BIOCHAR IN CITY TREE SUBSTRATES – AN ELEMENT FOR CLOSING WATER AND NUTRIENT CYCLES IN CITIES?

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Abstract
This study observed the effect of pyrolyzed materials (biochar) from plant residues, horse manure, and feces on tree substrate properties, birch tree health and growth over a period of 322 days. The results show that each of these biochars complies with the European Biochar Certificate (EBC) guidelines set forth by the EBC and no toxic heavy metals were detected. The biochar substrates enhanced the survival rate of the experimental birch trees.

Keywords
Biochar, substrates, city trees, leaching behavior

1. Introduction

Urban trees are suffering as their habitat is increasingly restricted by factors such as ever denser development, compaction of planting substrates, and pollutants in the leachate as well as in the air. Due to these harsh urban conditions, urban trees often grow to only a fraction of their natural lifespan. Thus, a newly planted urban tree will hardly reach an age older than 30 years on average (Roman et al. 2011). However, as a key component of the green infrastructure of metropolitan areas, urban trees play a major role in the provisioning of ecosystem services, such as the mitigation of climatic conditions and the overall aesthetics of the urban landscape. Thus, for example urban trees are crucial for shading and cooling cities and offer possibilities for rainwater management to relieve sewage systems. Trees that die too early cannot provide these important ecosystem services. Thus, their replacement requires an ever-greater effort. Ca^{2+} and Mg^{2+} in the leachates did not vary significantly over the entire measurement period, which may indicate that they originate from the irrigation water.

One possible solution for achieving sustainable green infrastructure and rainwater management is the use of structurally stable substrates that resist compaction and have an increased water holding capacity. Structurally stable tree substrates (SSS) can potentially retain water in the root zone of trees thus allowing for continued evapotranspiration during dry periods. Furthermore, these substrates can be used under traffic routes and thus offer the possibility for the expansion of the rooting area. This in turn can be used as a building stone for stormwater management concepts for resilient cities. Additionally, such substrates can be complemented with biochar. Biochar, the charcoal product gained through the pyrolysis of biomass in the absence of oxygen, is known to increase the additional amount of water that can be retained in substrates. (Abel, et al., 2013). Provided that this biochar is produced from biological waste containing nutrients (e.g., animal dung from horses or from human feces), it could even become a nutrient supplier for the trees at the same time. In summary, newly developed substrates must meet diverse requirements by improving on the soil's capabilities for water storage and nutrient delivery while simultaneously functioning as a foundational layer. The behavior and potential of biochar in urban, structurally stable tree substrates is poorly understood. Furthermore, little is known concerning which composition and materials are optimal to meet the various requirements. Ca^{2+} and Mg^{2+} in the leachates did not vary significantly over the entire measurement period, which may indicate that they originate from the irrigation water.

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This study aimed at comparing biochar obtained from three different raw materials: fecal matter (K), horses' dung (P) and a commercially available biochar charged with nutrients (V). In an experimental setup, the growth and health of young birch trees (*Betula pendula*), planted in SSS amended with the biochar variants was documented over a one-year period. Further measurements were taken to investigate the composition of the biochar variants and their influence on the seepage behavior of water in the SSS. Lastly the nutrients in the leachate were measured to determine the chemical influence of the charcoal variants on the substrates.

2. Methods

The trial was conducted with 1-year old birch trees. It took place from June 6, 2018 – April 24, 2019 (322 days) in a greenhouse in Waedenswil, Switzerland. The organic waste materials (horse manure and compost toilet substrate) were pyrolyzed. Samples of these two biochars as well as of a third - a commercially available nutrient-loaden plant-based biochar (serving as a reference) - were taken for further analysis.

Subsequentially, SSS based on crushed stone, sand, expanded shale and 5 and 10 vol % biochar was prepared and tested in a green house. The various compositions were set up within a random block design with 5 replicates per compositional variant. The composition of these substrate variants was based on research carried out at ZHAW in Waedenswil (Saluz, 2017), on tree experiments carried out in the city of Stockholm (personal recommendation by B. Embrén) as well as on experiences of Cornell University with "CU structured soil" (Grabowsky et al. 2002) The substrates in the trial were prepared and named as listed in Table 1.

