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'Waste' biochar for agricultural soil quality improvement

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Abstract

Biochar is a carbonaceous substance obtained from the pyrolysis of biomass under anoxic conditions. The use of biochar dates as far back as the ancient Amazonian times i.e, 'Terra Preta de Indio' where dark soils had more fertility compared to normal soils. The interest in biochar in recent years have increased due to its numerous benefits such as its ability to improve soil conditions in particularly tropical regions (it has minimal impact in boreal soils with high soil organic matter) remediate contaminated soils, purify water, etc.

In this study biochar made from four different feedstocks were investigated for their chemical suitability for agriculture use. These feedstocks were clean wood chips (CWC), waste wood (WT), digested sludge from MOVAR wastewater treatment plant (MOVAR) and digested sludge from Lindum waste handling company (DSL), all made at four different pyrolysis temperatures 500°C, 600°C, 700°C and 800°C (or 750°C).

To test the suitability of these biochar for agriculture use, the concentrations of main elements (Ca, Fe, K, Mg, Na, P, S, Si) and trace elements (As, Ba, Cd, Co, Cr, Cu, Mo, Ni, Pb, Sr, V and Zn) in all biochar were measured. A method development was carried out to enable biochar to be leached at a fixed pH because no suitable methodology was found after extensive literature review. To approximate the leachable concentrations of main and trace elements in the biochar when applied to soils with different pHs, a batch leaching test was carried out on all biochar at 4 different target pHs: ambient, 7.0, 5.5 and 4.0.

Concentrations of P and K (main elements) in the biochar investigated were far less than those found in commercial fertilizers. Some trace elements concentrations (As, Cu, Cr, Ni, Pb, Cd and Zn) in the biochar were above acceptable limits when compared with EBC (European Biochar Certificate) Agro and Agro Organic limits; though increasing pyrolysis temperature was able to reduce some trace elements, Cd and Pb, to acceptable limits. Concentrations of Cr were also above threshold limits in all biochar when compared with appropriate 'class' of the European Union (EU) Fertilizer Framework Directive.

Cu and Zn concentrations in leachate were particularly high for DSL, MOVAR and WT (except WT-600, WT-700, WT-800) when leachate concentrations of trace elements were compared with leachate concentrations from reference biochar, CWC. WT biochar had the most trace elements with concentrations higher than acceptable limits when leachate trace element concentrations were compared with threshold limits from waste deposited to 'inert landfills' in Norway.

In accordance with the EU's Fertilizer framework Directive and EBC standards, these biochar are currently not suitable for agricultural soil improvement purposes due to the high concentrations of trace elements, particularly As, Cu, Cr, and Zn. However further investigations as to how to reduce these trace elements could change the current stance.

Abbreviations and Acronyms

% - Percentage

As -Arsenic

Al – Aluminium

AIC - Akaike information criterion

Ba - Barium

BC - Biochar

Ca - Calcium

Cd - Cadmium

CEC – Cation Exchange Capacity

Co - Cobalt

Cr - Chromium

Cu - Copper

CWC – Clean wood chips

DSL- Digested sludge from Lindum waste handling company

EBC – European Biochar Certificate

EPA – Environmental Protection Agency

EU – European Union

Fe - Iron

Fig - Figure

HCl – Hydrochloric acid

K - Potassium

LOD – Limit of Detection

LOQ – Limit of Quantification

Mg - Magnesium

MINA - Faculty of Environmental Sciences and Natural Resource Management

Mo – Molybdenum

MOVAR – Digested sludge from MOVAR waste water treatment plant

Na - Sodium

NGI - Norwegian Geotechnical Institute

NMBU – Norwegian University of Life Sciences

Ni - Nickle

P - Phosphorus

Pb - Lead

S - Sulfur

Si - Silicon

Sr - Strontium

V - Vanadium

WT – Waste timber

Zn - Zinc

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1. INTRODUCTION

1.1 Biochar and its composition

Biochar is the product of burning biomass under anoxic conditions (Saletnik et al., 2019). Generally common wastes such as manures, sludges, agricultural residues, crops, wood chips etc are used as feedstocks. Converting waste into biochar contributes to environmental sustainability (Saletnik et al., 2019). Large amounts of waste are generated across the world every year: for instance, in Europe 8.7 million tonnes DS/y of sludge was produced in 2021 (EurEau 2021). In 2019, 815 000 tonnes of wood waste, 187 000 tonnes of park- and gardening waste, and 639 000 tonnes of wet organic waste was generated in Norway (Statistics Norway, 2021). Improper discharge of waste into the environment degrades ecosystems with their resulting ecosystem services. Thus, the need to dispose of these waste will be reduced if they are used as feedstock for biochar production as well as a reduction in the emission of methane from landfills; a contribution to mitigating global warming (Milich L., 1999). The pyrolysis process also reduces pathogenic organisms present in these wastes, especially sewage sludge, which can be detrimental to humans (Saletnik et al., 2019).

The origin of biochar can be traced to ancient Amazonian region, i.e, 'Terra Preta de Indio', where dark earth was created through slash and-char techniques, to improve soil fertility. The dark earth was later found to have high fertility compared to other soils where the slash and char was not practiced (Bezerra et al., 2016). ' Terra Preta' soils have large organic matter contents with high cation exchange capacity; an indication that there has been high carbon sequestration in the soil organic matter (Glaser et al., 2001). Due to the high fertility, more than one harvest season could be done on these soils without extra fertilization ((Glaser et al., 2001).

The main elements of biochar are C (carbon), H (hydrogen) and O (oxygen). Ash and trace amounts of other elements such as N (nitrogen) and sulfur (S), are also present (Liu et al., 2015). Large surface area, high cation exchange capacity, alkaline pH are unique characteristics of biochar. The elemental composition however varies for different biochar according to the feedstock used as well as the pyrolysis temperature (Ahmad et al., 2014). This difference in elemental composition has a great impact on the physicochemical properties of biochar. For instance, feedstock rich in lignin result in biochar with a slow mineralization rate and higher content of aromatic C (Windeatt et al., 2014). Luo et al, 2015 showed that feedstock determined the concentration of mineral components such as CO_3^{2-} and PO_4^{2-} on biochar which play important roles in sorption (Luo et al., 2015). The presence of contaminants in biochar also affects its properties. Polycyclic aromatic hydrocarbons (PAHs) and potential hazardous trace elements are some of the contaminants found in biochar, with the content of trace elements [Cadmium(Cd), Copper (Cu), Cobalt (Co), Chromium (Cr), Lead (Pb), Nickle (Ni), Zinc (Zn) and Arsenic (As). **From here forward these elements will be referred to as trace elements**] largely dependent on their concentration in the feedstock.

1.2 Biochar and impact on agricultural soils

It has been estimated that about 30% of the world's total land area and about 50% of arable land are acidic (< pH 7) (Von Uexküll & Mutert., 1995). In agriculture, acidification could be caused by excessive precipitation, oxidation of sulfur bearing minerals, input of ammonia, nitrate leaching, and the removal of basic cations during harvesting. Toxicity of Al and/or deficiency of C, P, N, Mo are the major factors affecting plant growth on acidic soils (Arshad et al., 2012). Nutrient deficiency results in poor yields and low quality of crops (Liu et al., 2016; Nyambo et al., 2018). For instance, iron-oxides sorbed to clay minerals, fix phosphorous under acid conditions making it unavailable for plant uptake.

pH is the most important factor controlling cation elemental speciation and solubility in soil and soil solution, though other soil properties such the cation exchange capacity (CEC) on soil organic matter, clays and oxide minerals are also important (Zhao et al., 2010). Soil pH in the acid range increases trace elements desorption (except As, with its sorption increasing with soil pH in the acid range) from soil constituents into soil solution, with increased bioavailability as a consequence (Zheng & Zhang., 2011).

Biochar has an acid neutralizing capacity when added to acidic soils because they are alkaline in nature. The feedstocks used for biochar are rich in base cations which remain in the biochar after the pyrolysis process (Liang et al., 2006). These base cations are partly liberated from the biochar when applied to soil improving the soil buffer capacity by replacing exchangeable Al^{n+} and H^+ (Gul et al., 2015; Liang et al., 2006). Depending on the pyrolysis temperature and the density of remaining functional groups on the biochar, biochar application increases the soil CEC, particularly in acidic soils (Yuan et al., 2011)

Soil degradation leading to loss of soil fertility and decrease in crop productivity is on ascendency throughout the world (Smith & Gregory., 2013). The degradation is mainly caused by acidification, salinity, compaction, decreased CEC, loss of water holding capacity due to the depletion of soil organic matter; this a big constraint to global food production (Bindraban et al., 2012), more especially with increasing human population.

Application of chemical fertilizers increase yield but negatively affects several ecosystems (with their related ecosystem services) with obvious ecological imbalances such as loss of biodiversity. Prolonged application further decreases soil fertility; also chemical fertilizers may not be affordable to most farmers especially in the developing countries (Vlek., 1990). Biochar use in agriculture can reduce the use of fertilizers which could contribute to sustainable agriculture, though it is more effective in degraded soils than 'undegraded' soils.

Both the biotic and abiotic components of soil interacts with biochar when it is added. Its addition to soils have been shown to improve soil fertility and plant growth (Agegnehu et al., 2015; Reverchon et al., 2013). It is rich in macro and micro elements such as N, P, Ca, and K (feedstock dependent) (Sg et al., 2021). When biochar is applied to soil, these main elements are released from the biochar surface into the soil which improves plants access to nutrients hence an increase in yield (Vaccari et al., 2011; Zhao et al., 2013; Zhao et al., 2014). It has low tensile strength hence it enhances root penetration in soil by reducing the tensile strength of soil (Saffari et al., 2021).

It is estimated that total amounts of animal P content produced annually is more than world fertilizer P output (Ramankutty et al., 2010). This makes “animal sludge” biochar a good alternative to mineral P fertilizers and P recycling (Glaser & Lehr., 2019)

The high surface area and the porous nature of biochar makes it effective in soaking up and retaining water as well as adsorbing nutrients, thereby improving soil nutrient and water retention capacity (Gong et al., 2019; Yu et al., 2009). However the amount of main elements in biochar does not mean it is all available to plants. Main elements in biochar are less compared to main elements in feedstocks (El-Naggar et al., 2015) as pyrolysis cause a loss of some nutrients

Biochar addition to soil also stimulates C mineralization through the utilization of its labile C by soil microorganisms (the carbon in biochar is made of both labile and recalcitrant carbon). (Cross & Sohi., 2011). However mineralization has been found to be greater in soils with low organic C content compared to soils with high organic C content (Zimmerman et al., 2011). A review by Wang et al 2016, also showed that mineralization of soil organic matter was higher in soils with low fertility than in soils with high fertility (Wang et al., 2016). The recalcitrant C in biochar lasts for a long time in soil thus increasing soil C input. Biochar addition to soil also decreases bioavailability hence plant uptake of pesticides in soil pore water and soil (Yu et al., 2009). As stated above, pyrolysis temperature also plays an important role on the physicochemical properties of all biochar.

However, in the same way as base cations are liberated after application, trace elements may be liberated into the soil and increase the fraction of bioavailable potentially hazardous trace elements in arable soils. Increased plants uptake and adverse effects on organisms is thus a risk following application of biochar made of e.g. feedstock rich in such elements (Zhang et al., 2020). From a human health point of view, it has been recognized that moderate contamination of arable land could cause considerable metal accumulation in edible parts of plants. At sub toxic concentrations for plant, such levels can contribute to substantial metal dietary intake by humans after long-term exposure via food consumption. Especially, rice is a staple food for more than half of the world’s population (Bandumula., 2017), and the “Itai-Itai”-disease is a tragic example of how Cd-polluted rice was the major source of Cd intake in the patients (Takeuchi et al., 1962).

A review by Nasreddine et al., 2002 estimates that plants contribute to about 50% of human lead intake happening through food (Nasreddine et al., 2002). Cadmium and Zn are fairly mobile hence readily absorbed by plant, whereas lead (Pb) is generally strongly bound in soil. But at high concentrations in low pH soils, Pb can be toxic to organisms even as toxic effect can be observed in small concentrations (Nasreddine et al., 2002). It is worth noting that mobility of trace elements may also increase in alkaline soils. This is often due to the formation of complexes with soil organic entities available to plants (Kicińska et al., 2022), although the plant uptake and toxicity is less prominent: Adamczyk-Szabela et al, 2015 have reported that herbs grown on alkaline soils (pH = 10) had as much high copper and manganese contents as herbs grown in acidic soils (pH = 5.1) (Adamczyk-Szabela et al, 2015). But a pH of 10 is a pH-range where commercial production of consumable crops is so to speak impossible.

1.3 Waste timber and sludge biochar

Waste timber (WT) is a mixture of discarded wood from industry, demolition, wood waste collected at municipal recycling stations etc (Sormo et al., 2021). These waste woods are normally lightly contaminated with binding agents, metals, paints etc. During pyrolysis, there is reduction in the mass of feedstock/biochar as some elements evaporate. The trace elements that do not evaporate accumulate (Sormo et al., 2020). Sørmo et al., 2020, showed that waste timber biochar did not meet the standards of the European Biochar Certificate (EBC 2012 - 2022) due to high concentrations of Cu (Copper), Pb (Lead), Zn (Zinc) and Polycyclic aromatic hydrocarbons (PAHs) which exceeded benchmark EBC values (Sormo et al., 2020). It was suggested that higher pyrolysis temperature can be used to reduce heavy metal concentrations, for instance, Pb and Zn, as metal volatilization will increase with increasing temperatures (> 800^oC) (Sormo et al., 2020).

Biochar made from Sewage Sludge (SSB) are rich in nutrients such as K (Potassium), P (Phosphorus) which makes it a potential fertilizer source (Karim et al., 2019; Yuan et al., 2016). SSB have a general trend of neutral to basic pH and low C content compared to waste timber biochar (Regkouzas & Diamadopoulos., 2019) and are rich in mineral content (Yuan et al., 2016). High ash content is a unique characteristic of SSB which relatively increases with temperature (Pulka et al., 2016). However SSB has high concentrations of Polycyclic aromatic hydrocarbons (PAHs), micro-pollutants, human bacterial pathogens, and trace elements (Pulka et al., 2016, Yuan et al., 2019). The high concentrations of potential hazardous trace elements in WT biochar and SSB may not necessarily pose a danger when the biochar is applied to soil; the potential hazardous trace elements may not be soluble due to biochar's alkaline pH, unless the soil is very acidic.

1.4 Effect of pyrolysis temperature on biochar properties

Pyrolysis temperature is the most significant factor that affects aromatic condensation and stability of biochar (McBeath et al., 2015). An increase in the pyrolysis temperature:

¶ decreases the number of O functional groups on the surface
¶ increase in C content (Zhao et al., 2017).
¶ results in a high aromatic structure (Kim et al., 2012),
¶ high surface area, thus an increase in micro-pore due to removal of volatile compounds at high temperatures (Tomczyk et al., 2020).

During pyrolysis there is loss of moisture by evaporation and release of volatile compounds from the feedstock, resulting in the enrichment of Ca, K, Mg, P in the biochar; a reduction in the –OH functional groups as a result of the dehydration and condensation (Agrafioti et al., 2013). Increasing the temperature also results in the loss of elements according to the volatility, decomposition of organic matter and the formation of micropores which increases the surface area of the biochar (Angin, 2013; Sormo et al., 2021; Sormo et al., 2020), i.e as temperature increases, some elements evaporate or are decomposed. Also, substances that could block the pores in biochar are burnt off or evaporates increasing the surface area.
The heating temperature of the feedstock affects the physicochemical properties of the resulting biochar. Higher temperatures of pyrolysis gives biochars with high C/N ratios compared to biochar from lower pyrolysis temperature (Figueiredo et al., 2017) because N is quite volatile so increasing temperatures cause more N loss and the C mostly left are recalcitrant.

The stability of biochar varies for different feedstocks at lower pyrolysis temperature. However, as temperature increases, biochar from different feedstock approach similar structures. Thus, at higher temperatures the stability may be similar for different biochar irrespective of their biochemical composition (McBeath et al., 2014; McBeath et al., 2015). It must be noted however that the change in structure in response to the increase in temperature and the carbon sequestration potential of the resulting biochar produced at higher temperatures are feedstock dependent. The lignin content of the feedstock significantly correlates with the C sequestration potential of the biochar (Zhao et al., 2013; Zhao et al., 2017). Increasing pyrolysis temperature brings about an increase in structural aromaticity which enhances biochar's resistance to microbial decomposition (Dhar et al., 2020; McBeath et al., 2014)

The residence time at the target pyrolysis temperature also plays an important role in the carbonization degree of biochar. Increasing residence time increases biochar stability, with less labile organic matter at lower temperatures (Cross & Sohi, 2011, 2013; Zornoza et al., 2016) showed that increasing residence time from 20 minutes to 80 minutes at 350^{o}C increased stability of biochar. Thus, shorter residence time at lower temperatures significantly impact biochar C mineralization in soils. However residence time seems to not have any impact at higher temperatures (550^{o}C and above) (Cross & Sohi., 2011, 2013).

Biochar produced at lower pyrolysis temperatures are richer in nutrients compared to those produced at higher temperatures. Nutrients have different volatilization temperatures, for instance, to have a more N enriched biochar, lower temperatures (about 400^{o}C) is more appropriate because N has a lower volatilization temperature (Biederman & Harpole., 2013).

P on the other hand has a high volatilization temperature (Biederman & Harpole., 2013). Increasing pyrolysis temperature transforms readily available P to less labile and less mobile fractions. Less mobility enhances P availability to plants through a reduction in its runoff and leaching (Filipović et al., 2020). However P evaporates from biochar at temperatures 700^{o}C and above (Filipović et al., 2020). Increasing pyrolysis temperature (to about 500^{o}C) transforms water soluble K to inorganic K whiles increasing temperature above 700^{o}C leads to K loss through volatilization and decomposition; thus biochar made at lower pyrolysis temperature have more nutrients compared to biochar made at higher temperatures, and are therefore more suitable for nutrient enhancement (Hossain et al., 2020). Biochar made at higher temperatures however are more preferable for C sequestration in the soil (Figueiredo et al., 2017)

Though biochar have an alkaline pH, pyrolysis temperature influence pH as well. pH increases with increasing temperature due to the carbonization effect that happens at higher temperatures, also the reduction of organic functional groups on biochar surface contributes to this rise in pH (Regkouzas & Diamadopoulos, 2019).

