter J, Behrens S (2016) Elucidating the Impacts of Biochar Applications on Nitrogen Cycling Microbial Communities, in Ralebitso-Senior, T. K., Orr, C. H. (ed.): Biochar Application: Essential Soil Microbial Ecology. Elsevier, Amsterdam, the Netherlands, pp 163–198
35. Reza, M. T., Andert, J., Wirth, B., Busch, D., Pielert, J., Lynam, J. G., Mumme, J. (2014): Hydrothermal carbonisation of biomass for energy and crop production. *Appl. Bioenergy*. 1, 11–29.
36. Bargmann, I., Rillig, M. C., Buss, W., Kruse, A., Kücke, M. (2013): Hydrochar and biochar effects on germination of spring barley. *J. Agron. Crop Sci*. 199, 360–373.
37. Bargmann, I., Rillig, M. C., Kruse, A., Greef, J-M., Kücke, M. (2014): Effects of hydrochar application on the dynamics of soluble nitrogen in soils and on plant availability. *J. Plant Nutr. Soil Sci.* 177, 48–58.
38. Penn CJ, Camberato JJ (2019) A Critical review on soil chemical processes that control how soil pH affects phosphorous availability to plants. Agriculture 9(6):120
39. Röhrdanz M, Greve T, de Jager M, Buchwald R, Wark R (2019) Co-composted hydrochar substrates as growing media for horticultural crops. Sci Hortic 252:96–103
40. Steiner C, Bayode AO, Ralebitso-Senior TK (2016) Feedstock and Production Parameters: Effects on Biochar Properties and Microbial Communities, in Ralebitso-Senior TK, Orr CH (ed.): Biochar Application: Essential Soil Microbial Ecology. Elsevier, United Kingdom, pp 41–54
41. de Jager M, Giani L (2021) An investigation of the effects of hydrochar application rate on soil amelioration and plant growth in three diverse soils. Biochar. https://doi.org/10.1007/s42773-021-00089-z
42. Dai L, Li H, Tan F, Zhu N, He M, Hu G (2016) Biochar: a potential route for recycling of phosphorus in agricultural residues. GCB Bioenergy 8:852–858
43. Melo TM, Bottlinger M, Schulz E, Leandro WM, de Oliveira SB, de Aguiar Filho AM, El-Naggar A, Bolan N, Wang H, Ok YS, Rinklebe J (2019) Management of biosolids-derived hydrochar (Sewchar): Effect on plant germination, and farmers' acceptance. J Environ Manage 237:200–214
44. Bargmann I, Martens R, Rillig MC, Kruse A, Kücke M (2013) Hydrochar amendment promotes microbial immobilization of mineral nitrogen. J Plant Nutr Soil Sci 177:59–67