Table 1
Substrate Types in Random block design

Variant	Dosage	Abbrevation
Control negative	-	Cn
Control positive (fertilized)	-	Cp
Plant-based biochar VE	5 vol%	V1
(charged with nutrients)	10vol%	V2
Biochar of horse dung PM	5 vol%	P1
	10vol%	P2
Biochar of fecal matter KT	5 vol%	K1
	10vol%	K2

Table2
Methods of leachate analysis

Perimeter	Method
Yield	Measured in the continuous production process. Mass determination before and after pyrolysis.
Bulk density	VDLUFA-Method A 13.2.1 (VDLUFA, 1991)
pH and electrical conductivity	pH- (Hach-Lange PHC301) und EC-probes (Hach-Lange CDC401) ISO 10390
Ash content	Residue analyzed gravimetrically after heating in a muffle furnace (Nabertherm L3) at 550°C according to EBC (2012).
Carbon, nitrogen, and hydrogen	CHN-Analyzer (Leco Tru Spec Micro) after DIN 51732 (Beuth, 2014)
Chemical and other element compositions	(ICP-OES) analyzed after microwave digestion (ultraCLAVE 4) at 250°C and 120 bar for ten minutes of 0.2 g sample with 5 mL HNO3, 1 mL H2O2, and 0.3 mL HF. Eurofins GmbH

The analytical methods for the biochar were chosen according to the guidelines set forth by the European Biochar Certificate (EBC). Thus, measurements were taken to analyse the most important physical characteristics and chemical characteristics of the coal variants and to determine their suitability for a possible certification according to the EBC (Table 2).

To assess the leaching of nutrients and heavy metals and thus investigate possible impacts on the groundwater as well as the behavior of the coal in the substrate, a leachate analysis was conducted regularly as listed in table 3.

Table 3
Methods of leachate analysis

Parameter	Method	Frequency
pH	Hach-Lange PHC301, ISO 10390 (2015)	Every 2nd week
Electrical conductivity	Hach-Lange CDC401, ISO 10390 (2015)	Every 2nd week
Na, NO_3^-, NH_4, PO_4^{3-}, K	Ion chromatography (IC)	4 x during trial
Cl, SO_4, Mg,	Ion chromatography (IC)	5 x during trial
Non-purgable organic carbon (NPOC)	TOC-L, Shimadzu	Beginning of trial and 2 months after beginning of trial
Total nitrogen (TN)	CHN Analyzer Leco TruSpec Macro	Beginning of trial and, 2 months after beginning of trial
Content heavy metals	Inductively coupled plasma mass spectrometry (ICP-MS)	Beginning of trial

To assess the influence of the addition of biochar on tree growth, different parameters were measured (Table 4). Furthermore, pictures were taken of all plants at the end of the experiment for further documentation.

Table 4
Method of plant observation

Parameter	Method	Frequency
Height	Maximum length with scale	Beginning of trial, after 6 months and at the end of trial
Chlorophyll	Dualex Force A	At the end of trial
Root length	Maximum length with scale	At the end of trial
Root volume	Average of two width measurements times maximum root length	At the end of trial
Stem shoots	visual	At the end of trial

Statistical comparisons between the compositional variants were performed with the R programming language using Kruskal-Wallis and Wilcox tests, since most parameters did not show a normal distribution.

3. Results

3.1. Biochar characterization - nutrients

The concentration of the three main macronutrients nitrogen (N), phosphorus (P) and potassium (K) found in all three biochar-samples are shown in Fig. 1. The VE-biochar and the PM-biochar showed very similar macronutrient contents, while the KT-biochar contained slightly less potassium and significantly more nitrogen and phosphorus. The increased N and P content in the KT-biochar can be explained by the human feces in the starting material. In addition to solid feces, the starting material also contained sawdust soaked in urine. Urine contains a high concentration of these nutrients (Rose *et al.*, 2015).