2. RESEARCH AIM AND OBJECTIVES

2.1 Purpose of Study

This study is to find out if biochar produced from waste (sewage sludge and waste timber) can be safely used for soil quality improvement in agriculture.

To this, 4 different biochar:

1. Clean wood chips (CWC) biochar – made from clean wood residues from forestry. This is the reference biochar
2. Waste timber biochar – made from a mixture of discarded wood from industry, demolition, wood waste collected at municipal recycling stations
3. DSL biochar - made from anaerobically digested sewage sludge from Lindum waste handling company As, using the Cambi process ((a thermal hydrolysis of sludge which uses temperature and pressure to disintegrate and dissolve sludge). This digested sludge is used for biogas production.
4. MOVAR - Digested sewage sludge through traditional anaerobic methods, from MOVAR waste water treatment plant also used for biogas production

will be produced at 4 different pyrolysis temperature 500 °C, 600°C, 700°C and 800°C(or 750°C).

2.2 Research Objectives and Hypotheses

Amount of main elements and trace elements in the various biochar will be analyzed and the mobility of these elements assessed through batch leaching at 4 target pHs (ambient, 4.0, 5.5 and 7.0)

The Research objectives for this work are to:

1. Evaluate the effect of pyrolysis temperature on the presence of main and trace elements in the biochar (main elements defined in section 6.1)
2. Develop a method for leaching elements from biochar at a desired pH
3. Evaluate how pH affects the leaching of elements from biochar
4. Relate the production conditions/biochar properties to observed leaching behavior
5. Investigate which of the biochar produced will be best suited for soil quality improvement in agriculture

Based on the objectives stated above, the thesis has the following hypothesis:

1. The concentration of trace elements can be reduced by increasing pyrolysis temperature, while at the same time retain certain elements with nutritional value
2. Leaching of elements in biochar is pH dependent

3. MATERIALS AND METHODS

3.1 Feedstocks for Biochar

The feedstocks used for the biochar were:

- Clean wood chips (CWC) - Clean wood pellets were bought from Hallingdal Trepellets AS and were not pretreated before pyrolysis.
- Waste timber (WT) - The waste wood was put in a wood chipper to reduce size to about 1 – 2 cm which were then pelletized
- Digested sludge from Lindum (DSL) and Movar waste water treatment plant (MOVAR) were dried in an industrial size pilot tumble drier unit (with an attached heat pump) made by Scanship AS which takes about 2 tonnes of sludge per run. The dried powdered sludge is then pressed into pellets, before pyrolysis as shown in fig 2.

Pyrolysis was at 4 different temperatures (500°C, 600°C, 700°C, 800°C (or 750°C) and analyzed for concentration of elements of interest in this study: Arsenic (As), Barium (Ba), Calcium (Ca), Cadmium (Cd), Cobalt (Co), Chromium (Cr), Copper (Cu), Iron (Fe), Potassium (K), Magnesium (Mg), Molybdenum (Mo), Sodium (Na), Nickle (Ni), Phosphorus (P), Lead (Pb), Sulfur (S), Silicon (Si), Strontium (Sr), Vanadium (V) and Zinc (Zn).

To estimate the concentration of elements that will leach from biochar in soils with different pHs, the biochar were leached at four target pHs (ambient, 7, 5.5, 4) through batch leaching; ambient pH is the unaltered pH of biochar, i.e, biochar and only deionized water solution. This study was carried out at Lindum As, Drammen, Norwegian Geotechnical Institute (NGI), Oslo and the Faculty of Environmental Sciences and Natural Resource Management (MINA) at the Norwegian University of Life Sciences (NMBU), Ås, as illustrated in fig 1.

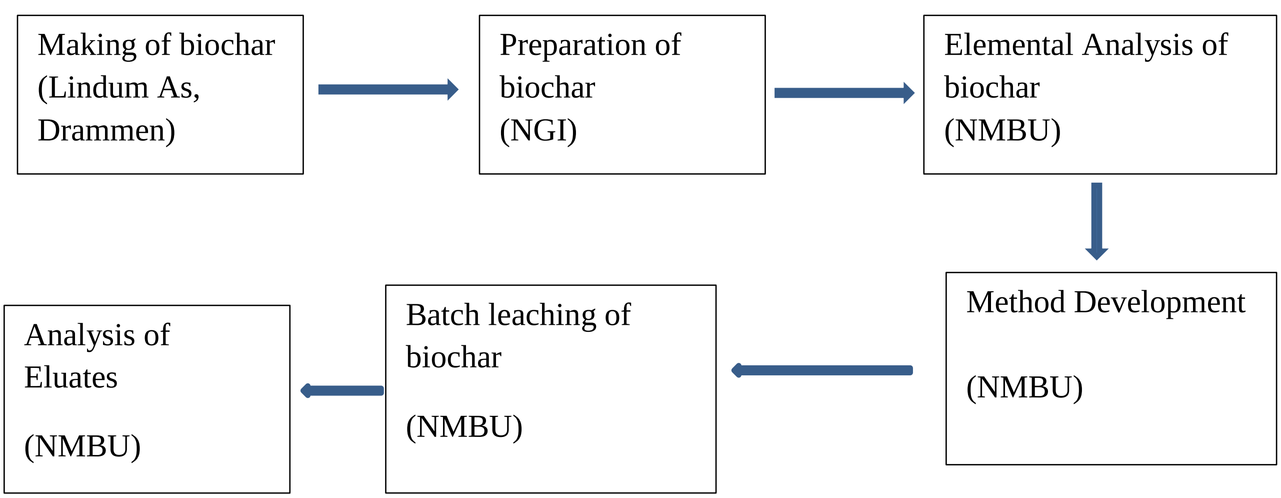


Fig 1. Summary of the materials and methods carried out in this study

Fig 2. Pellets of digested sludge

3.2 Making of biochar

As illustrated in fig 3, a medium scale Biogreen pyrolysis equipment with an electrically heated Spirajoule was used to pyrolyze digested sludge [digested sludge from Lindum (DSL), and digested sludge from MOVAR (MOVAR)] and wood [waste timber (WT) and clean wood chips (CWC)] into biochar. The feedstock is fed into the chamber through an inlet. It is then transferred along the reactor and transformed by the temperature in the pyrolysis chamber, thus the spirajoule transfers the heat to the feedstock. Conditions of processing are uniformly maintained in the pyrolysis chamber to ensure uniform material conversion. The residence time of the product is determined by the speed of the spirajoule which is set by the operator. Gases from the pyrolysis are channeled through a condenser which condenses gases with the appropriate temperature to oil. The remaining gases are transferred to a burner where they are combusted at about 800^{o}C along with a small flow of propane

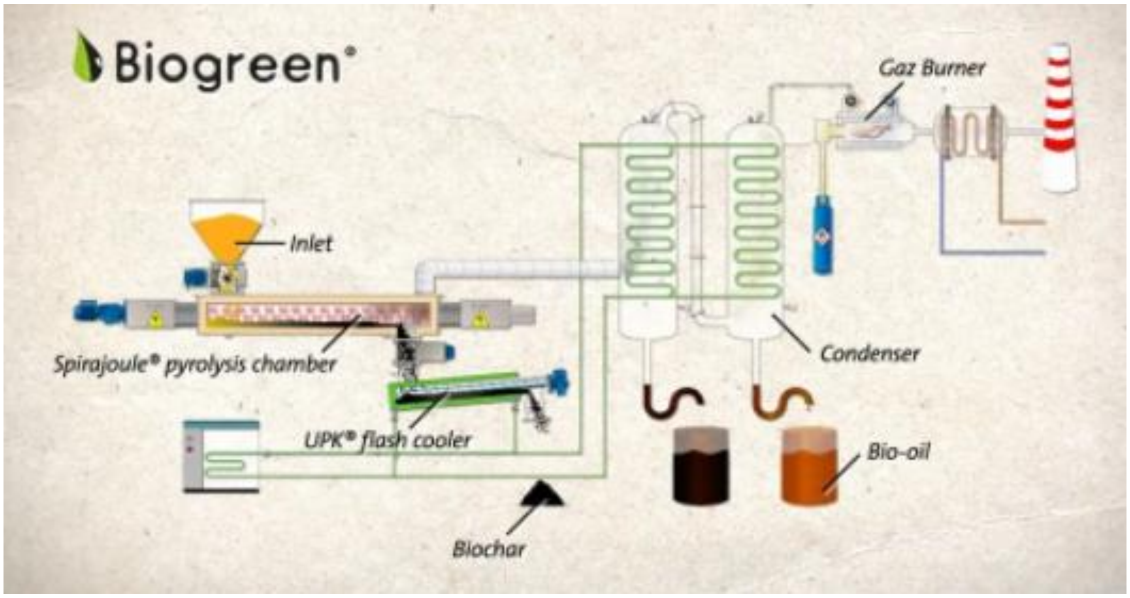


Fig 3. Principle of the Biogreen pyrolysis equipment. Heat for pyrolysis is from a cylindrical metal in the pyrolysis chamber (Source: https://www.biogreen-energy.com/pyrolysis-equipment, Accessed 15th May, 2022)

3.3 Preparation of biochar

Bulk samples of 2-10kg were made during each pyrolysis run, depending on the feedstock. About 150g of sub samples were taken from each bulk sample by random grab sampling. The sub samples were air-dried and milled in a Retch S1 ball mill at 50 rpm. Biochar made at 500°C and 600°C were milled for 5 minutes while biochar made at 700°C and 800°C (or 750°C) were milled for 10 minutes because they were harder. After milling, sub-samples were passed through a 1mm RETCH sieve (DIN 4188, stainless steel) to ensure particle size were less than 1mm.

3.4 Elemental Analysis of biochar

Each biochar was analyzed for concentrations of elements of interest in this study: As, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mo, Na, Ni, P, Pb, S, Si, Sr, V and Zn using inductively coupled plasma optical emission spectroscopy (ICP-OES) and inductively coupled plasma mass spectrometry (ICP-MS) according to standard procedures (EPA, "Method 7473", with some adjustments). Analyses were carried out in triplicates for all samples.

About 0.15g of biochar was measured in Teflon tubes to which 5ml of nitric acid and 1ml of water was added. Sample series were then decomposed by Ultraclave-Milestone instrument up to 260°C for 90 mins. Samples were allowed to cool, diluted up to 50mL in plastic ultrapure tubes (Sarsted, Germany- product) and analyzed by ICP-OES Agilent 5100 and ICP-MS 8800 triple quad Agilent. Blanks and were analyzed and corrected for as well as reference samples.

3.5 Method Development

To be able to leach biochar at a desired pH, a method development was carried out as no established methodology was found to do such a test. Several different approaches were carried out as summarized in fig 4. Leaching biochar at a specific pH was difficult because biochar buffers the pH in several pH ranges due to the buffering mechanisms of different minerals and functional groups in the biochar matrix. To keep a biochar-water solution at a specific pH, the buffering capacity need to be broken without dropping to a pH below what is wanted. Also, the pH doesn't have to change significantly throughout the duration of the leaching test (because there is a mix of slow and fast buffering mechanisms).

For titrations, biochar were put in tubes (10 – 20 tubes, 5ml for each biochar) which were then weighed to determine the weight of biochar in the tube. Different volumes of deionized water were added to biochar as outlined in appendix A. Titrations were carried out by adding different volumes of 1M HCl (unless otherwise stated) to the biochar-deionized solution to get a solid liquid ratio of 1:5, see appendix A. The solutions were stirred at regular intervals and pH's measured at 4, 8, 24, 48, 72, 144 hours (Unless otherwise stated) after HCl addition. pH measurements were taken when biochar had settled at bottom of solution

All pH measurements were done with PHM210 Standard pH meter (Radiometer, MeterLab®) with a glass electrode (Thermo Scientific™ Orion™ 8172BNWP ROSS™ Sure-Flow™). Calibrations were done with pH 4 and pH 7 buffer solutions.
To determine how much HCl to add to a biochar solution to get a desired pH for the batch leaching tests, plots of pH values in appendix A were generated; Appendix B

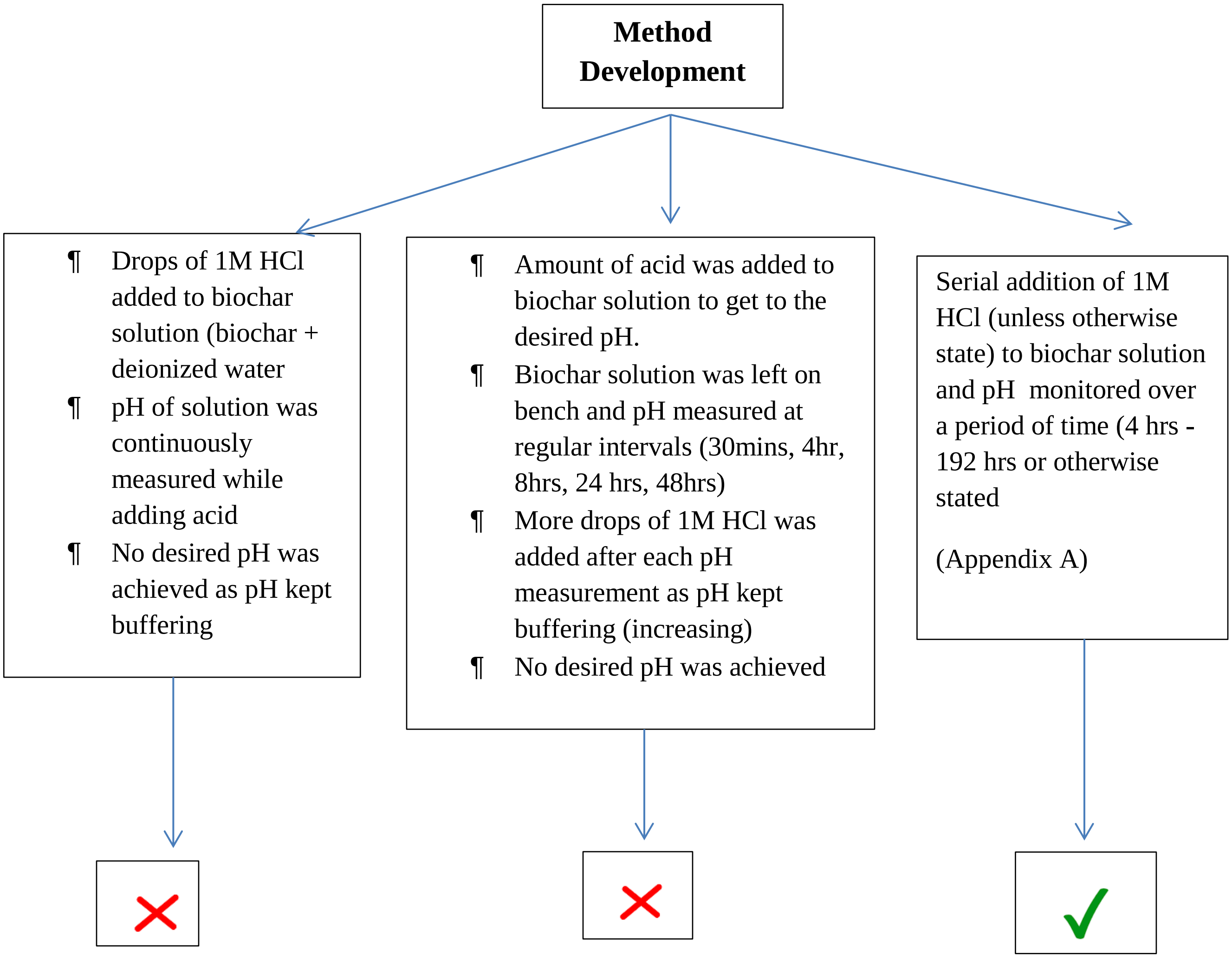


Fig 4. Summary of method development

3.6 Batch leaching test

To estimate the concentration of elements from biochar that will leach in soils at different pHs, a batch leaching test was carried out according to EPA *Method 1313* - "Liquid-Solid Partitioning as a Function of Extract pH for Constituents in Solid Materials using a Parallel Batch Extraction Procedure" with some modifications.

The batch leaching was carried out in triplicates with a biochar to liquid (deionized water and HCl) ratio of 1:5. Leaching was done at four target pHs (ambient pH, 7.0, 5.5 and 4.0) for each biochar. The pHs were achieved by adding appropriate volumes of 1M HCl (Unless otherwise stated) to biochar solution at regular intervals (8, 24 and 48 hours, see appendix C). The volumes of HCl added were estimated from plots generated in 'method development'. The volumes of HCl were added in batches to avoid a sharp drop in pH of biochar solution which would affect the leaching of the metals, appendix C.

The samples were kept at room temperature on the bench and the solution shaken at regular intervals after 4hrs, 8hrs, 24hrs, 30hrs, 48hrs and 54hrs by hand. The supernatant was decanted and filtered through 0.45µm Whatman filter pater on the 72nd hour after first HCl addition. An illustration of the batch leaching process is in fig 5.