References

45. Bento LR, Castro AJR, Moreira AB, Ferreira OP, Bisinoti MC, Melo CA (2019) Release of nutrients and organic carbon in different soil types from hydrochar obtained using sugarcane bagasse and vinasse. Geoderma 334:24–32
46. Hardy B, Sleutel S, Dufey JE, Cornelis J-T (2019) The long-term effect of biochar on soil microbial abundance, activity and community structure is overwritten by land management. Front Environ Sci 7(110):1–14
47. Bamminger C, Marschner B, Jüschke E (2014) An incubation study on the stability and biological effects of pyrogenic and hydrothermal biochar in two soils. Eur J Soil Sci 65:72–82
48. Mukherjee S, Weihermueller L, Tappe W, Vereechen H, Burauel P (2016) Microbial respiration of biochar- and digestate-based mixtures. Biol Fertil Soils 52:151–164
49. Bai M, Wilske B, Buegger F, Esperschütz J, Kammann CI, Eckhardt C, Koestler M, Kraft P, Bach M, Frede H-G, Breuer L (2013) Degradation kinetics of biochar from pyrolysis and hydrothermal carbonization in temperate soils. Plant Soil 372:375–387
50. Malghani S, Jüschke E, Baumert J, Thuille A, Antonietti M, Trumbore S, Gleixner G (2014) Carbon sequestration potential of hydrothermal carbonization char (hydrochar) in two contrasting soils; results of a 1-year field study. Biol Fertil Soils 51:123–134
51. Dicke C, Lanza G, Mumme J, Ellerbrock R, Kern J (2014) Effect of hydrothermally carbonized char application on trace gas emissions from two sandy soil horizons. J Environ Qual 43:1790–1798. https://doi.org/10.2134/jeq2013.12.0513
52. Fang J, Gao B, Chen J, Zimmerman AR (2015) Hydrochars derived from plant biomass under various conditions: Characterization and potential applications and impacts. Chem Eng J 267:253–259
53. Duddigan S, Shaw L, Alexander P, Collins C (2019) A comparison of physical soil organic matter fractionation methods. Appl Environ Soil Sci 2019:1–12. https://doi.org/10.1155/2019/3831241
54. Lanza G, Stang A, Kern J, Wirth S, Gessler A (2018) Degradability of raw and post-processed chars in a two-year field experiment. Sci Total Environ 628–629:1600–1608. https://doi.org/10.1016/j.scitotenv.2018.02.164
55. Kalinina O, Cherkinsky A, Chertov O, Goryachkin S, Kurganova I, Lopes de Gerenyu V, Lyuri D, Kuzyakov Y, Giani L (2019) Post-agricultural restoration: Implications for dynamics of soil organic matter pools. Catena 181:104096. https://doi.org/10.1016/j.catena.2019.104096
56. Centre for Stable Isotope Research and Analysis of the Georg-August-University of Göttingen, Germany
57. Baronti S, Alberti G, Camin F, Criscuoli I, Genesio L, Mass R, Vaccari FP, Ziller L, Miglietta F (2017) Hydrochar enhances growth of poplar for bioenergy while marginally contributing to direct soil carbon sequestration. GCB Bioenergy 9:1618–1626
58. Del Galdo I, Six J, Peressotti A, Cotrufo MF (2003) Assessing the impact of land-use change on soil C sequestration in agricultural soils by means of organic matter fractionation and stable C isotopes. Global Change Biol 9:1204–1213. https://doi.org/10.1046/j.1365-2486.2003.00657.x
59. Reza MT, Mumme J, Ebert A (2015) Characterization of hydrochar obtained from hydrothermal carbonization of wheat straw digestate. Biomass Convers Biorefin 5:425–435. https://doi.org/10.1007/s13399-015-0163-9
60. Eibisch N, Helfrich M, Don A, Mikutta R, Kruse A, Ellerbrock R, Flessa H (2013) Properties and degradability of hydrothermal carbonization products. J Environ Qual 42:1565–1573

References

61. George C, Wagner M, Kücke M, Rillig MC (2012) Divergent consequences of hydrochar in the plant-soil system: Arbuscular mycorrhiza, nodulation, plant growth and soil aggregation effects. Appl Soil Ecol 59:68–72. https://doi.org/10.1016/j.apsoil.2012.02.021
62. Connin SL, Virginia RA, Chamberlain CP (1996) Carbon isotopes reveal soil organic matter dynamics following arid land shrub expansion. Oecologia 110:374–386
63. Lehmann J, Czimczik C, Laird D, Sohi S (2009) Stability of biochar in the soil, in Lehmann J, Joseph S (ed.) Biochar for environmental management: Science and Technology. Earthscan, London, UK, pp. 183–198
64. Christensen BT (2001) Physical fractionation of soil and structural and functional complexity in organic matter turnover. Eur J Soil Sci 52:345–353. https://doi.org/10.1046/j.1365-2389.2001.00417.x
65. Haddix ML, Paul EA, Cotrufo MF (2016) Dual, differential isotope labelling shows the preferential movement of labile plant constituents into mineral-bonded soil organic matter. Glob Chang Biol 22:2301–2312. https://doi.org/10.1111/gcb.13237
66. Woolf D, Lehmann J, Cowie A, Cayuela ML, Whitman T, Sohi S (2019) Biochar for Climate Change Mitigation: Navigating from Science to Evidence-Based Policy. In: Lal R, Stewart BA (eds) Soil and Climate. CRC Press, Taylor & Francis Group, Florida, pp 219–348
67. Gan HY, Schöning I, Schal P, Ammer C, Schrumpf M (2020) Soil Organic Matter Mineralization as Driven by Nutrient Stoichiometry in Soils Under Differently Managed Forest Stands. Front For Glob Change 3:99. https://doi.org/10.3389/ffgc.2020.00099
68. Lehmann J (2019) Biochar beyond carbon sequestration: Life-cycle emission reductions, nutrient recycling and food security. Engineering Conferences International (ECI) Digital Archives. Bio-Char II: Production, Characterization and Applications. Conference Proceedings. (15 Sept.)