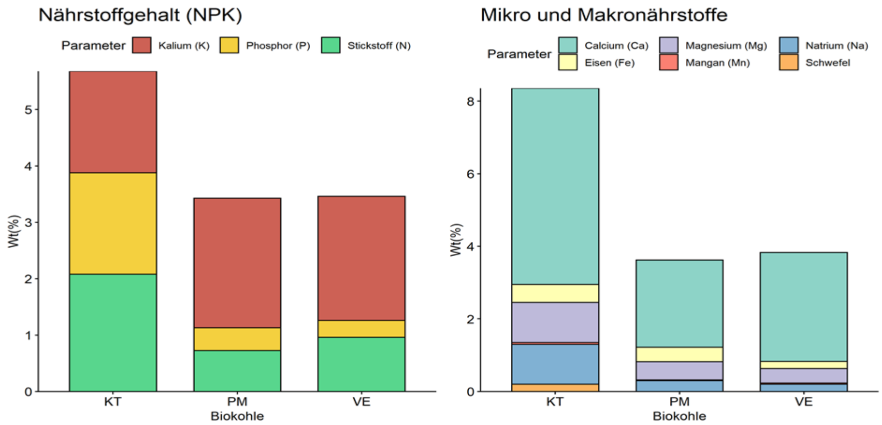

Fig. 1. Concentration of macronutrients for each biochar (% wt.)

The KT-biochar showed the highest concentration of additional important nutrients such as calcium (Ca), magnesium (Mg), iron (Fe) and sulfur (S). However, with the main exception of silicon the VE- and PM-biochars showed similar nutrient concentrations. The authors assume that the nutrients in the VE-biochar are due to nutrient "charging" during the production process. The nutrients in the KT-biochar are most likely derived from the human digestive system.

3.2. Leaching behavior – electric conductivity

The electrical conductivities (EC) of the leachates (Fig. 2) at the beginning of the experiment showed large differences between the controls (Cn and Cp, ca. 450 µS/cm) and the biochar amended substrates, ranging from approx. 1000 µS/cm (K1, 5 vol.% biochar) to > 2500 µS/cm (P2, 10 vol.% biochar). Between 6/6/2018 and 10/16/2018, the conductivity of the leachates decreased for all biochar amended substrates. This can be explained by the leaching of ions due to watering the trees. From October 2018 on, the EC in all leachates was slightly lower than the average conductivity of the drinking water in Waedenswil.

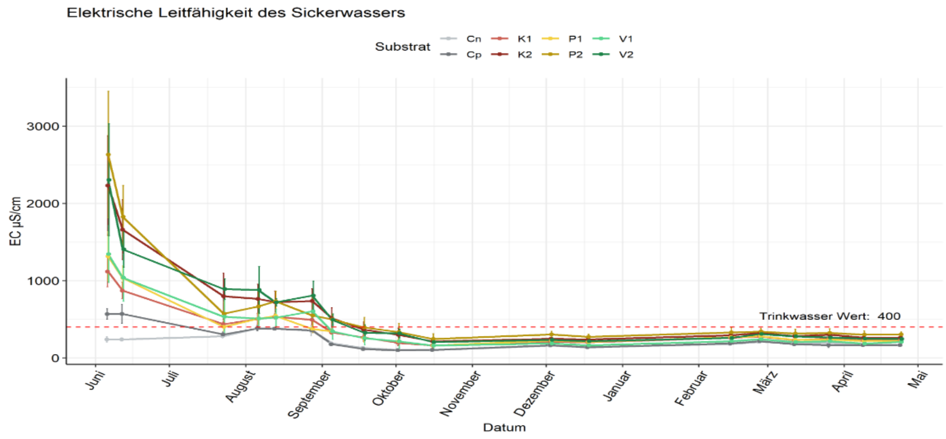

Fig. 2. Electrical conductivity (EC) of the leachates in µS/cm

At the beginning of the experiment (6/6/18), all leachates from substrates with 10% carbon content had a conductivity that was about 2 x higher than those with 5% carbon content. This difference between the substrates decreased during the first 4 months due to leaching, but was still noticeable towards the end of the experiment. At the end of the experiment, the substrates with 10% carbon content had a 14-23% higher conductivity in the leachate compared to those with 5% carbon content (mean values 2/14/19 - 4/24/19, n= 6).