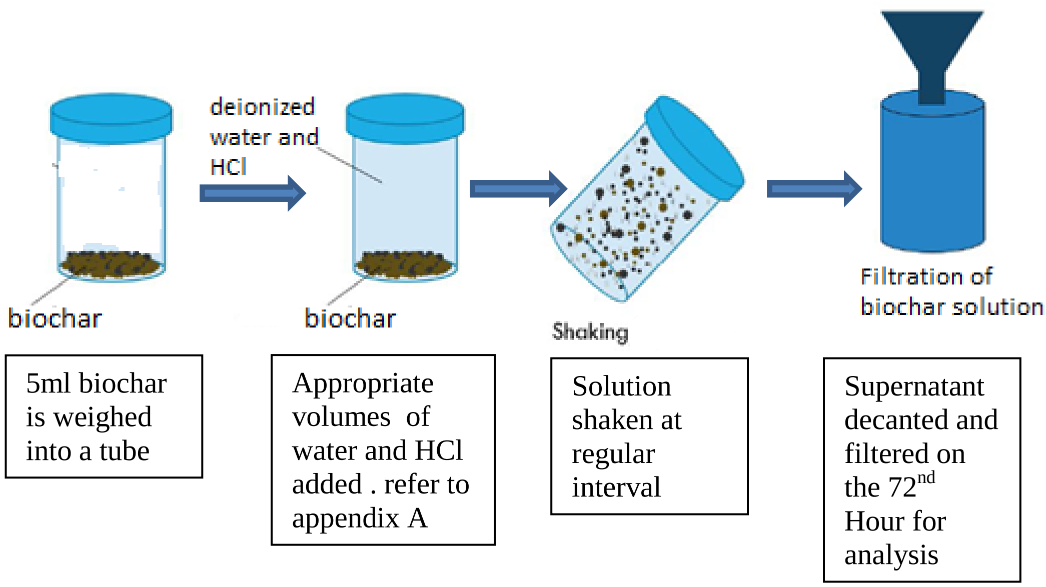


Fig 5. Illustration of batch leaching test

3.7 Analysis of Leachates

Double distillated nitric acid was added to eluates (9. 0 mL of sample +1 mL of HNO3) and samples analyzed by ICP-OES and ICP-MS instruments for the same elements as in biochar mentioned above As, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mo, Na, Ni, P, Pb, S, Si, Sr, V and Zn. Appendix E

3.8 Quality control and assurance

All analysis were done in triplicates to reduce the impact of random error. Only recommended materials (according to EPA *Method 1313*) were used and all equipment used were thoroughly washed and dried before using to minimize sample contamination.

Certified material were decomposed and analyzed together with samples to check analysis quality, precision, accuracy and recovery for all elements. Laboratory blanks were also used for determination of LOD (limit of detection) and LOQ (limit of quantification).

4. DATA ANALYSIS

Means and standard deviations of elements were calculated from the triplicates of each sample for both biochar and eluates. These are the values used for the respective analysis of data

Calculation of amount of element leached in kg of biochar

Elements leached in eluates were converted from µg/L to µg/kg for trace elements and mg/L to mg/kg for major elements:

$$\underset{(\text{mg/kg or } \mu\text{g/kg})}{LA} = Q_{(mg/L)} * \left[\frac{(V_{(mL)}/1000)}{(W_{(g)}/1000)} \right]$$

Where, LA = Leachable amount of elements

Q = Concentration of element in eluate

V = Volume of liquid used in batch leaching

W = Weight of biochar used in batch leaching

In instances where the measured value of element was less than LOQ, half the value of LOQ was used.

Percentage Element Leached:

The % of leached element was estimated by dividing the concentrations of element in eluate by the concentrations of respective element in biochar:

$$PL = \left[\frac{E\ (\text{mg/kg or } \mu\text{g/kg})}{B\ (\text{mg/kg or } \mu\text{g/kg})} \right] * 100$$

Where, PL = Percentage of elements leached

E = Mean concentrations of element in eluate

B = Mean concentrations of element in biochar

5.STATISTICAL DATA TREATMENT

A multiple linear regression analysis, in R programing was used to estimate the relationship between the leaching of trace elements (Cu and Zn) and the factors affecting leaching for a subset of the data. Zn and Cu were chosen because concentrations of both elements were higher than European Biochar Certificate (EBC) limits in all biochar except clean wood chips biochar (CWC). The parameters included in the regression analysis were feedstock used for biochar (Feedstock), Pyrolysis temperature (Temp), pH at which elements were leached (ph), Aluminium concentration in biochar (Al) and Fe concentration in biochar (Fe). The final selection of the variables that affect leaching of Zn and Cu was based on the stepwise regression analysis where the Akaike's ‘An Information Criterion method. (AIC) was used to choose to the best model.

6. RESULTS AND DISCUSSION

6.1 Overview of main and trace elements in all biochar

The elements of interest in this study (As, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mo, Na, Ni, P, Pb, S, Si, Sr, V and Zn) were grouped into main and trace elements based on relative abundance and requirement by plants:

1. Main elements: Ca, Fe, K, Mg, Na, P, S, Si. The focus on main elements was narrowed down to elements that are useful nutrients for plants, i.e, Ca, Fe, K, Mg, Na, P. Though Fe is a trace element from a nutrient perspective, It is classified as a main element in this study (due to high concentrations found in biochar). From here forward, these elements listed above will be referred to as main elements.
2. Trace elements: As, Ba, Cd, Co, Cr, Cu, Mo, Ni, Pb, Sr, V and Zn. The focus on trace elements was also narrowed down to the most toxic ones, i.e, As, Cd, Cr, Co, Cu, Ni, Pb and Zn. It is worth noting that Co, Cu and Zn are essential micronutrients for plants up to a critical threshold where they become problematic.

An overview of the main elements in biochar is given in fig 6a and 6b (zoomed), plotted from means of concentrations of elements in biochar, Appendix D.

The wood biochar, ie waste wood and clean wood chips biochar (WT and CWC respectively) had a smaller concentrations of main elements compared to the digested sludge from Lindum and MOVAR biochar (DSL and MOVAR respectively) figs 6a and 6b; the concentrations of elements with nutritional value in biochar is dependent on the concentrations of the elements in the feedstock and the pyrolysis temperature (Rajkovich et al., 2012). Sludge is characterized by high concentrations of some of the main elements considered in this study, for instance, P and K, as well as micronutrient content (Rajkovich et al., 2012); wood-based biochar however have low concentrations of these elements but high in lignin and cellulose (Piash et al., 2021) hence the low concentrations of main elements in the wood biochar compared to the digested sludge biochar.

Digested sludge biochar (DSL and MOVAR) had the most Fe compared to the other biochar, $FeCl_3$ (Iron chloride) is used as a flocculent in the treatment of wastewater to remove micro-organisms and suspended solids (Tolkou et al., 2015). The high level of Fe in DSL than MOVAR biochar could be due to the usage of high levels of Fe in the treatment of wastewater in DSL than the Fe used in the treatment of wastewater in MOVAR. Additionally, Lindum As (source of DSL) uses the Cambi method for its sludge digestion process for biogas production (Cambi ASA., 2021). The Cambi method is more comprehensive than the traditional digestion method employed in the digestion of MOVAR. It also gives rise to sludge with less volatiles, resulting in an up-concentration of the non-degradable elements such as Fe (Abu-Orf & Goss, 2012).

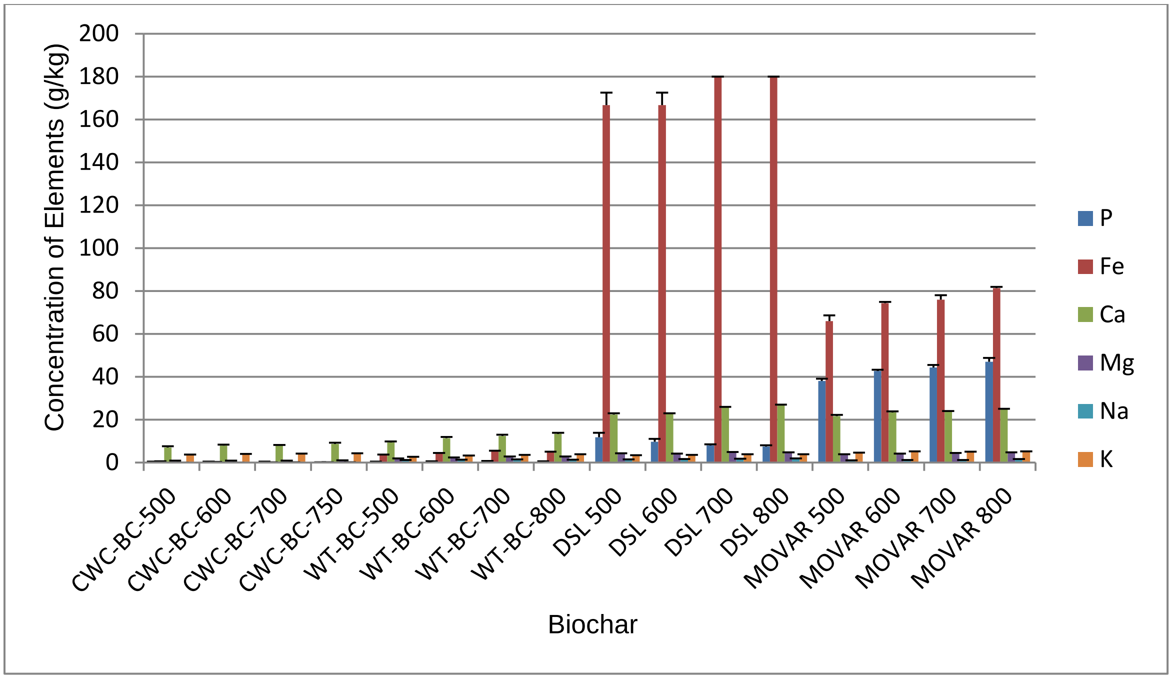


Fig 6a: Overview of Main elements in biochar. *(CWC = clean wood chip, WT= waste timber, DSL = digested sludge from Lindum, MOVAR = digested sludge from MOVAR, BC= biochar, Number attached to biochar is pyrolysis temperature used in making biochar, Error bars = Standard deviations of means of elements, n=3).*

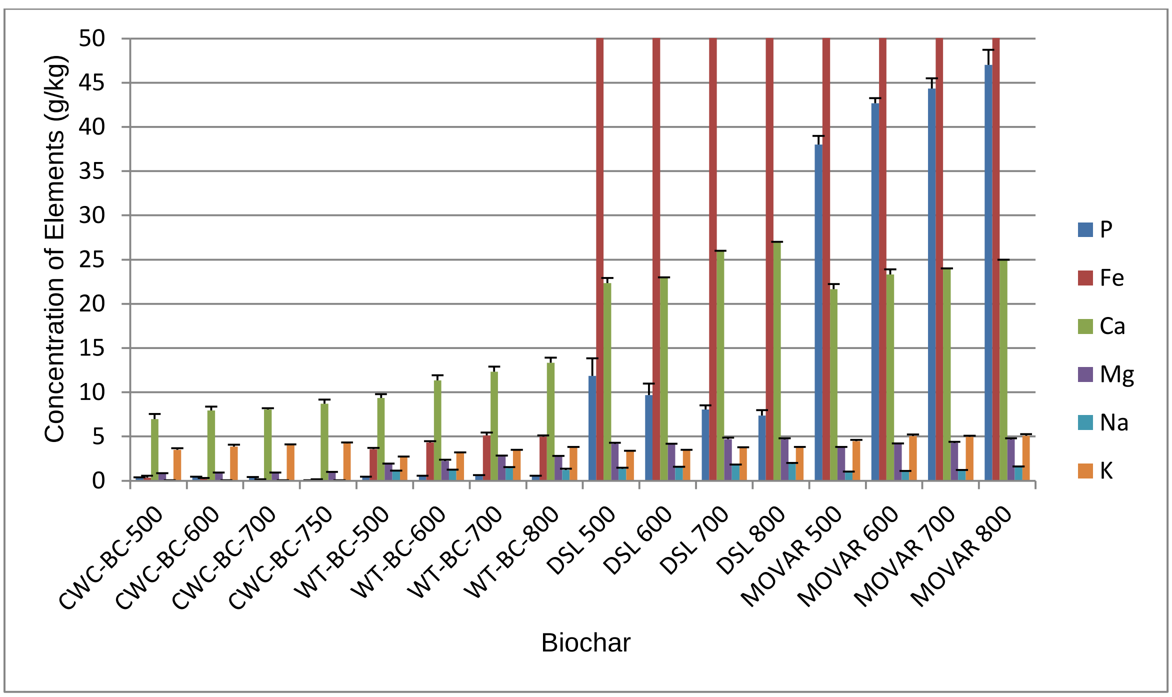


Fig 6b: Overview of Main elements in biochar (**fig 6a zoomed**). *(CWC = clean wood chip, WT= waste timber, DSL = digested sludge from Lindum, MOVAR = digested sludge from MOVAR, BC= biochar, Number attached to biochar is pyrolysis temperature used in making biochar, Error bars = Standard deviations of means of elements, n=3).*

Increasing pyrolysis temperature from 500^{o}C through to 800^{o}C did not decrease the amount of main elements, i.e, Ca, Fe, K, Mg, Na, P in biochar, fig 7 . Thus, the main elements did not volatilize but remained in the final mass. These main elements increased with increase in pyrolysis temperature; increasing pyrolysis temperature results in loss of volatile compounds and moisture evaporation hence a decrease in yield (Appendix J), and enrichment of the above mentioned main elements (Agrafioti et al., 2013).

P however decreased (CWC - 90%, WT – 13%, DSL – 9%, of concentrations at 700^{o}C -800^{o}C) except in MOVAR biochar, fig 7; Several studies have found P in sludge biochar to be in inorganic form and also volatilize at temperatures above 700^{o}C (Hossain et al., 2020; Yuan et al., 2016). P not decreasing in MOVAR could be due to the prevalent form of P in MOVAR having a boiling point higher than the pyrolysis temperatures used hence P did not decrease in MOVAR biochar (Lu et al., 2015).

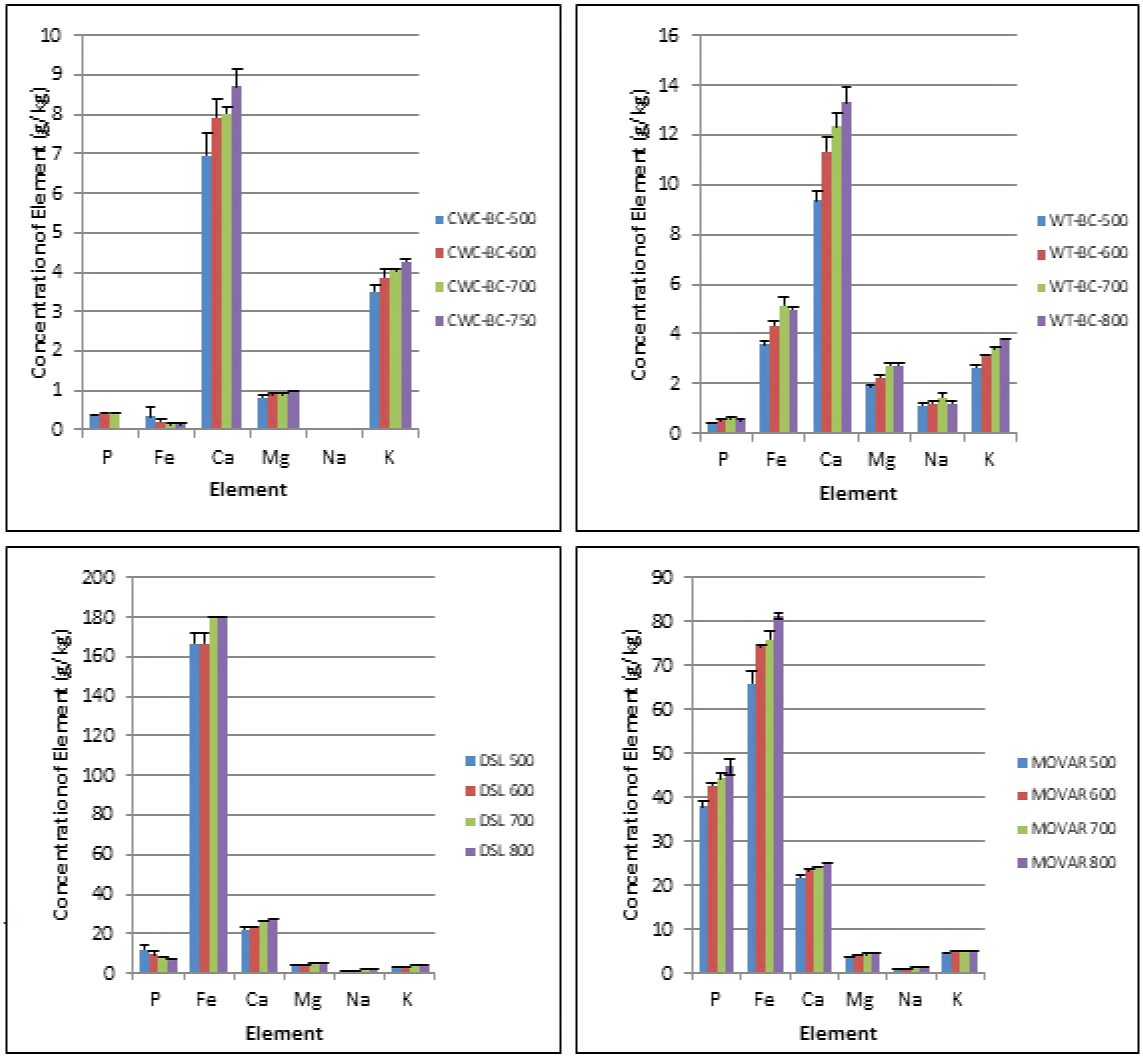


Fig 7 Comparison of main elements in biochar at different pyrolysis temperatures (CWC = clean wood chip biochar, WT= waste timber biochar, DSL = digested sludge from Lindum biochar, MOVAR = digested sludge from MOVAR biochar, Number attached to biochar is pyrolysis temperature used in making biochar, Error bars = Standard deviations of means of conc. of elements, n=3. *Top left = CWC, top right = WT, bottom left = DSL, bottom right = MOVAR).*

6.2 Concentrations of main elements in biochar in relation to commercial fertilizers

The amount of N, P and K in commercial fertilizers is dependent on the type of fertilizer. For instance a 20-5-5, 10-10-10, 20-20-20 depicts the percentages of these nutrients in the fertilizer (Ayoub A.T., 1999). Table 1 Shows the percentages of P and K in the various biochar. Except MOVAR biochar, the percentage of P in all the other biochar was about 1%. Percentage K was less than 1 in all biochar. Thus the percentages of P and K in biochar were lesser than their respective percentages in commercial fertilizers.