Image references

a) Stephane LEITENBERGER/REA, In Cailloce L. (03.12.2018) When productivism is bad for agriculture. CNRS News. https://news.cnrs.fr/articles/when-productivism-is-bad-for-agriculture. Accessed 09.04.2021
b) Latifundist.com. (05.11.2019) World's largest biogas plant started running at full capacity in Ukraine. Retrieved from: https://latifundist.com/en/novosti/46049-v-ukraine-na-polnuyu-moshchnost-zarabotala-krupnejshaya-v-mire-biogazovaya-stantsiya. Accessed 14.04.2021.
c) Cayton, H. (14.01.2020) Exposure to past disturbances affects species' response to current habitat fragmentation. Conservation Corridor https://conservationcorridor.org/digests/2020/01/disturbance-regime/. Accessed 09.04.2021
d) European Federation for Transport and Environment AISBL. (07.05.2012) Biofuels: dealing with indirect land use change (ILUC). https://www.transportenvironment.org/publications/biofuels-dealing-indirect-land-use-change-iluc. Accessed 09.04.2021
e) Agupdate.com. Accessed 09.04.2021
f) Baker J, Ross C. (2017) Recycling Carbon. Cross Slot. https://www.crossslot.com/page.php?142. Accessed 09.04.2021
g) Pixabay. Zalf.de. (04.12.2019) Usage of crop residues for bioenergy: is it possible without harming the environment? Retrieved from: https://www.zalf.de/en/aktuelles/Pages/PB2/Usage_of_crop_residues_for_bioenergy.aspx Accessed on: 14.04.2021
h) Lehmann J. (2019) Biochar beyond carbon sequestration: Life-cycle emission reductions, nutrient recycling and food security. Engineering Conferences International (ECI) Digital Archives. Bio-Char II: Production, Characterization and Applications. Conference Proceedings. (15 Sept.).
i) GP Biotec Ltd. (2021) Digestate. Retrieved from: https://www.gpbiotec.co.uk/digestate-fertiliser/ Accessed 12.04.2021
j) Chalker-Scott L. (2014) Biochar: a gardener's primer. WSU Extension Fact Sheet FS147E. Washington State University Extension Publications.
k) Chalker-Scott L. (2014) Biochar: a gardener's primer. WSU Extension Fact Sheet FS147E. Washington State University Extension Publications.
l) Le Page M. (04.11.2016) Trials planned for GM superwheat that boosts harvest by 20%. New Scientist. Retrieved from: https://www.newscientist.com/article/2111377-trials-planned-for-gm-superwheat-that-boosts-harvest-by-20/ .Accessed on 24.04.2021
m) Corn India. (31.07.2008) Importance and Utilization of Maize. Agronomy, Biochemistry, Breeding, Chemistry, Genetics, Genomics, Molecular Biology, Physiology. Retrieved from: https://cornindia.com/importance-and-utilization-of-maize/ .Accessed on 24.04.2021