3.3. Leaching behavior – pH value

A review of the pH values in the leachates in Fig. shows that during the first 2 1/2 months (6/6 - 8/28/18, 83 days), for all substrates, pH values were above 8 and up to Δ pH 1.6 apart. For all substrates, the pH of the leachates reached a maximum on 8/28/18, after which it steadily stabilized to pH 7.8 by 12/3/18. The pH differences of the leachates were then still Δ pH 0.17. The small Δ pH differences between the controls and the biochar-amended substrates after 12/3/18 indicate that the biochar does not have a long-term effect on the pH of the leachate, and thus of the substrate. This pH-drop from up to pH 9.5 to below pH 8 during the first 3.5 months coincides with the washout of about 90% of the easily soluble ions and can probably be explained by alkaline ions in the leachate.

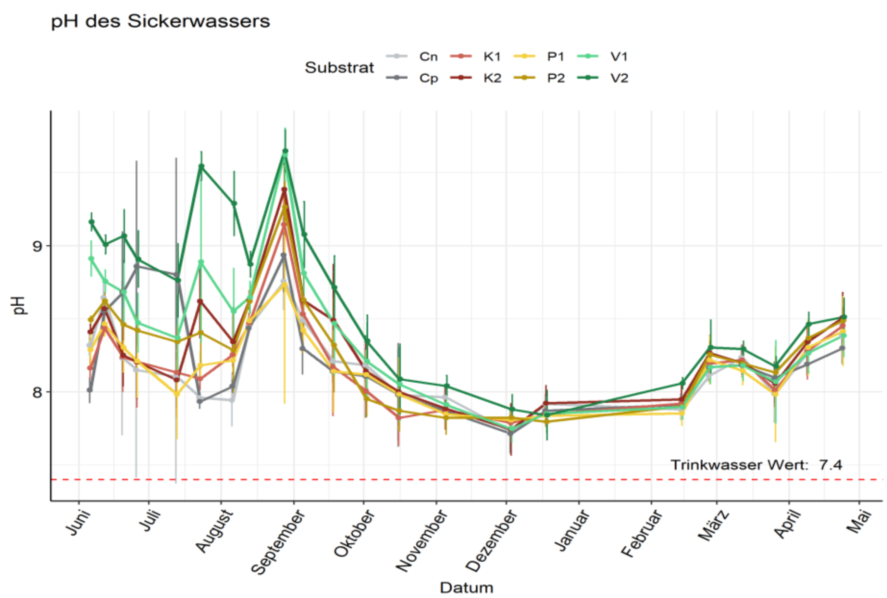

Fig. 3. pH values in leachates over time, for each substrate

3.4. Leaching behavior - nutrients

With the exception of the unfertilized negative control Cn, the NPK concentrations decreased similar to the conductivity over the duration of the experiment as the. In the case of the biochar amended substrates (KT, PM, VE), a high leaching of potassium is noticeable, which is the higher the more biochar was added to the substrate. In contrast, the leaching of nitrate dominates in the positive control (Cp) (Fig.4). The initial leaching of phosphate is conspicuous in the preparations with plant charcoal (V1, V2).

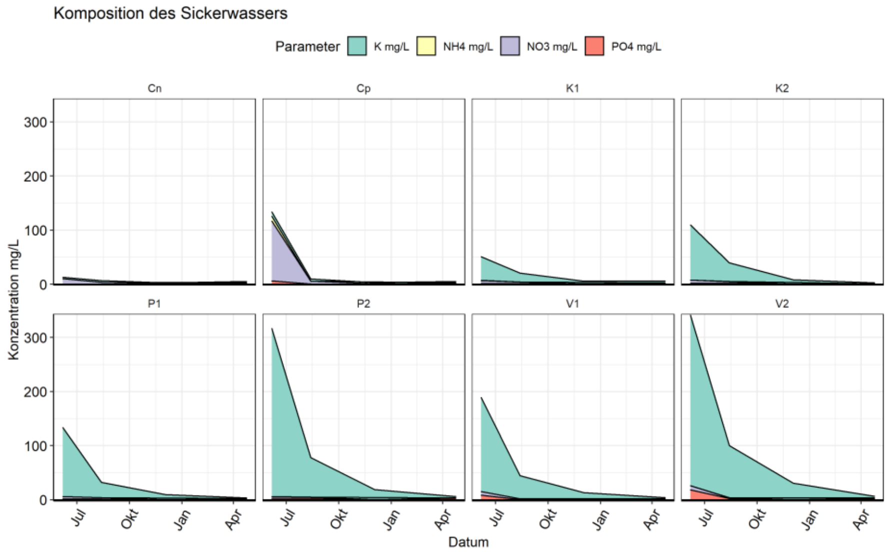

Fig. 4. NPK concentrations in leachates (mg/l)