Table 1: Percentages of P and K found in the various biochar pyrolyzed at different temperatures

Biochar	% of Element in biochar	
	P (%)	K (%)
CWC-BC-500	0.04	0.35
CWC-BC-600	0.04	0.39
CWC-BC-700	0.04	0.40
CWC-BC-750	0.00	0.43
WT-BC-500	0.04	0.27
WT-BC-600	0.05	0.31
WT-BC-700	0.06	0.34
WT-BC-800	0.05	0.38
DSL 500	1.18	0.33
DSL 600	0.97	0.35
DSL 700	0.80	0.37
DSL 800	0.74	0.38
MOVAR 500	3.80	0.45
MOVAR 600	4.27	0.50
MOVAR 700	4.43	0.50
MOVAR 800	4.70	0.51

(CWC = clean wood chip, WT= waste timber, DSL = digested sludge from Lindum, MOVAR = digested sludge from MOVAR, BC= biochar, Number attached to biochar is pyrolysis temperature used in making biochar).

Although total P, K is not an expression of plant available P and K, there is a correlation between total concentrations of P and K and the plant available fractions. For instance, zero concentrations of P and K will mean no availability of these main elements for plant while a high concentration increase the potential plant available fraction. The focus of adding these biochar to agriculture soils should therefore not be to provide essential plant nutrient, as to improve other important soil characteristics such as increased soil CEC, acid neutralizing capacity or increased pH, water retention and infiltration, etc as discussed in section 1.2. The above mentioned characteristics of biochar also helps improve plant productivity. For instance, in sandy and acidic soils, biochar with high ash content improved plant productivity due to its liming effect as well as nutrient use efficiency (Dai et al., 2020). Biochar from poultry litter and cow manure improved crop yield 42% and 150% respectively though the concentrations of P and K were similar to what was found in this study (Ding et al., 2016) .

Other studies have shown similar contents of P and K as found in this study. For instance, Tsai et al 2012, found swine manure biochar to have a higher P percentage compared to wood-based biochar (Tsai et al. 2012), Roberts et al, 2015 had P and K percentages in swine manure and wood-based biochar in the ranges as found in this studies: Sawdust [P (0.01%), K (0.12%)], manure [P (0.05 – 0.44 %), K (0.1 – 0.36%)], Ligno-cellulosic P [(0.01 – 0.06%), K(0.17 – 0.52)] (Roberts et al., 2015)

6.3 Concentrations of Trace elements in Biochar

Figs 8a and 8b Shows an overview of trace elements in biochar, plotted from the means of concentrations of trace elements in biochar, appendix D

Waste timber biochar had a high total concentration of trace elements compared to the CWC biochar, The processing of wood (from which waste timber was obtained) contributes to the high concentrations of some of the trace elements. For instance high concentrations of As, Cu and Cr (figs 8a and 8b) is due to the usage of Chromated copper arsenate (CCA) in wood impregnation to protect it from insects and microbial attack (Rabajczyk et al., 2020). Waste timber contains all kinds of wood products that are lightly contaminated but not impregnated. Though CCA impregnated wood is treated separately at waste handling sites, some of these impregnated woods end up in the waste timber fraction due to improper handling at the waste site, insufficient information on the wood material being treated with CCA, or some degree of negligence.

The concentration of Zn was high in waste timber biochar (WT) as well as the digested sludge biochar (DSL and MOVAR) figs 8a and 8b. The high concentrations of Zn in WT biochar could be from the remains of Zn-plated nails in the waste timber (Sormo et al., 2020). Also ZnO (Zinc oxide) is a coating used to preserve wood and also as a UV stabilizer (Salla et al., 2012). Cu and Zn are widely used in industries such as paints and dyes, fertilizer and pesticides production, mining, etc. The wastewater from these industries have high concentrations of the Cu and Zn which end up in the sewage sludge (V.G et al., 2016) hence the high concentrations of Zn and Cu in DSL and MOVAR. Also the usage of galvanized pipes in the treatment of waste water could have contributed to the high levels of Zn in the sewage sludge (Lee et al., 2018)

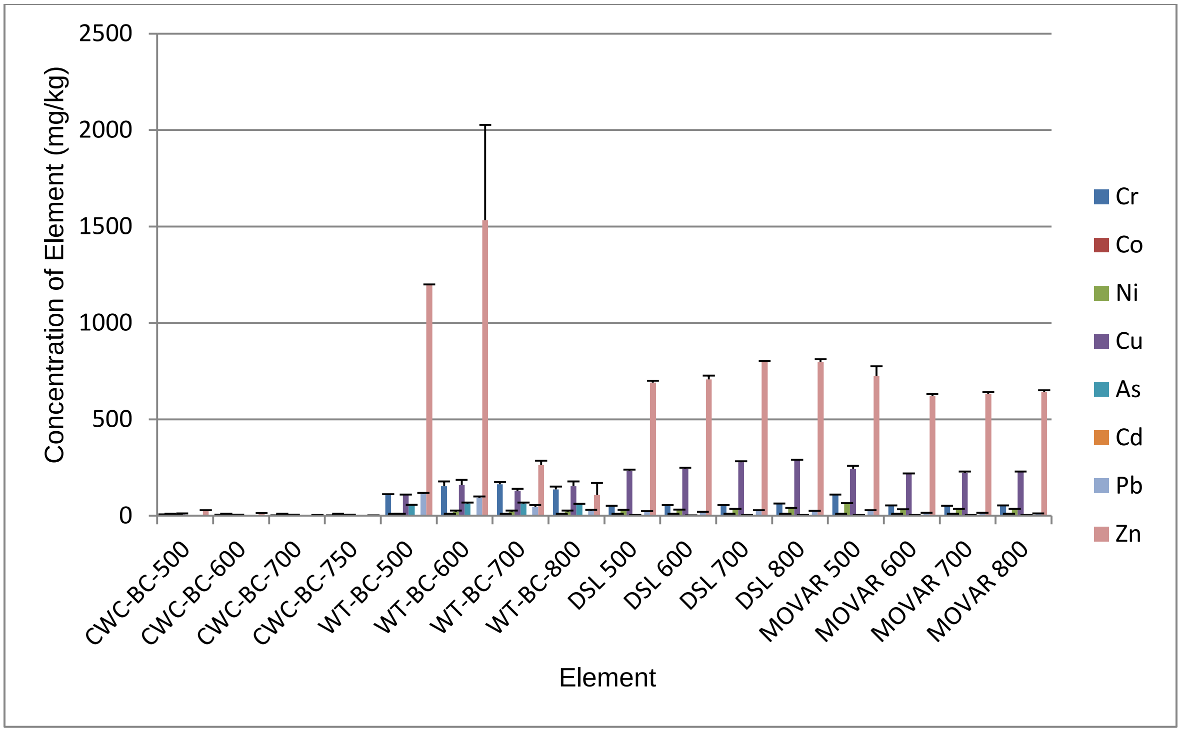


Fig 8a. Overview of trace elements in biochar. *(CWC = clean wood chip, WT= waste timber, DSL = digested sludge from Lindum, MOVAR = digested sludge from MOVAR, BC= biochar, Number attached to biochar is pyrolysis temperature used in making biochar, Error bars = Standard deviations of means of conc. Of elements, n=3).*

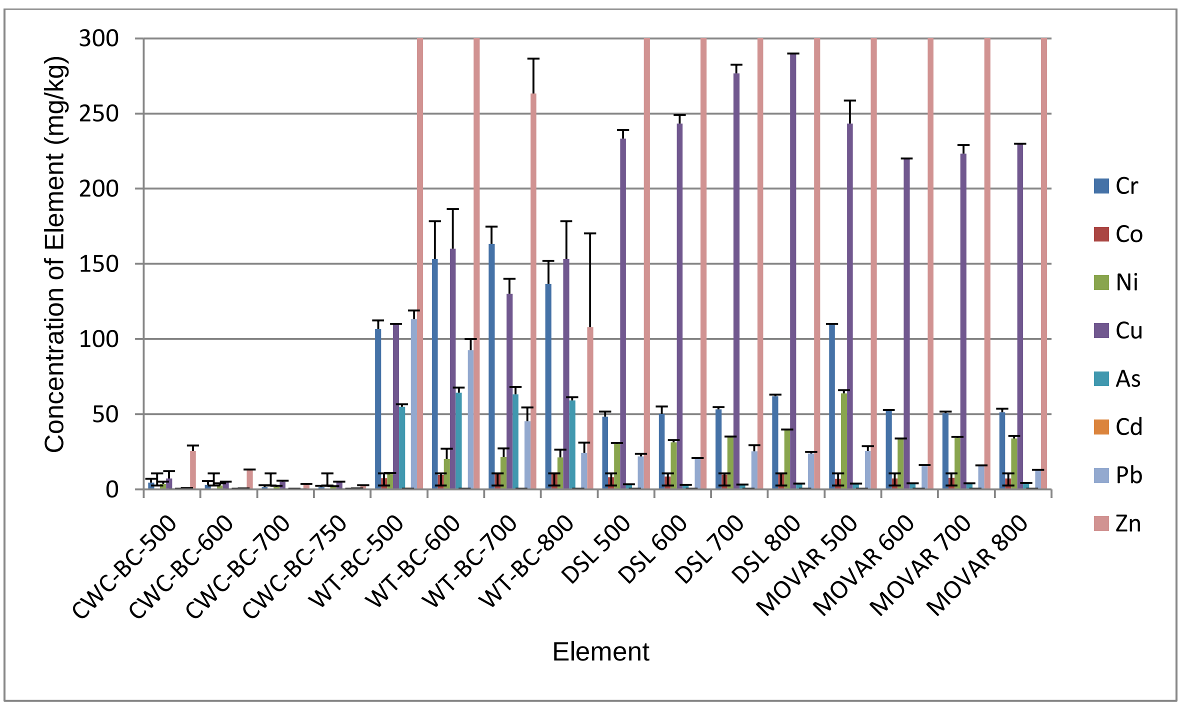


Fig 8b (**fig 8a zoomed**) Overview of trace elements in biochar. *(CWC = clean wood chip, WT= waste timber, DSL = digested sludge from Lindum, MOVAR = digested sludge from MOVAR, BC= biochar, Number attached to biochar is pyrolysis temperature used in making biochar, Error bars = Standard deviations of means of conc. Of elements, n=3).*

6.4 Effect of Pyrolysis Temperature On Trace elements

To test hypothesis 1 of this study (i.e, the concentrations of trace elements can be reduced by increasing pyrolysis temperature, while at the same time retain certain elements with nutrient value), concentration of trace elements in biochar at the different pyrolysis temperatures were compared with EBC (European Biochar certificate) limits as well as the appropriate standard of the European Union's (EU's) fertilizer framework directive. 'EBC class is an admissibility of biochar for a given purpose regarding applicable laws, regulations and relevant industry standards', EBC (2012-2022).

Because the 4 biochar in this study potentially will be used to improve agricultural soil properties, the 2 EBC classes related to the usage of biochar for agricultural purposes were chosen for the comparison of levels of trace elements:

1. EBC Agro - Biochar certified with EBC-Agro meet all requirements of the new EU fertilizer product regulation, EBC (2012-2022).

2. The EBC-AgroOrganic – In addition to meeting all requirements of the new EU fertilizer product regulation, it also meets all requirements of the EU Commission regulation on organic production, EBC (2012-2022)

Figs 9a and 9b shows a comparison of the trace elements of interest with the 2 EBC classes mentioned above (Pink line represents EBC AgroOrganic limits, red line represents EBC Agro limits).

Cr concentrations in waste timber (WT) biochar were beyond both EBC Agro and EBC AgroOrganic limits but lower than these limits in all other biochar. Increasing pyrolysis temperature did not reduce the concentrations of Cr in WT biochar to the EBC limits. Cr concentrations in MOVAR at pyrolysis temperature of 500^{o}C (MOVAR 500) was higher than EBC AgroOrg and EBC Agro limits but increasing the temperature to 600^{o}C reduced Cr levels to acceptable limits. Increasing pyrolysis temperature rather seemed to increase the amount of Cr but this seemingly increase is due to reduction in yield as shown in appendix J, Fig 9a.

There are no EBC limits for Co but increasing pyrolysis temperature accumulated the amount of Co in all biochar except clean wood chips biochar. Thus, Co did not evaporate with increase in pyrolysis temperature, fig 9a.

The wood biochar (WT and CWC) had acceptable limits of Ni for agriculture use according to EBC limits. In the digested sludge (DSL and MOVAR) biochar however, Ni concentrations exceeded EBC Agro-Organic levels but were acceptable for EBC Agro limits. Increasing pyrolysis temperature did not decrease Ni concentrations to EBC Agro Organic limits Fig 9a.

Cu concentrations in all biochar, except CWC (Clean Wood Chip biochar) exceeded EBC limits for both EBC AgroOrganic and EBC Agro. Increasing pyrolysis temperature did not reduce the concentrations of Cu in biochar, fig 9a

Fig 9b shows As levels in all biochar were within EBC Agro and EBC AgroOrganic limits except biochar from waste timber (WT) which did not decrease with increasing pyrolysis temperature.

Under reducing conditions as found in pyrolysis, Cr, Ni, Cu, As exist as sulfides or as elemental forms (Dong et al., 2015). The increasing of pyrolysis temperature not decreasing the concentration of these trace elements (thus lower volatilization) could be due to the pyrolysis temperature being lower than the boiling point of the prevalent specie of these metals present in biochar (Lu et al., 2015). The high concentration of Cr in MOVAR decreased with increasing pyrolysis temperature ($500^{o}C$ – $600^{o}C$), thus the prevalent form of Cr in MOVAR had a boiling point within this temperature range hence was volatilized.

Though Cd concentrations in waste timber, MOVAR and DSL were higher than EBC AgroOrganic limits (but lower than EBC Agro limits), increasing pyrolysis temperature reduced the amount of Cd in biochar to below EBC AgroOrganic limits. A similar trend was observed by RC et al., 1987 , Cd is reduced to Cd^{o} during pyrolysis which is then volatilized at temperatures above 600 °C (RC et al., 1987), thus pyrolysis temperature can be used to reduce the concentrations of Cd in biochar, Fig 9b.

Pb concentrations were only high than EBC AgroOrganic and EBCAgro limits in WT (waste timber) biochar, fig 9b. However, increasing pyrolysis temperature reduced the concentration of Pb to below both EBC Agro and EBC Agro-Org limits. This trend is consistent with the findings of Hans et al, 2017. They found that Pb reacts with C compounds which make it susceptible to volatilization (Hans et al., 2017). Thus increasing pyrolysis temperature can be used to reduce the concentrations of Pb in biochar, Fig 9b.

Zn was higher than EBC AgroOrganic and EBC Agro limits in all biochar except CWC (Clean wood chips) biochar, fig 9b. Increasing pyrolysis temperature decreased Zn concentrations in WT (waste timber) biochar to below both EBC limits; this trend however was not observed in the digested sewage sludge biochar (DSL and MOVAR). In the digested sewage sludge biochar, increasing pyrolysis temperature did not reduce the concentration of Zn. This observation could be due to the Zn in the digested sludge biochar (DSL and MOVAR) being bound to other elements or compounds that make them more stable than the Zn in the WT biochar or that when Zn in digested sludge biochar volatilizes, it reacts with other elements/compounds in the gaseous phase that precipitates it back into the solid phase, Zhang et al., 2020 found a similar trend in biochar where evaporated elements precipitated back into biochar (Zhang et al., 2020)

Characteristics of trace elements in biochar at different pyrolysis temperature in some studies have shown similarities to those found in this study. For instance Dong et al, 2015 found that at pyrolysis temperature of about $700^{o}C$, Cu, Ni and Cr are retained in the solid phase while Cd, Pb and Zn vaporize (Dong et al., 2015; Lu et al., 2015).

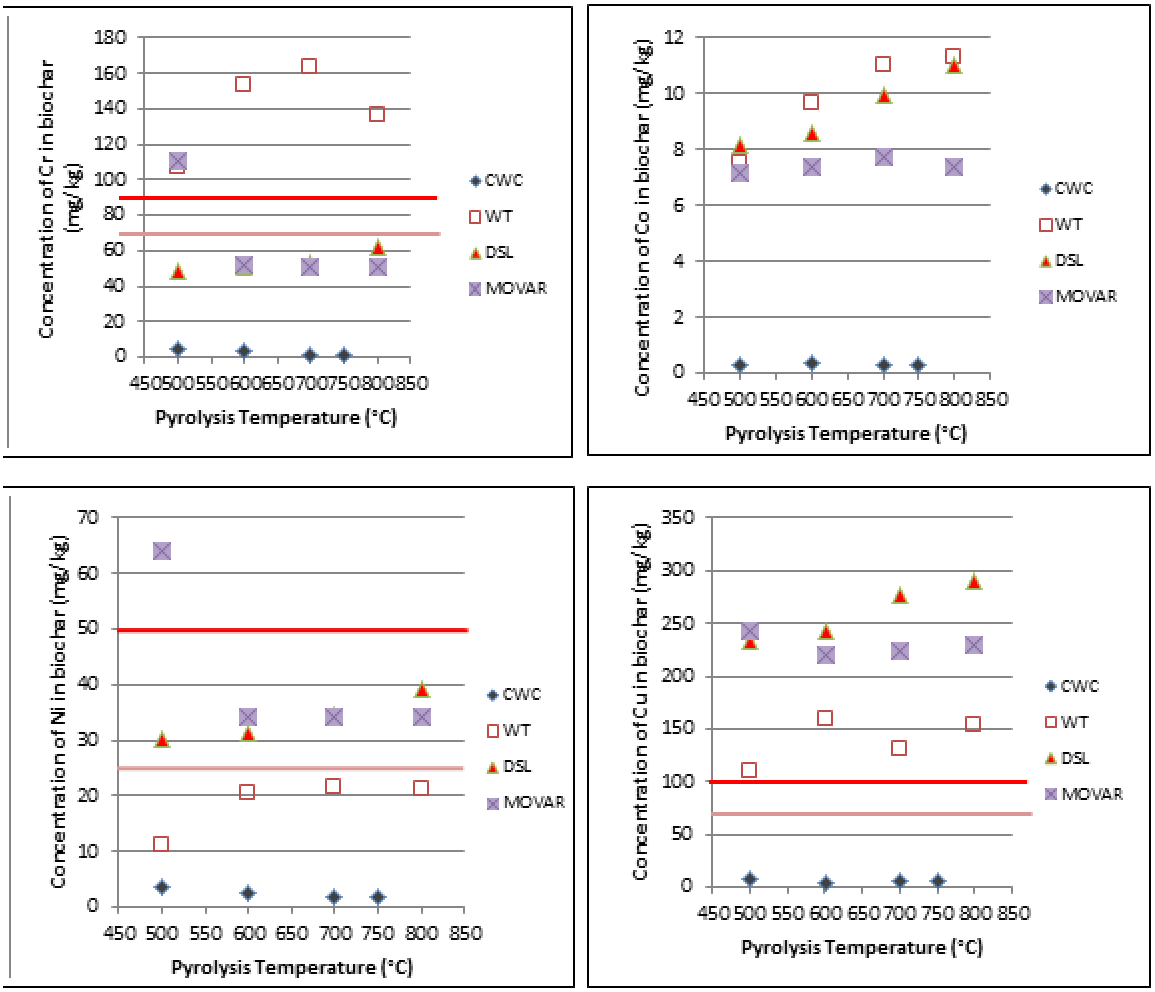


Fig 9a Concentrations of trace elements in biochar at the various pyrolysis temperatures[(*Cr: top left*, *Co: top right*, *Ni: bottom left*, *Cu: bottom right*) (CWC = clean wood chip, WT= waste timber, DSL = digested sludge from Lindum, MOVAR = digested sludge from MOVAR, BC= biochar, n=3. Red line = EBC Agro limits, Pink line = EBC Agro Organic limits)].