The ions Ca^{2+}, Cl^{-}, Mg^{2+}, Na^{+} und SO_4^{2-} were leached out significantly more from the two substrates KT and PM than from the substrate VE and the two control substrates Cn and Cp. This is mainly due to the concentrations of Na^{+} and Cl^{-}. The concentration decline of Na^{+} and Cl^{-} in the leachates coincides with the decline of the total conductivity (Fig. 5). The relatively high proportion of these two ions can be explained by the presence of human or horse urine in the source material. In comparison, the concentrations of Ca^{2+} and Mg^{2+} in the leachates did not vary significantly over the entire measurement period, which may indicate that they originate from the irrigation water.

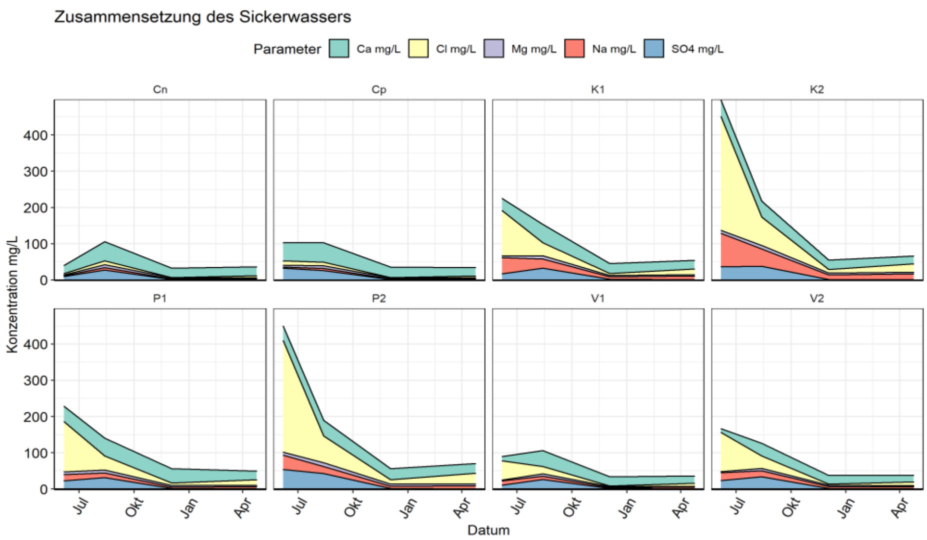

Fig. 5. Calcium, chloride, magnesium and sulphate ions in leachates (mg/l)

The heavy metals in the leachate were measured once at the beginning of the experiment. Very small amounts were found, with arsenic only present in three of the biochar amended substrates (V1, V2, P2), with concentrations very low and below the predetermined thresholds.

3.5. Tree measurements

The general conditions in the substrates were defined by a low water storage capacity, an initially high pH, with no additional fertilization (except by the biochar), with high temperature fluctuations from June-October as well as with being temporarily dried out. The growth of the birch trees during the 322 days was accordingly low (Fig. 6).