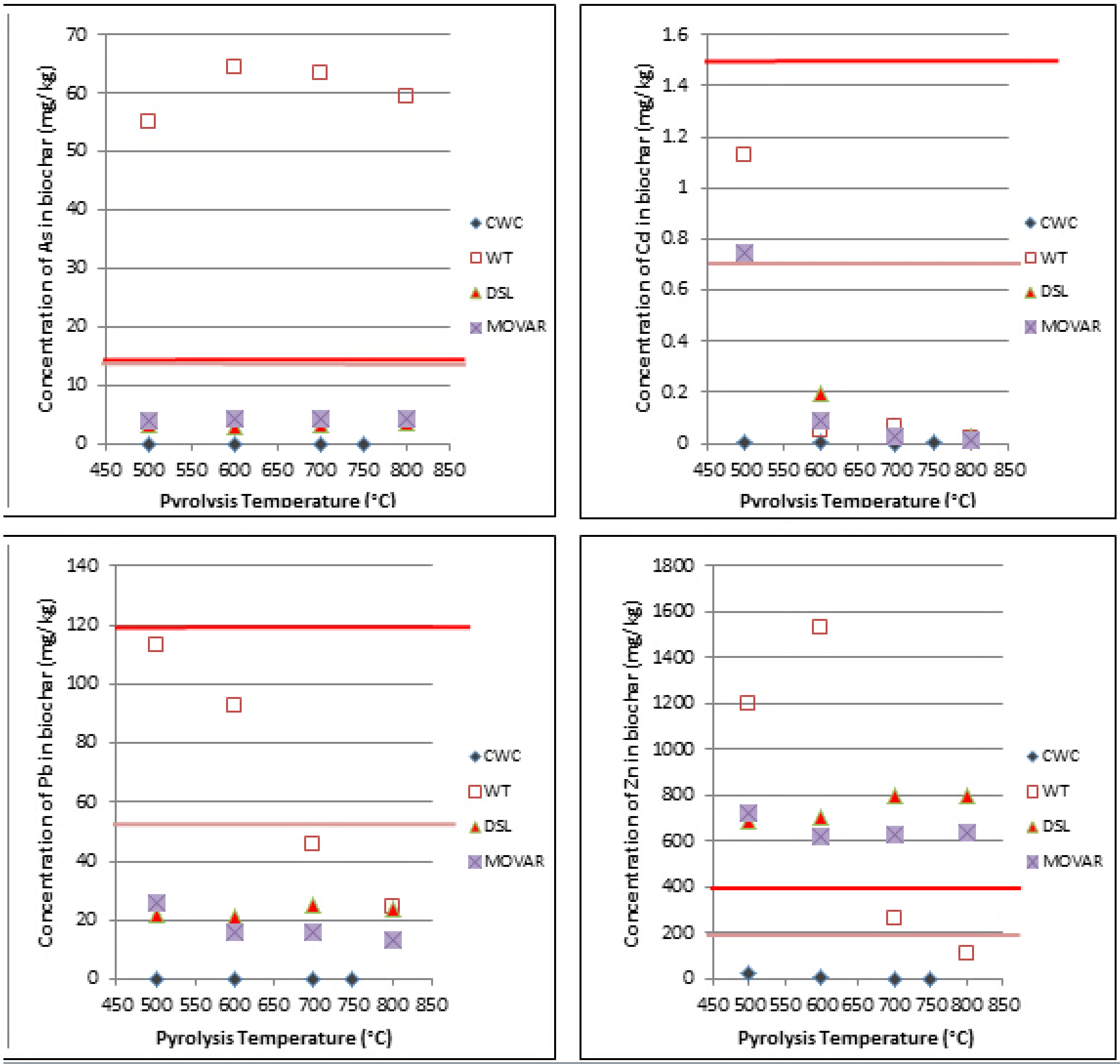


Fig 9b Concentrations of trace elements in biochar at the various pyrolysis temperatures[(*As: top left, Cd: top right, Pb: bottom left, Zn: bottom right*) (CWC = clean wood chip, WT= waste timber, DSL = digested sludge from Lindum, MOVAR = digested sludge from MOVAR, BC= biochar, n=3. Red line = EBC Agro limits, Pink line = EBC Agro Organic limits)].

Concentrations of the trace elements in biochar were also compared with threshold values for ‘contaminants’ in a solid ‘organic soil improver’ according to the European Union (EU) fertilizer framework directive Table 2. The threshold values have been listed in appendix M. As, Cd, Cu, Ni and Pb concentrations in all biochar , i.e, clean wood chips (CWC), waste timber (WT), digested sludge from Lindum (DSL) and MOVAR were lower than their respective threshold concentrations. Contrary, Cr concentrations in all biochar [(except CWC 700 (clean wood chip biochar made at pyrolysis temperature 700^{o}C) and CWC 750(clean wood chip biochar made at pyrolysis temperature 750^{o}C)] were higher than the threshold concentrations. Though the Cr concentration was high in the reference biochar, Clean wood chips biochar, (CWC 500 and CWC

600), the percentage difference was lower (130% higher for CWC 500, 55% higher for CWC 600) compared to the percentage difference in the other biochar; for instance Digested sludge Lindum made at pyrolysis temperature 500^{o}C, (DSL 500) had a percentage difference of about 2,400% from the threshold concentration, [DSL 500 had the comparative least Cr concentration amongst the other biochar i.e waste timber (WT) and digested sludge from MOVAR (MOVAR)]. Zn concentrations were lower than threshold values for all biochar except waste timber biochar (WT) made at pyrolysis temperature 500^{o}C and 600^{o}C, table 2

Table 2. Comparison of concentrations of trace elements in biochar with threshold values for an 'organic soil improver' for the Fertilizer Framework Directive of EU**.**

		Cr (mg/kg)	Ni (mg/kg)	Cu (mg/kg)	As (mg/kg)	Cd (mg/kg)	Pb (mg/kg)	Zn (mg/kg)
Biochar	Pyr. Temp	2	50	300	40	2	120	800
		Concentrations of trace elements (mg/kg) in biochar						
CWC	500	4.6	3.6	7.3	0.0	0.0	0.1	25.7
CWC	600	3.1	2.6	4.9	0.0	0.0	0.6	12.7
CWC	700	1.7	1.8	5.2	0.0	0.0	0.1	3.2
CWC	750	1.6	1.9	5.1	0.0	0.0	0.3	2.8
WT	500	106.7	11.0	110.0	55.0	1.1	113.3	1200.0
WT	600	153.3	20.3	160.0	64.3	0.0	92.7	1533.3
WT	700	163.3	21.7	130.0	63.3	0.1	45.3	263.3
WT	800	136.7	21.3	153.3	59.3	0.0	24.3	108.0
DSL	500	48.3	30.3	233.3	3.2	0.7	22.0	690.0
DSL	600	50.3	31.3	243.3	2.9	0.2	21.0	706.7
DSL	700	53.3	34.7	276.7	3.1	0.0	25.3	796.7
DSL	800	62.0	39.3	290.0	3.5	0.0	24.0	796.7
MOVAR	500	110.0	64.0	243.3	3.8	0.7	25.7	723.3
MOVAR	600	52.3	34.0	220.0	4.1	0.1	15.7	620.0
MOVAR	700	50.7	34.3	223.3	4.2	0.0	16.0	630.0
MOVAR	800	51.3	34.0	230.0	4.4	0.0	13.0	640.0

The displayed values are means (n=3) of concentrations of ICP-OES analysis of biochar. CWC = clean wood chips, WT = waste wood, MOVAR = digested sludge from MOVAR, DSL = digested sludge from Lindum . *Yellow highlighted values are threshold concentrations of the EU fertilizer framework for an organic soil improver, green highlighted values are acceptable concentrations by the EU fertilizer framework directive and red-highlighted values are concentrations higher than threshold values of the EU fertilizer framework directive for an organic soil improver.*

Comparison of trace elements concentrations in the biochar investigated in this study with European Biochar Certificate (EBC) Agro and Agro Organic limits as well as the standards for an 'organic soil improver' by EU's Fertilizer framework directive shows As, Cr, Cu and Zn as the trace elements that much attention should be paid to. Thus, As concentrations in all waste timber (WT) biochar, Cr concentrations in all WT biochar, Cu concentrations in all biochar (except clean wood chips biochar) and Zn concentrations in all the digested sludge biochar [all Digested sludge from Lindum (DSL) and all digested sludge from MOVAR (MOVAR) biochar] were higher than EBC limits. Cr concentrations were particularly high in all biochar (all WT, all DSL, all MOVAR) when compared with EU's fertilizer framework directive; Zn concentrations in waste timber (WT 500 and WT 600) were also high.

Though DSL and MOVAR had some concentrations of trace elements higher than the 2 standards, waste timber biochar was the biochar with the most concentrations of trace elements higher than threshold limits when compared with the European fertilizer framework directive and the European Biochar Certificate. Thus As and Cu (EBC limits), Cr (both EBC and EU fertilizer framework directive) were beyond acceptable limits in all waste timber (WT) biochar. Zn (EU fertilizer framework directive) was also high in WT 500 and WT 600, see figs 9a, 9b and table 2.

6.5 Titrations

The pHs of the biochar solution at hours 4, 8, 24 and 48 buffered. However they were stable at hour 72hrs hence the the 72nd hour was chosen as the appropriate hour for batch leaching. pH measurements at the various selected hours is given in appendix A

6.6 Leaching of Main Elements

Leaching of main elements in biochar was not prioritized because the percentage concentration of main elements, for instance, P and K were lower than the what is found in commercial fertilizers, table 1. Therefore adding these biochar to soils may not contribute significantly to soil nutrient improvement. However the additional benefits of biochar addition to soil as discussed under section 1.2 should be the focus.

6.7 Leaching of trace elements

The leaching of trace elements were analyzed through a batch leaching test as described in section 3.6 of materials and methods, data for leaching of all trace elements considered in this study is in appendix E. The focus on leaching in this study was on elements which were higher than EBC AgroOrganic and EBC Agro limits (Co is not considered because it does not have any EBC limit) and which did not decrease with increasing pyrolysis temperature, thus:

- As - in waste timber (WT) biochar
- Cr – in waste timber (WT) biochar
- Ni - in sewage sludge biochar (DSL and MOVAR)
- Zn – in sewage sludge (DSL and MOVAR) biochar
- Cu – in all biochar except clean wood chips (CWC) biochar

Though Cd and Pb concentrations were high in some of the biochar fig 9b, , increasing pyrolysis temperature decreased the amount of these trace elements in biochar to within acceptable EBC Agro Organic and EBC Agro limits. Also, the high Zn levels in WT biochar were reduced by increasing pyrolysis temperature.

Generally, leaching of trace elements increased with decreasing pH for each pyrolysis temperature. The decrease in pH increases the solubility of the metal hence an increase in leachability, (Zheng & Zhang, 2011)

Figs 10a, 10b and 10c show the leaching fractions of the above mentioned trace elements plotted from percentage leached data, appendix H. Leaching of Zn and As, decreased with increasing pyrolysis temperature. As temperature increases only the stable species of trace elements remain in biochar, hence leaching is reduced. This is consistent with other findings (Li et al., 2020; Lin et al., 2017), where the leaching of trace elements in biochar decreased with increase in pyrolysis temperature. However at target pH 4 the leachable amount of As increases with increase in pyrolysis temperature. It is suggestive that As could be bound to oxides for instance Fe in biochar acting as a carrier leaching for As, increasing pyrolysis temperature dissociates the oxide bond hence as the pH is lowered to pH of 4, the leaching increases, appendix L shows concentrations of Fe in biochar.

Apart from the Ni leaching from the MOVAR biochar, the percentage leached Cr and Ni, at all pyrolysis temperature and pHs were both in the range of 1-1.4%, fig 10a. Anyhow, leaching of Cr increased with increasing pyrolysis temperature. Ni leaching as well increased with increasing pyrolysis temperature in MOVAR and DSL biochar until temperature of 800^{o}C where it decreased. Ni and Cr could be bound to oxides of other elements in biochar. Increasing pyrolysis temperature dissociate the oxide bond, increasing the lability or cationic elements with the decreasing pH (Zhang et al., 2020). Moreover, at 800^{o}C the leachable forms of Ni in MOVAR have been eliminated as found by other studies (Li et al., 2020; Lin et al., 2017).

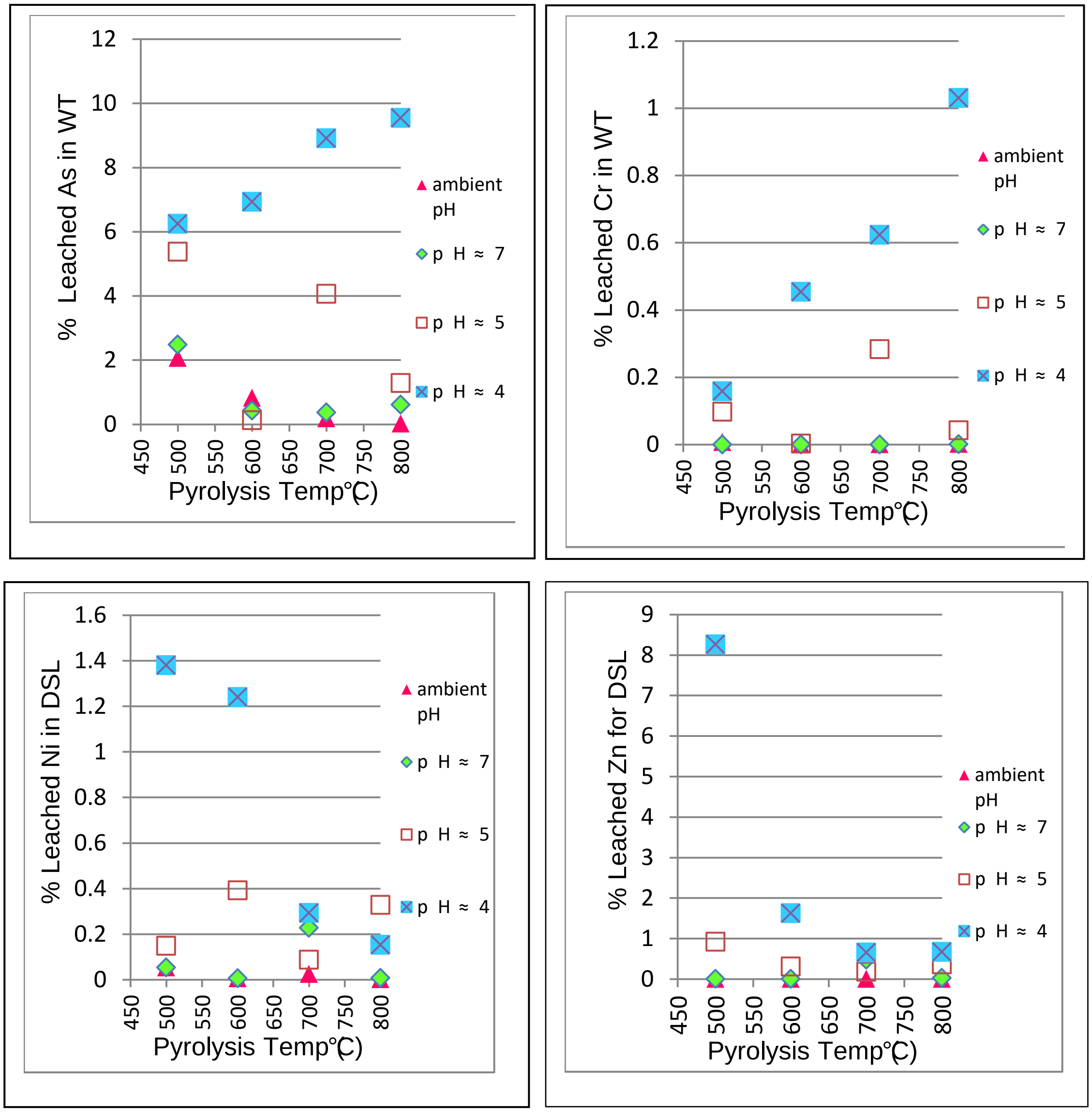
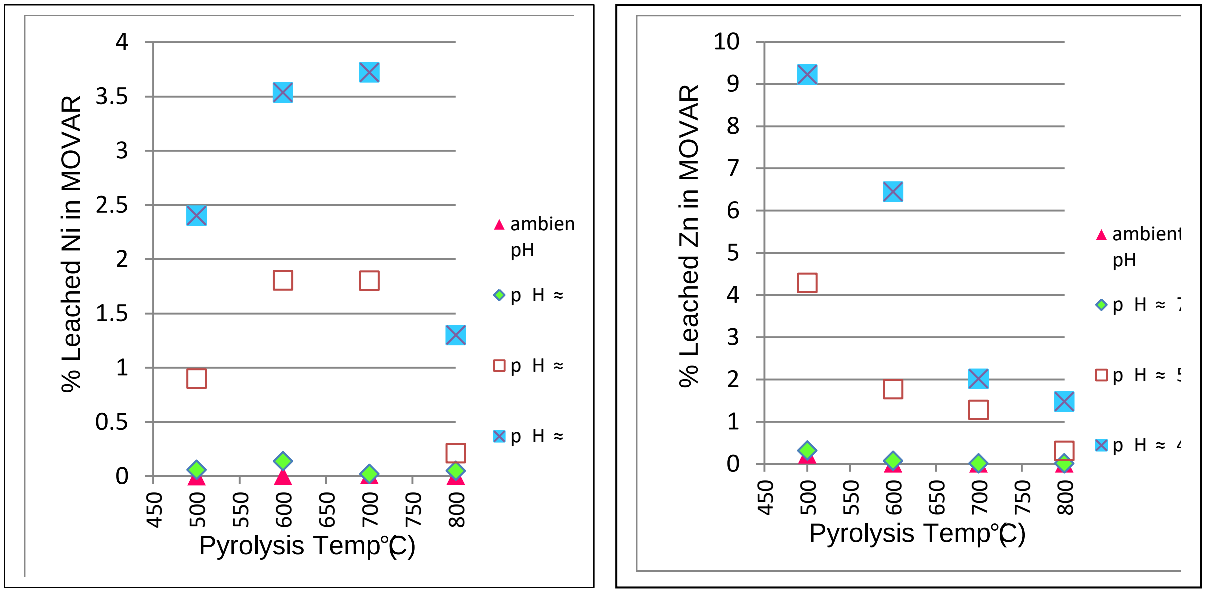


Fig 10a. Percentages of trace elements leached from biochar at the various pyrolysis temperatures and target pHs *(ambient pH= Unaltered pH of biochar solution, As: top left, Cr: top right, Ni: bottom left, Zn: bottom right) (WT= waste timber biochar, DSL = digested sludge from Lindum biochar).*



10b. Percentages of trace elements leached from biochar at the various pyrolysis temperatures and target pHs *(ambient pH= Unaltered pH of biochar solution, Ni: left, Zn :right) (MOVAR = digested sludge from MOVAR biochar).*

Cu was above EBC limits in all biochar, except clean wood chips (CWC) biochar. Fig 10c shows percentage Cu leached in biochar at all target pH and pyrolysis temperature. The leachable fraction of Cu generally decreased with increasing pyrolysis temperature for a particular target pH. It is speculated that Cu may be bound to other elements that increase with increasing pyrolysis temperature, making more Cu stable hence a decrease in leaching as pyrolysis temperature increase.

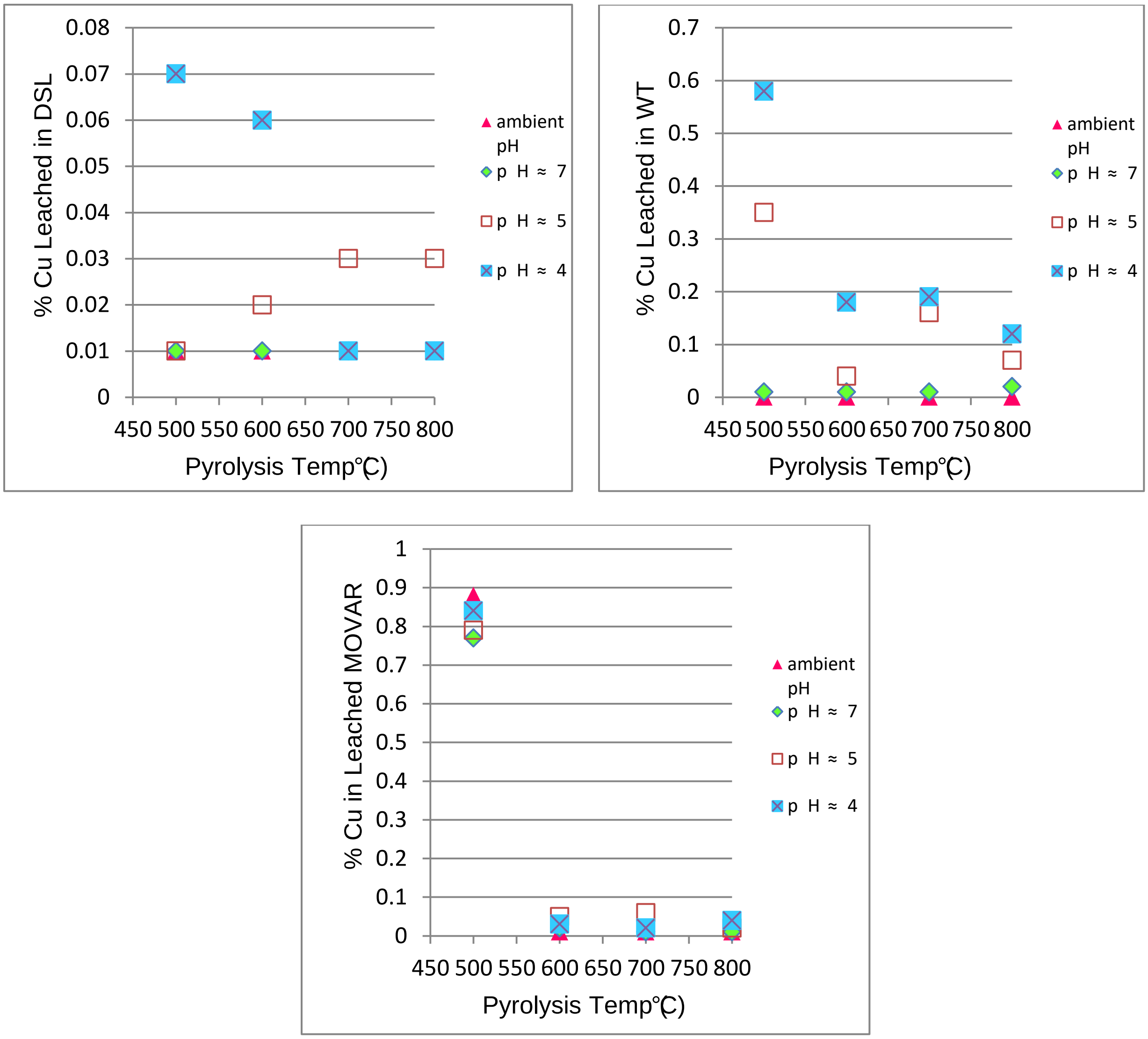


Fig 10c. Percentages of Cu leached from biochar at the various pyrolysis temperatures and target pHs (ambient pH= Unaltered pH of biochar solution, *top left = digested sludge from Lindum(DSL) biochar, top right = waste timber biochar (WT)biochar, bottom = digested sludge from MOVAR (MOVAR) biochar*).

Comparing the leaching of trace elements from the waste biochar, i.e digested sludge from Lindum (DSL), digested sludge from MOVAR (MOVAR) and waste timber biochar (WT), with the reference biochar ,i.e, clean wood chips (CWC) biochar showed that leaching of trace elements from the waste biochar were mostly higher than leaching from the reference biochar (CWC), Appendix F. For instance, Concentrations of Cu and Zn leached from all DSL, MOVAR and WT biochar were higher than Cu and Zn leached from the reference biochar (CWC) except WT-600, WT-700, WT-800 (number attached is pyrolysis temperature) leached at pHs 10.23, 11.64 and 11.98 respectively (ambient pHs of biochar). Concentrations of As leached from all waste timber (WT) biochar were higher than concentrations in leachates of the reference biochar. Cd concentrations in leachates of all WT biochar were also higher than the concentrations of leachates in the reference biochar except WT- 600 and WT – 700, both leached at ambient pH. None of the waste biochar (DSL, MOVAR and WT). Thus, for a particular waste biochar, the leaching of some trace elements were equal or lower than the concentrations leached from the reference biochar, whilst the leaching of other trace elements were higher than what is leached from the reference (No single waste biochar had concentrations of all trace elements in leachate within acceptable limits' with regards to the reference biochar), see appendix F.

Leachate concentrations of trace elements in the waste biochar (DSL, MOVAR and WT) were compared with threshold concentrations for leaching from waste deposited to "inert landfills" in Norway, appendix G. An 'acceptable leaching concentrations' for clean materials were deduced from the threshold values (Acceptable leaching concentration = threshold concentration /10). Leaching from the reference biochar, clean wood chips (CWC) biochar, was not included as biochar made from CWC has acceptable amounts of trace elements according to EBC (European Biochar Certificate) standards and such biochar are already in use. Ni and As concentrations in leachate of waste timber (WT) were particularly high than 'acceptable limits'; As concentrations in leachate were acceptable for the digested sludge biochar (DSL and MOVAR). However the digested sludge biochar (DSL and MOVAR) had high leachate concentrations of Zn whilst leachate concentrations of Zn in WT were acceptable. In all, waste timber (WT) biochar had the most trace elements with higher concentrations of leachate higher than the 'acceptable limits' see appendix G. No biochar leached at pH < 7 had all its trace elements concentrations in leachate within acceptable limit. Table 3 shows the list of biochar with acceptable leachate concentrations of trace elements when compared with threshold values for leaching from waste deposited into 'inert landfills' in Norway.

Table 3 Biochar with acceptable leaching of all trace elements

Biochar	Pyrolysis temp	Target pH
WT	800	Ambient
DSL	500	Ambient
DSL	600	7
DSL	700	Ambient
DSL	800	Ambient
DSL	800	7
MOVAR	600	Ambient
MOVAR	700	Ambient
MOVAR	700	7
MOVAR	800	Ambient
MOVAR	800	7

(WT= Waste timber, DSL = Digested Sludge from Lindum, MOVAR = Digested Sludge from MOVAR)

6.7 Factors affecting leaching

A stepwise regression analysis in R programming was used to investigate the factors affecting the leaching of trace elements (Cu and Zn) from biochar

A list of the models tested in the stepwise regression analysis is in appendix K. The best models using the AIC (Akaike's Information Criterion) were:

Cu-leached = lm (Cu ~ Feedstock + Temp*ph*Al + Fe) ______________ (1)

Zn-leached= lm(Zn ~ feedstock + temp*ph*Al + Fe) ______________ (2)

Where:

Cu= copper Concentration

Zn = Zinc Concentration

Al = Aluminium concentration in biochar

Fe = Iron concentration in biochar

ph = pH in leachate

temp = pyrolysis temperature

The R^2 value of 0.71 for Cu leached [(1) above] and 0.73 for Zn leached [(2) above] shows a high level of correlation (about 70% correlation) between Cu and Zn leached and the variables tested. Also the P values of the models above ($P = 4.29e^{-12}$ for Cu-leached, $P= 1.305e^{-12}$ for Zn-leached), shows significance, thus $P < 0.05$ hence the variables tested significantly affect the leaching of Cu and Zn. .

The models suggested that Cu and Zn leaching are dependent on the concentration of the elements in the various feedstocks, pyrolysis temperature, pH in leachate, as well as the quantities of Al and Fe in biochar; pH affects leaching differently in biochar produced at the various pyrolysis temperatures (500^{o}C, 600 ^{o}C, 700 ^{o}C, 800 ^{o}C or 750 ^{o}C) (Section 6.2). It is speculated that pH is more important for the release of Cu and Zn from Al minerals but does not interact much with leaching from Fe minerals; also temperature does not change Cu and Zn associated with Fe to a significant degree. Temperature however changes Al in a way that causes less leaching of Cu and Zn associated with Al at high temperatures, thus Cu and Zn may bound up in Al minerals that increase with increasing temperature, such as CuAl2O4 (Sheng et al, 2018)

This model however is indicative of the above mentioned trends; further studies is needed to understand and establish the mechanisms.

7 CONCLUSION AND RECOMMENDATION

In conclusion the biochar from waste timber (WT biochar), digested sludge from Lindum (DSL) and digested sludge form MOVAR biochar are currently not fit for agricultural soil improvement because they did not meet the standards of the EU's fertilizer framework directive and the European Biochar Certificate (EBC) Agro and AgroOrganic standards.

Hypothesis 1 (The concentration of trace elements can be reduced by increasing pyrolysis temperature, while at the same time retain certain elements with nutrient value) of this study was not fully supported by the findings. Not all trace elements were reduced by increasing pyrolysis temperature; thus whilst the concentrations of Cd, Pb and Zn were reduced by increasing pyrolysis temperature, concentrations of As, Cr, Cu and Ni did not follow this trend. Main elements concentrations did not decrease with increasing pyrolysis temperature but were rather up-concentrated (except P). Thus the pyrolysis temperature used in this study can be used to reduce the concentrations of some trace elements and also maintain some elements of nutritional value but cannot reduce the concentrations of all trace elements.

Hypothesis 2 (Leaching of elements in biochar is pH dependent) was supported by the findings of the study. Leaching of trace elements increased with decreasing pH at a specific pyrolysis temperature. Thus decreasing pH increased the mobility/solubility of trace elements

Though the concentrations of some trace elements were within EBC and EU's fertilizer framework directive's acceptable limits in some biochar (for instance Ni in waste timber biochar, Pb in all biochar), for a particular biochar to be acceptable for agriculture purposes, it is recommended that the appropriate standard of the EU's fertilizer framework directive is met. It is also recommended that all EBC Agro and/or EBC Agro Organic standards are met. These were however not the case in the waste biochar investigated in this study; for instance Cu concentrations all in digested sludge from Lindum (DSL) biochar, all digested sludge from MOVAR (MOVAR) biochar and all waste timber (WT) biochar were beyond both EBC Agro and EBC AgroOrganic limits. Cr concentrations in these 3 biochar were also higher than EU's fertilizer framework directive limits; this makes all the biochar investigated (except the reference biochar, clean wood chips biochar) currently unfit for agricultural purposes (Unlike biochar from clean wood chips).

Comparison of concentration of trace elements in leachates of digested sludge from Lindum (DSL) biochar, digested sludge from MOVAR (MOVAR) biochar as well as waste timber (WT) biochar with concentrations in leachates of the reference biochar and waste deposited into 'inert landfill' in Norway showed high levels of particularly Zn and Cu in leachates (see section 6.7 for discussion).

Apart from the reference biochar, none of the biochar (DSL, MOVAR and WT) had acceptable limits for all trace elements investigated when compared with the EU's fertilizer framework directive – a legislation and therefore strongly recommended to be adhered to, hence further investigations is needed to be able use the biochar investigated in this study [digested sludge from lindum (DSL), digested sludge from MOVAR (MOVAR) and waste timber (WT) investigated in this study for agricultural soil quality improvement.

It is recommended that proper sorting techniques are implemented at the waste timber sorting sites to avoid 'impregnated wood' being added to waste timber collection; this can significantly reduce Ni concentrations in waste timber biochar.

Further investigations on how to reduce the concentrations of the problematic trace elements found in this study (As, Cu, Cr, and Zn) is recommended as this will increase the potential of the biochar investigated in this study to be used for agricultural purposes; the feedstock for digested sludge biochar and waste timber biochar are in abundance and being able to use these feedstocks for biochar will have a positive impact on the environment. A study of whether the current biochar [Digested Sludge biochar (DSL and MOVAR) and the waste wood biochar (WT) can be used for remediation purposes will be a step in the right direction as they are currently deemed unfit for agricultural use.

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9. APPENDICES

Appendix A	Titration Matrix for Method Development
Appendix B	Selected plots from titration matrix
Appendix C	HCl Volumes for batch leaching tests
Appendix D	Means of concentrations of main and trace elements in biochar
Appendix E	Means of concentrations of main and trace elements in eluates
Appendix F	Comparison of concentrations of trace elements in eluates with reference biochar eluate
Appendix G	Comparison of concentrations of trace elements in eluates with threshold values for leaching from waste deposited to "inert landfills" in Norway
Appendix H	Percentages of trace elements leached from biochar
Appendix J	Biochar yield data
Appendix K	Models tested for factors affecting leaching of Cu and Zn
Appendix L	Concentrations of Iron (Fe) and Aluminium (Al) in biochar
Appendix M	Threshold values of trace elements for an organic soil improver, EU fertilizer framework directive

Appendix A Titration Matrix for Method Development

pH measurements of biochar solution [(biochar + deionized water + 1M HCl (or 3M HCl)] during method development. The pH measurements(colored rows) were taken at different hours from when HCl was added as indicated under column Eq. time (Hrs). CWC = clean wood chips, WT = waste wood, MOVAR = digested sludge from MOVAR waste handling company, DSL = digested sludge from Lindum waste handling company, BC=biochar, number attached to biochar is pyrolysis temperature used in making biochar. Numbers displayed on columns are numbers assigned to containers (50ml tubes) holding biochar solution;.Column H_2O and HCl are volumes of water and HCl added to biochar respectively to get a solid: liquid ratio of 1:5

CWC-BC-500					1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17		18		19		20	
	days	Eq.tim (Hrs)	dry matter	Final vol.	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O
	0.25	4	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.5	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					3.5		2.16		2		2		2		2		1		1		1		1		1.3		1.3		1		1		1		1		1		1		1		0.9	
	0.33	8	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					5.3		2.34		2		2		2		2		2		2		1		1		1.3		1.3		1		1		1		1		1		1		1		0.9	
	1	24	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					6.5		2.85		2		2		2		2		2		2		2		1		1.4		1.4		1		1		1		1		1		1		1		0.9	
	2	48	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					6.8		3.68		3		2		2		2		2		2		2		2		1.4		1.4		1		1		1		1		1		1		1		0.8	
	3	72	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					7.1		4.55		4		2		2		2		2		2		2		2		1.4		1.4		1		1		1		1		1		1		1		0.9	
	6	144	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					7.2		5.33		3		3		2		2		2		2		2		2		1.5		1.4		1		1		1		1		1		1		1		0.9	
	8	192	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					7.3		5.7		4		3		2		2		2		2		2		2		1.5		1.4		1		1		1		1		1		1		1		0.9	

WT-BC-500					1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17		18		19		20	
	days	Eq.tim (Hrs)	dry matter	Final vol.	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O
	0.25	4	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					6.4		4.22		3		2		2		2		2		2		2		2		1.5		1.3		1		1		1		1		1		1		1		1	
	0.33	8	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					6.7		5.5		4		2		2		2		2		2		2		2		1.6		1.5		1		1		1		1		1		1		1		1	
	1	24	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					7		6.12		5		4		3		3		2		2		2		2		1.9		1.7		2		2		1		1		1		1		1		1	
	2	48	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					7.1		6.3		6		4		4		3		3		3		2		2		2		1.7		2		2		1		1		1		1		1		1	
	3	72	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					7.2		6.55		6		5		4		3		3		3		2		2		2.1		1.8		2		2		1		1		1		1		1		1	
	6	144	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					7.2		6.79		6		5		4		4		3		3		2		2		2.3		1.9		2		2		2		1		1		1		1		1	