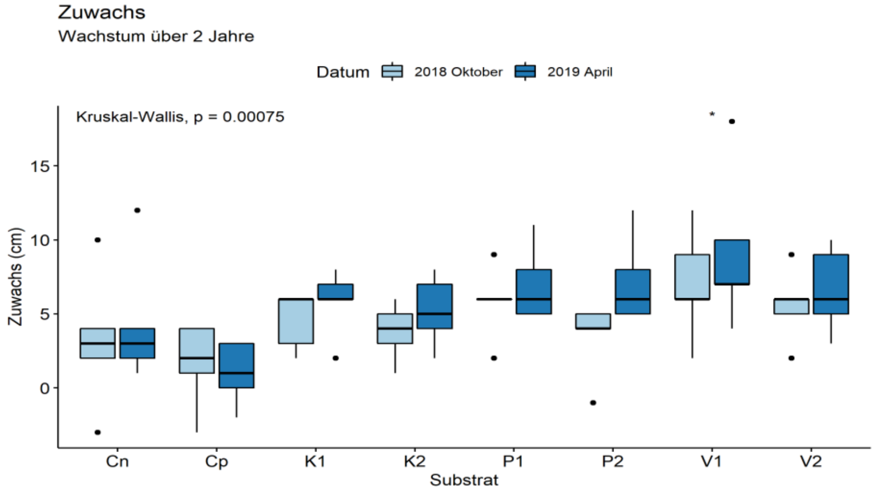

Fig. 6. Absolute tree growth (cm) by substrates after 4 months (October 2018) and at the end of the experiment (April 2019)

The relative size increase of the birch trees with respect to their initial size is a more interesting parameter compared to their absolute size. Here, the stagnation of the growth of the negative controls Cn and the dieback of the positive controls Cp becomes visible. All biochar amended substrates show higher growth values on average (with V1 being significantly compared to Cn). This is an indication that the addition of plant-based biochar can have a positive effect on seedling development.

The roots "with biochar" survived the duration of the experiment and were very vital in one of the setups.

The root volume in biochar-amended substrates was on average 270-310% higher at the end of the trail compared to the negative controls. 5% charcoal in the substrate was sufficient to significantly improve the conditions for the birch trees (Fig. 7).

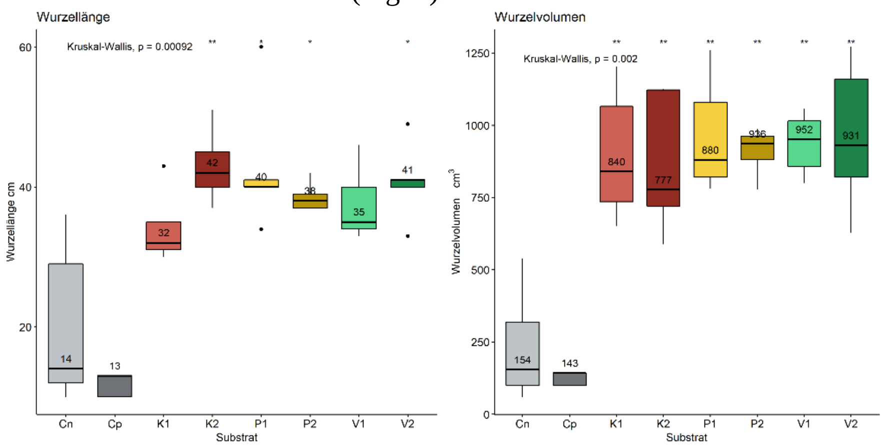

Fig. 7. Root length (cm) and root volume (cm^3) by substrates over experimental period (322 days)

4. Discussion

The experiment shows that when using biochar amended substrates, some leaching is to be expected. Biochar combined with little amounts of organic matter could provide a better nutrient holding capacity. This in term improves upon the benefits provided by structural stable substrates and is therefore a bases for sustainable tree growth in cities.

Thus, SSS amended with biochar and organic material may enable multifunctional urban spaces to be made more tree friendly. Thus, by using biochar amended SSS, it is also possible to increase the ecosystem services of green spaces and to incorporate them into a strategy for the mitigation of the urban heat island effect. The substrates serve here as a root space with nutrients, a foundational layer but also as an element for water storage. The use of fecal carbon in tree substrate may contribute to closing water and nutrient cycles in cities and put value on an otherwise unused resource.

Our results demonstrate that the addition of biochar to a structurally stable tree substrate can significantly improve conditions for tree seedlings in terms of tree survival. The main reason for this is likely to be its effect on increasing the substrate's water storage capacity. The surprising vitality of the birch seedlings in the approach with 5% faecal charcoal suggests that the roots may also be able to tap the nutrients bound in the biochar structure. It has additionally shown that heavy metal accumulation is not to be expected. However, the extent to which the biochar supports tree growth cannot be conclusively answered. It shows, however, that both nutrient storage and water storage of the biochar from an amount of 5 Vol% may have a big impact on the vitality of the trees.

Fecal-based biochar should therefore be used in the latest developments in substrates for innovative and sustainable urban developments. The results of this study lay a foundation for these innovations.

5. Acknowledgment

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