CWC-BC-600					1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17		18		19		20	
	days	Eq.tim (Hrs)	dry matter	Final vol.	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2C	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O
	0.25	4	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					5.5		2.45		2		2		2		2		2		1		1		1		1.3		1.2		1		1		1		1		1		1		1		0.9	
	0.33	8	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					6.2		2.88		2		2		2		2		2		2		2		1		1.4		1.3		1		1		1		1		1		1		1		0.9	
	1	24	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					6.8		5.28		3		2		2		2		2		2		2		2		1.5		1.4		1		1		1		1		1		1		1		0.9	
	2	48	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					6.9		5.89		4		3		2		2		2		2		2		2		1.5		1.4		1		1		1		1		1		1		1		0.9	
	3	72	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					7.1		6.28		5		3		2		2		2		2		2		2		1.6		1.4		1		1		1		1		1		1		1		0.9	
	6	144	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					7.3		6.64		5		4		3		2		2		2		2		2		1.6		1.5		1		1		1		1		1		1		1		0.9	
	8	192	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					7.4		6.78		5		4		3		2		2		2		2		2		1.6		1.4		1		1		1		1		1		1		1		0.9	

WT-BC-600					1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17		18		19		20	
	days	Eq.tim (Hrs)	dry matter	Final vol.	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2C	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O
	0.25	4	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					6.8		6.56		6		5		4		3		2		2		2		2		1.5		1.6		2		1		1		1		1		1		1		1	
	0.33	8	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					7.6		7.04		7		6		5		4		3		2		2		2		1.8		1.7		2		2		1		1		1		1		1		1	
	1	24	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					8.1		7.55		7		6		6		5		5		4		3		2		2.3		2.2		2		2		2		2		1		1		1		1.1	
	2	48	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					8.3		7.58		7		7		6		6		5		4		4		3		2.6		2.5		2		2		2		2		1		1		1		1.1	
	3	72	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					8.4		7.81		7		7		7		6		5		5		4		4		3.7		3.3		3		3		2		2		1		1		1		1.2	
	6	144	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					8.6		8.13		8		7		7		7		5		5		4		4		3.8		3.4		3		3		2		2		1		1		1		1.1	
	8	192	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					8.6		8.17		8		8		7		7		6		5		5		4		4		3.6		3		3		2		2		1		1		1		1.1	

CWC-BC-700					1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17		18		19		20	
	days	Eq.tim (Hrs)	dry matter	Final vol.	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2C	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O
	0.25	4	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					6.4		4.73		2		2		2		2		2		2		2		1		1.3		1.3		1		1		1		1		1		1		1		0.9	
	0.33	8	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					6.9		5.86		3		2		2		2		2		2		2		1		1.4		1.4		1		1		1		1		1		1		1		0.9	
	1	24	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					7.3		6.64		5		3		2		2		2		2		2		2		1.6		1.5		1		1		1		1		1		1		1		0.9	
	2	48	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					7.4		6.97		6		4		3		2		2		2		2		2		1.6		1.5		1		1		1		1		1		1		1		0.9	
	5	120	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					7.8		7.12		6		5		3		3		2		2		2		2		1.6		1.5		1		1		1		1		1		1		1		0.9	
	7	168	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					7.9		7.39		7		5		4		3		2		2		2		2		1.6		1.5		1		1		1		1		1		1		1		0.9	

WT-BC-700					1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17		18		19		20	
	days	Eq.tim (Hrs)	dry matter	Final vol.	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2C	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O
	0.25	4	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					9		6.88		6		5		4		4		3		3		2		2		1.8		1.8		2		2		2		1		1		1		1		1.1	
	0.33	8	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					9.1		7.94		7		6		6		4		4		4		3		2		2.1		2		2		2		2		1		1		1		1		1.1	
	1	24	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					9.5		8.57		8		7		6		5		5		4		4		3		2.8		2.5		2		2		2		2		2		1		1		1.2	
	2	48	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					9.7		8.82		8		7		6		6		6		5		4		4		3.5		3.5		3		3		2		2		2		1		1		1.2	
	5	120	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					9.7		8.99		9		8		7		6		6		5		5		4		4.2		3.6		3		3		2		2		2		1		1		1.2	
	7	168	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					9.5		9		9		8		7		7		6		5		5		4		4.3		4		4		3		3		2		2		1		1		1.2	

CWC-BC-750					1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17		18		19		20	
	days	Eq.tim (Hrs)	dry matter	Final vol.	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2C	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O
	0.25	4	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					6.7		5.85		3		2		2		2		2		2		2		1		1.4		1.4		1		1		1		1		1		1		1		0.9	
	0.33	8	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					6.9		6.27		4		3		2		2		2		2		2		2		1.5		1.4		1		1		1		1		1		1		1		0.9	
	1	24	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					7.3		6.83		6		3		3		3	2.2	2		2		2		2		1.6		1.5		1		1		1		1		1		1		1		0.9	
	2	48	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					7.5		7.07		7		5		3		3		2		2		2		2		1.6		1.5		1		1		1		1		1		1		1		0.9	
	5	120	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					8		7.42		7		6		4		3		2		2		2		2		1.6		1.5		1		1		1		1		1		1		1		0.9	
	7	168	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					8		7.43		7		6		5		3		2		2		2		2		1.6		1.5		1		1		1		1		1		1		1		0.9	

WT-BC-800					1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17		18		19		20	
	days	Eq.tim (Hrs)	dry matter	Final vol.	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2C	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O
	0.25	4	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					11		9.94		9		8		7		6		5		4		3		3		2.3		2.1		2		2		2		1		1		1		1		1.1	
	0.33	8	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					11		10.3		9		9		7		6		6		5		4		4		2.6		2.5		2		2		2		2		1		1		1		1.1	
	1	24	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					11		10.6		10		9		8		7		6		5		5		5		3.6		3.4		3		3		2		2		2		1		1		1.2	
	2	48	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					11		10.6		10		9		8		8		6		6		5		5		4.3		4.1		4		3		2		2		2		1		1		1.2	
	5	120	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					11		10.6		10		9		9		8		7		6		5		5		4.3		4.1		4		4		3		2		2		1		1		1.2	
	7	168	5	25	0.4	24.6	0.6	24	1	24	1	24	1	23.8	1	24	2	23.4	2	23	2	23	2	22.8	2.4	23	2.6	22.4	3	22	3	22	4	21.5	4	21	5	20.5	5	20	6	19.5	6	19
pH					11		10.5		10		9		9		8		8		7		6		5		4.4		4.3		4		4		3		2		2		1		1		1.2	

DSL 500					1		2		3		4		5		6		7		8		9		10		11	
	days	Eq.tim (Hrs)	dry matter	Final vol.	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O
	0.25	4	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	3	22	4	21
pH					6.58		5.81		5.5		5.4		4.55		4.4		4.1		3.84		3.76		2.96		1.91	
	0.33	8	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	3	22	4	21
pH					6.42		6.19		5.9		5.6		5.14		4.9		4.58		4.36		4.27		3.74		2.74	
	1	24	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	3	22	4	21
pH					6.45		6.29		6.1		5.9		5.57		5.3		5.04		4.74		4.61		4.15		3.65	
	2	48	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	3	22	4	21
pH					6.61		6.44		6.3		6.1		5.87		5.7		5.43		5.1		4.92		4.32		3.94	
	3	72	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	3	22	4	21
pH					6.71		6.48		6.4		6.2		5.93		5.7		5.58		5.18		5.07		4.35		4	

DSL 600					1		2		3		4		5		6		7		8		9		10		11		12	
	days	Eq.tim (Hrs)	dry matter	Final vol.	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O
	0.25	4	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	2.4	22.6	3	22	4	21
pH					6.22		6.24		5.6		5		4.67		4.3		4.11		4.03		3.55		3.01		2.6		1.9	
	0.33	8	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	2.4	22.6	3	22	4	21
pH					6.24		6.27		5.7		5.4		5.14		4.8		4.52		4.43		4.07		3.77		3.51		2.8	
	1	24	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	2.4	22.6	3	22	4	21
pH					6.22		6.31		5.9		5.7		5.45		5.2		4.92		4.82		4.36		4.12		3.94		3.6	
	2	48	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	2.4	22.6	3	22	4	21
pH					6.32		6.44		6		5.9		5.65		5.4		5.2		5.1		4.6		4.28		4.09		3.8	
	3	72	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	2.4	22.6	3	22	4	21
pH					6.36		6.43		6.1		5.9		5.71		5.5		5.28		5.1		4.6		4.25		4.13		3.8	

DSL 700					1		2		3		4		5		6		7		8		9		10		11		12	
	days	Eq.tim (Hrs)	dry matter	Final vol.	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O
	0.25	4	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	2.4	22.6	5	20	7	18
pH					7.11		6.45		6.4		6.1		5.95		5.8		6.24		5.66		5.59		5.48		3.4		2.8	
	0.33	8	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	2.4	22.6	5	20	7	18
pH					7.37		6.63		6.6		6.9		6.63		6.5		6.59		6.83		6.56		6.44		4.4		3.1	
	1	24	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	2.4	22.6	5	20	7	18
pH					7.51		7.34		7.2		7.1		6.98		6.8		6.98		6.8		6.8		6.52		4.8		3.7	
	2	48	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	2.4	22.6	5	20	7	18
pH					7.8		7.54		7.4		7.2		7.2		7.2		7.16		6.98		6.9		6.5		5		3.9	
	3	72	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	2.4	22.6	5	20	7	18
pH					7.92		7.87		7.5		7.2		7.28		7.3		7.23		7.1		7.02		6.93		5		4	
															3M HCl was used for sample 11 and 12													

DSL 800					1		2		3		4		5		6		7		8		9		10		11		12	
	days	Eq.tim (Hrs)	dry matter	Final vol.	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O
	0.25	4	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	2.4	22.6	7	18	8	17
pH					6.5		6.31		6.1		6		5.91		5.8		5.74		5.7		5.66		5.48		3.9		3.7	
	0.33	8	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	2.4	22.6	7	18	8	17
pH					6.54		6.52		6.5		6.3		6.27		6.2		6.1		6		6.11		5.94		4.3		3.8	
	1	24	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	2.4	22.6	7	18	8	17
pH					6.72		6.88		6.6		6.4		6.33		6.3		6.24		6.21		6.2		6.17		4.4		3.7	
	2	48	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	2.4	22.6	7	18	8	17
pH					7.07		6.96		6.8		6.6		6.47		6.4		6.35		6.3		6.27		6.2		4.44		3.8	
	3	72	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	2.4	22.6		18	8	17
pH					7.71		7.63		7.7		7.3		7.15		7.1		6.93		6.86		6.8		6.73		4.5		3.9	
															3M HCl was used for sample 11 and 12													

HCl added to DSL 700 and DSL 800 for containers 6 to 12 was 3M.

MOVAR 500					1		2		3		4		5		6		7		8			
	days	Eq.tim (Hrs)	dry matter	Final vol.	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O		
	0.25	4	5	25	0.4	24.6	0.6	24.4	0.8	24.2	2.5	23	3	22	4	21	5	20	7	18		
pH					6.83		6.51		6.2		3.8		3.64		3.4		3.36		2.56			
	0.33	8	5	25	0.4	24.6	0.6	24.4	0.8	24.2	2.4	23	3	22	4	21	5	20	7	18		
pH					7.22		6.7		6.6		4.4		4.25		3.8		3.61		3.34			
	1	24	5	25	0.4	24.6	0.6	24.4	0.8	24.2	2.4	23	3	22	4	21	5	20	7	18		
pH					7.42		6.9		6.8		4.8		4.56		4.2		3.99		3.67			
	2	48	5	25	0.4	24.6	0.6	24.4	0.8	24.2	2.4	23	3	22	4	21	5	20	7	18		
pH					7.61		7.26		7		5.5		4.92		4.4		4.1		3.72			
	3	72	5	25	0.4	24.6	0.6	24.4	0.8	24.2	2.4	23	3	22	4	21	5	20	7	18		
pH					7.68		7.35		7.1		5.9		5.36		4.4		4.3		3.79			

MOVAR 600					1		2		3		4		5		6		7		8		9	
	days	Eq.tim (Hrs)	dry matter	Final vol.	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O
	0.25	4	5	25	0.4	24.6	0.8	24.2	1.2	23.8	1.6	23	2.4	22.6	4	21	6	19	7	18	9	16
pH					6.71		6.23		5.9		5.5		4.02		2.9		2.32		2.26		2.2	
	0.33	8	5	25	0.4	24.6	0.8	24.2	1.2	23.8	1.6	23	2.4	22.6	4	21	6	19	7	18	9	16
pH					6.8		6.25		6.1		6		5.17		3.7		3.22		3.12		3	
	1	24	5	25	0.4	24.6	0.8	24.2	1.2	23.8	1.6	23	2.4	22.6	4	21	6	19	7	18	9	16
pH					7.3		6.69		6.4		6.4		6.03		4.5		3.93		3.71		3.57	
	2	48	5	25	0.4	24.6	0.8	24.2	1.2	23.8	1.6	23	2.4	22.6	4	21	6	19	7	18	9	16
pH					7.67		7.37		6.8		6.6		6.18		5.6		4.69		4.36		3.91	
	3	72	5	25	0.4	24.6	0.8	24.2	1.2	23.8	1.6	23	2.4	22.6	4	21	6	19	7	18	9	16
pH					7.68		7.44		7		6.6		6.18		5.8		4.72		4.6		4.01	

MOVAR 700					1		2		3		4		5		6		7		8		9		10		11			
	days	Eq.tim (Hrs)	dry matter	Final vol.	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	H_2O	HCl	H_2O	HCl		
	0.25	4	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	19	7	18	5		
pH					6.34		6.31		6.1		5.9		5.9		5.8		5.68		5.58		5.53			2.05		1.7		
	0.33	8	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	19	7	18	5		
pH					5.97		5.87		6.2		6.1		6.02		6		5.89		6.1		6.21			2.69		2.22		
	1	24	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	19	7	18	5		
pH					6.18		6.11		6		5.9		6.01		6		5.94		5.93		5.92			3.32		2.71		
	2	48	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	19	7	18	5		
pH					6.2		6.22		6.1		6		6.1		6		5.96		6		5.97			3.94		2.8		
	3	72	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	19	7	18	5		
pH					6.6		6.36		6.3		6.2		6.12		6.1		6.08		6.05		6.03			4.57		2.89		
																			3M HCl for samples 10 and 11									
MOVAR 800					1		2		3		4		5		6		7		8		9		10		11		12	
	days	Eq.tim (Hrs)	dry matter	Final vol.	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O	HCl	H_2O
	0.25	4	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	4	21	7	18	8	17
pH					6.41		6.2		6		5.8		5.8		5.8		5.7		5.42		4.93		3.01		2.02		1.4	
	0.33	8	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	4	21	7	18	8	17
pH					6.46		6.27		6.2		6.1		5.91		5.9		5.78		5.59		5.59		3.56		2.53		2	
	1	24	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	4	21	7	18	8	17
pH					6.54		6.32		6.2		6.1		6.01		6		5.98		5.9		5.81		4.68		3.1		2.6	
	2	48	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	4	21	7	18	8	17
pH					6.55		6.42		6.2		6.1		607		6.1		6.01		6		5.94		5.22		3.51		2.9	
	3	72	5	25	0.4	24.6	0.6	24.4	0.8	24.2	1	24	1.2	23.8	1.4	23.6	1.6	23.4	1.8	23.2	2	23	4	21	7	18	8	17
pH					6.71		6.55		6.4		6.4		6.33		6.2		6.16		6.02		5.93		5.32		4.63		3.3	

HCl added to MOVAR 700 for containers 8 to 11 was 3M.

Appendix B Selected Plots from titration matrix

Selected plots of pH values from appendix A (This was done for all biochar). Hour 72 was chosen for batch leaching as pH stabilized from this point. Volumes of HCl to be added to biochar solution for batch leaching were estimated from these plots for each biochar.

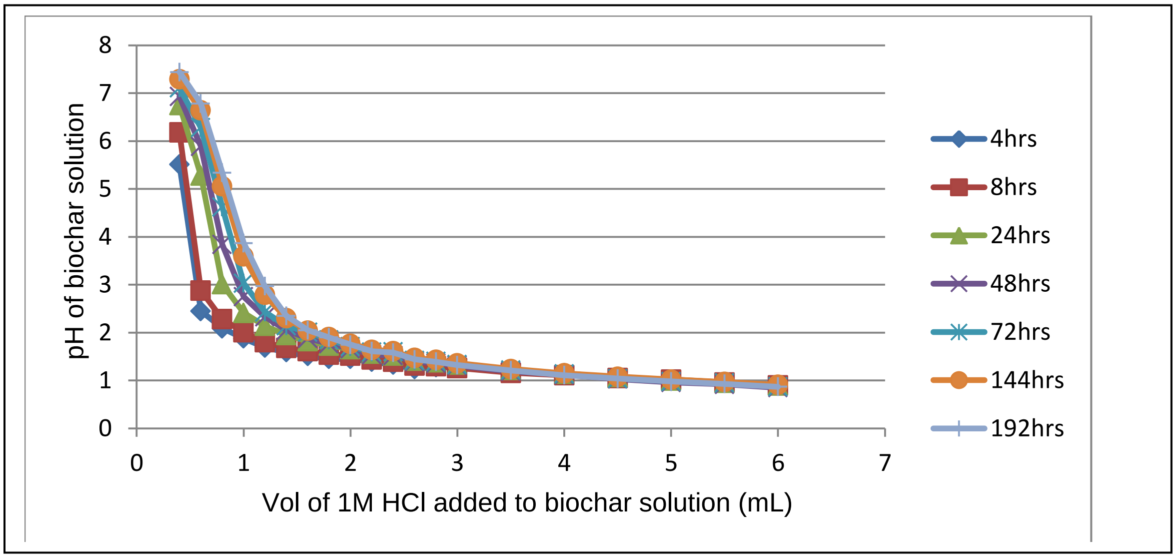

Fig B1. pH plots for clean wood chips pyrolysed at 600°C biochar (CWC-BC-600)

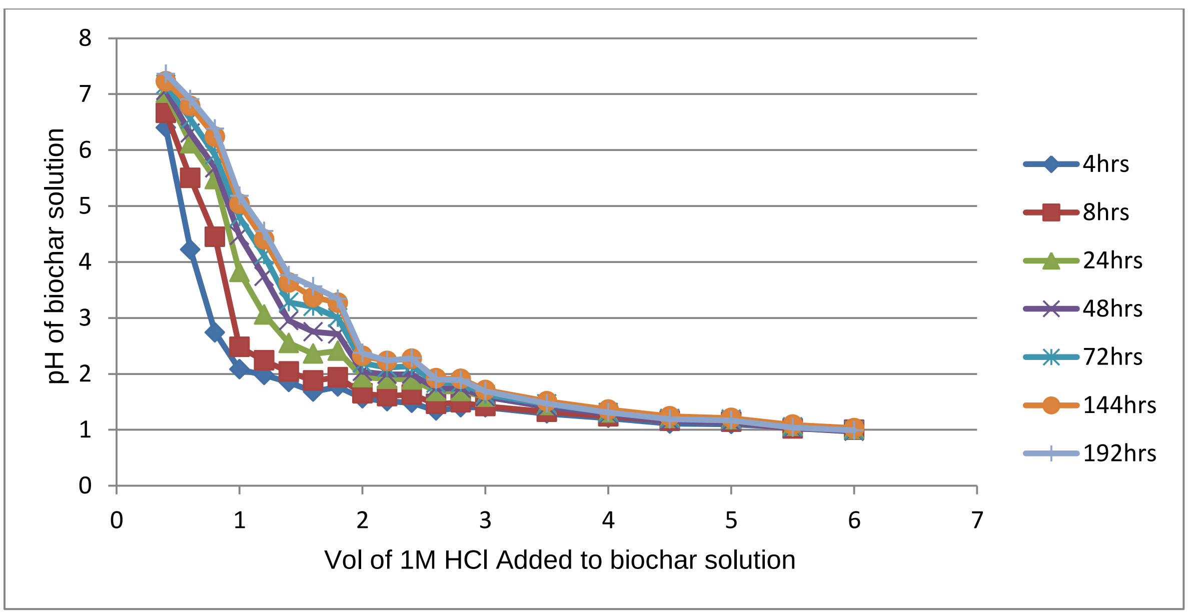

Fig B2. pH plots for waste timber pyrolysed at 500°C biochar (WT-BC-500)

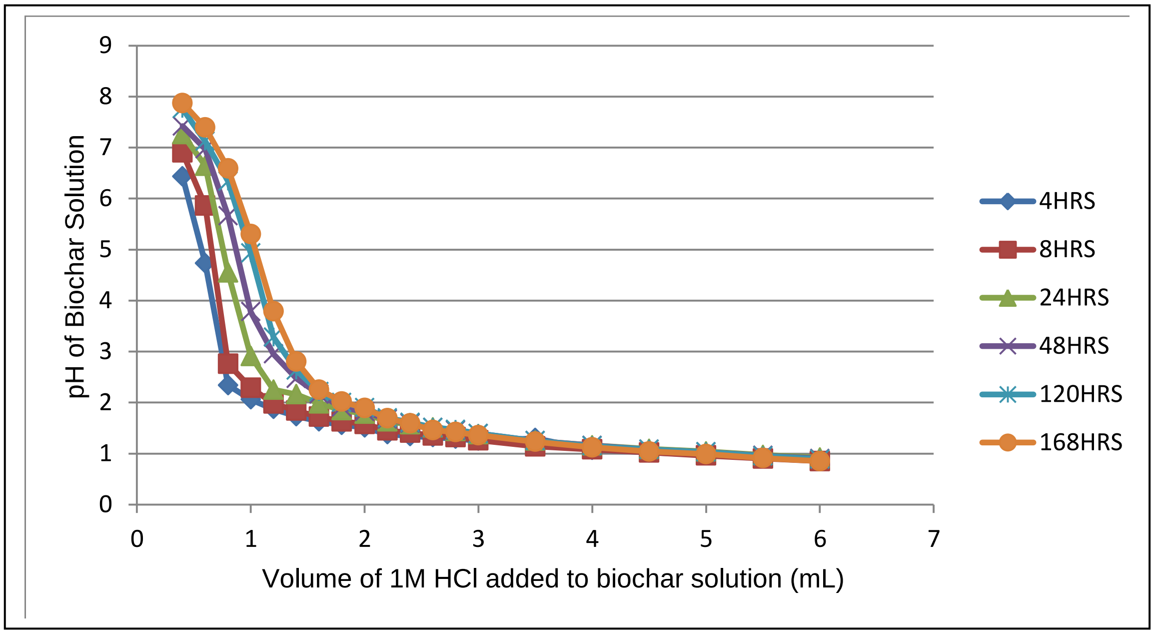

Fig B3. pH plots for clean wood chips pyrolysed at 700^{o}C biochar (CWC-BC-700)

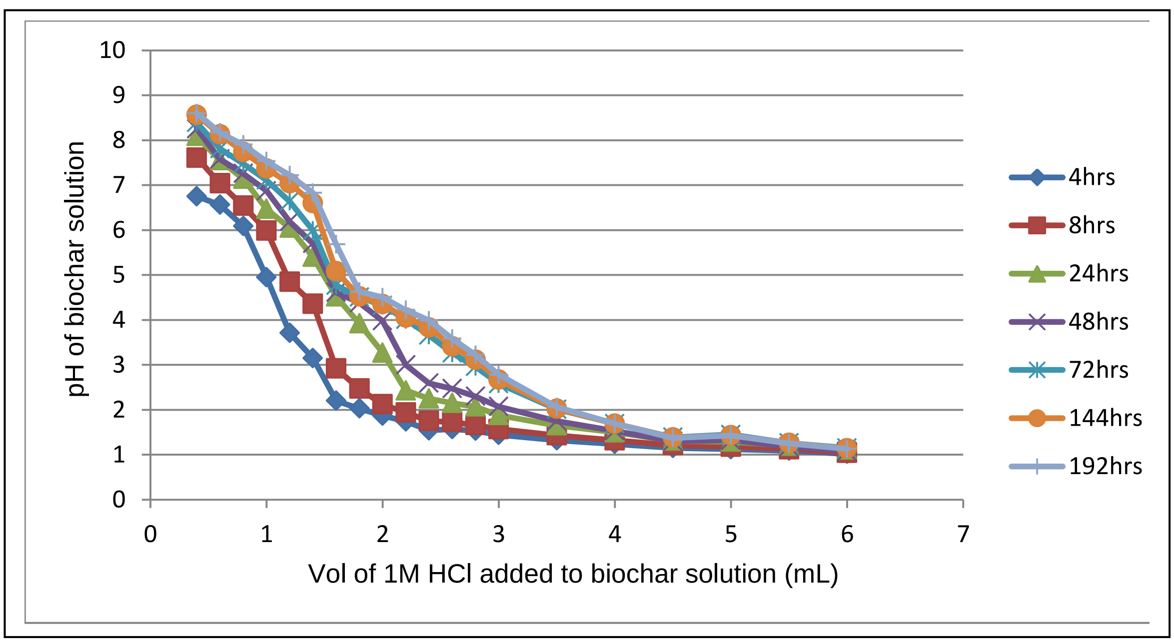

Fig B4. pH plots for waste timber pyrolysed at 600^{o}C biochar (WT-BC-600)

Appendix C HCl volumes for batch leaching tests

The volumes of HCl to be added to biochar solution to get a target pH were estimated from plots (as shown in appendix B). The estimated total volumes were added over a period of 48 hours (as shown) to avoid a sharp drop in pH of solution.

			Volume (mL) HCl Added to Biochar Solution					
Biochar	Pyrolysis Temp.	Target pH	Total HCl Added	Time Interval for HCl addition				Molarity of HCl
				Start (0 hrs)	8hrs	24hrs	48hrs	
CWC	500	7	0.2	0.1		0.1		1
		5.5	0.45	0.2		0.25		1
		4	0.65	0.3		0.25	0.1	1
CWC	600	7	0.3	0.1		0.1	0.1	1
		5.5	0.6	0.2		0.2	0.2	1
		4	0.8	0.3	0.3	0.2		1
CWC	700	7	0.5	0.3		0.2		1
		5.5	0.75	0.2	0.2	0.25	0.1	1
		4	0.95	0.3	0.3	0.25	0.1	1
CWC	750	7	0.65	0.3	0.2	0.15		1
		5.5	0.9	0.4	0.3	0.2		1
		4	1.1	0.4	0.4	0.3		1
WT	500	7	0.2	0.1		0.1		1
		5.5	0.85	0.3	0.3	0.25		1
		4	1.05	0.4	0.3	0.25	0.1	1
WT	600	7	0.5	0.3		0.2		1
		5.5	1.15	0.5	0.5	0.15		1
		4	2.1	0.9	0.8	0.4		1
WT	700	7	1	0.4	0.3	0.3		1
		5.5	1.75	0.6	0.6	0.45	0.1	1
		4	2.3	1	1	0.3		1
WT	800	7	1.5	0.6	0.6	0.3		1
		5.5	1.85	0.8	0.8	0.25		1
		4	2.95	1	1	0.45	0.1	1

			Volume (mL) HCl Added to Biochar Solution					
Biochar	Pyrolysis Temp.	Target pH	Total HCl Added	Time Interval for HCl addition				Molarity of HCl
DSL	500	5.5	1.5	0.5	0.3	0.5	0.2	1
		4	3.5	1	1	1	0.5	1
DSL	600	5.5	1.25	0.5	0.2	0.35	0.2	1
		4	2	1.7			0.3	1
DSL	700	7	1.9	0.7	0.3	0.7	0.2	1
		5.5	2	1	0.3	0.5	0.2	3
		4	5.5	2.5	1	1.5	0.5	3
DSL	800	7	1.3	0.6	0.2	0.3	0.2	1
		5.5	4	1.6	1	1	0.4	3
		4	7.1	4.1	0.8	1.5	0.7	3
MOVAR	500	7	0.7	0.3	0.2	0.2		1
		5.5	2.6	1	0.6	0.6	0.4	1
		4	5	2	1	1.5	0.5	1
MOVAR	600	7	0.95	0.45	0.2	0.3		1
		5.5	3.8	1.8	0.6	1	0.4	1
		4	8	4	1.5	2	0.5	1
MOVAR	700	7	0.2	0.1		0.1		1
		5.5	5.3	2	1.3	1.5	0.5	3
		4	7	3	1	2	1	3
MOVAR	800	7	0.2	0.1		0.1		1
		5.5	2.8	1.2	0.6	0.7	0.3	1
		4	7	3	1.5	1.5	1	1

Appendix D Means and standard Deviations (SD) of Concentrations of main and trace elements in biochar

Elemental composition of biochar. The displayed values are means (n=3) of concentrations of ICP-OES/MS analysis of biochar. CWC = clean wood chips, WT = waste wood, MOVAR = digested sludge from MOVAR, DSL = digested sludge from Lindum , BC=biochar, number attached to biochar is pyrolysis temperature used in making biochar. The standard deviation depicts a measure of variation in the set of values

SD = × ï$\overline{X}$)(*X*

ã *n - 1*

Where SD = Standard deviation, X is a value in the dataset, $\overline{x}$ *is the average and* n *is the sample size.*

V. Liquid (mL)	pH		ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES
		LOD	0.000886	0.137229	0.003311	0.080727	0.139775	0.004866	0.004748	0.001101	0.016008	0.000	0.015	0.000	0.08449	0.000	0.000	0.000	0.016898	0.015	0.000	0.001669
		LOQ	0.002954	0.457429	0.011037	0.26909	0.465916	0.016221	0.015826	0.00367	0.053359	0.000	0.05	0.000	0.281634	0.000	0.000	0.000	0.056327	0.050	0.000	0.005565
			V	Cr	Co	Ni	Cu	As	Mo	Cd	Pb	Ba	Ca	Fe	K	Mg	Na	P	S	Si	Sr	Zn
		Sample Name	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
		Lab Blank	<LD	<0,38	<LD	<0,27	<0,47	<LD	<LD	<LD	0.059	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<0,05	<LD	<LD
		Lab Blank	<LD	<LD	<LD	<LD	<0,47	<LD	<LD	<LD	0.071	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<0,05	<LD	<LD
		Lab Blank	<LD	<LD	<LD	<LD	<0,47	<LD	<LD	<LD	0.061	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<0,05	<LD	<LD
		Lab Blank	<LD	<LD	<LD	<0.27	<0.47	<LD	<LD	<LD	0.061	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<0.05	<LD	<LD

Limit of Detection and Limit of Quantification values of elements analyzed in biochr. In instances where the measured value of element was less than LOQ, half the value of LOQ was used.

			Means of Main Elements in Biochar					
B. Name	Si	P	S	Fe	Ca	Mg	Na	K
	g/kg	g/kg	g/kg	g/kg	g/kg	g/kg	g/kg	g/kg
CWC-BC-500	0.08	0.36	14	0.33	6.96667	0.81667	0.044	3.5
CWC-BC-600	0.08	0.40667	17.7	0.21	7.9333	0.88333	0.05067	3.86667
CWC-BC-700	0.09	0.41	17	0.12533	8.0333	0.90667	0.05167	4.0333
CWC-BC-750	0.11	0.04433	18.7	0.13667	8.7	0.96333	0.05733	4.26667
WT-BC-500	2.733333333	0.433333333	1.566666667	3.566666667	9.366666667	1.866666667	1.133333333	2.666666667
WT-BC-600	2.233333333	0.533333333	1.933333333	4.333333333	11.33333333	2.233333333	1.2	3.133333333
WT-BC-700	2.466666667	0.613333333	2.266666667	5.133333333	12.33333333	2.733333333	1.433333333	3.433333333
WT-BC-800	2.366666667	0.536666667	2.533333333	4.966666667	13.33333333	2.733333333	1.2	3.766666667
Digested sludge Lu	0.573333333	11.83333333	8.066666667	166.6666667	22.33333333	4.166666667	1.366666667	3.333333333
Digested sludge Lund	0.506666667	9.666666667	6.366666667	166.6666667	23	4.133333333	1.5	3.5
Digested sludge Lund	0.62	8.033333333	7.233333333	180	26	4.7	1.833333333	3.733333333
Digested sludge Lund	0.713333333	7.366666667	8.1	180	27	4.7	1.933333333	3.766666667
MOVAR 500	0.773333333	38	7.433333333	66	21.66666667	3.766666667	0.983333333	4.466666667
MOVAR 600	1.146666667	42.66666667	7.866666667	74.33333333	23.33333333	4.166666667	1.1	5.033333333
MOVAR 700	1.073333333	44.33333333	8.366666667	76	24	4.3	1.2	4.966666667
MOVAR 800	1.09	47	8.233333333	81.33333333	25	4.7	1.6	5.066666667

			SD of Main Elements in biochar					
Name	sd.Si	sd.P	sd.S	sd.Fe	sd.Ca	sd.Mg	sd.Na	sd.K
	g/kg	g/kg	g/kg	g/kg	g/kg	g/kg	g/kg	g/kg
CWC-BC-500	0.01	0.03	0.302391725	0.23812	0.57735	0.04509	0.00173	0.17321
CWC-BC-600	0.881917104	0.03215	0.413192494	0.08544	0.45092	0.04509	0.00611	0.20817
CWC-BC-700	1.644294288	0.01	0.041765327	0.03931	0.15275	0.02309	0.00058	0.05774
CWC-BC-750	0.01155	0.01155	0.00577	0.03786	0.45826	0.02309	0.00153	0.05774
WT-BC-500	0.635085296	0.005773503	0.057735027	0.152752523	0.404145188	0.057735027	0.057735027	0.057735
WT-BC-600	0.351188458	0.028867513	0.057735027	0.152752523	0.577350269	0.152752523	0.1	0.057735
WT-BC-700	0.251661148	0.037859389	0.057735027	0.321455025	0.577350269	0.115470054	0.152752523	0.057735
WT-BC-800	0.56862407	0.02081666	0.057735027	0.152752523	0.577350269	0.057735027	0.1	0.057735
Digested sludg	0.090737717	2.020725942	0.929157324	5.773502692	0.577350269	0.115470054	0.057735027	0.057735
Digested sludge L	0.047258156	1.30128142	0.665832812	5.773502692	0	0.057735027	0	0
Digested sludge L	0.079372539	0.493288286	0.680685929	0	0	0.173205081	0.057735027	0.057735
Digested sludge L	0.225018518	0.602771377	0.953939201	0	0	0.1	0.057735027	0.057735
MOVAR 500	0.195021366	1	0.288675135	2.645751311	0.577350269	0.057735027	0.015275252	0.152753
MOVAR 600	0.493997301	0.577350269	0.057735027	0.577350269	0.577350269	0.057735027	0	0.208167
MOVAR 700	0.200333056	1.154700538	0.057735027	2	0	0.1	0	0.11547
MOVAR 800	0.215174348	1.732050808	0.152752523	0.577350269	0	0.1	0	0.208167

			Means of Trace Elements in Biochar									
B. Name	V	Cr	Co	Ni	Cu	As	Mo	Cd	Pb	Sr	Ba	Zn
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
CWC-BC-500	0.10567	4.56667	0.30333	3.6333	7.3	0.021	0.13333	0.00064	0.14833	0.033	0.18667	25.6667
CWC-BC-600	0.10033	3.096667	0.32667	2.63333	4.86667	0.014133	0.08267	0.00066	0.064	0.03733	0.23333	12.6667
CWC-BC-700	0.096	1.686667	0.3	1.766667	5.16667	0.010733	0.05633	0.00044	0.08033	0.03633	0.21667	3.2
CWC-BC-750	0.107	1.63	0.32333	1.9	5.06667	0.014667	0.057	0.0011	0.306	0.03967	0.23667	2.8
WT-BC-500	6.3	106.6666667	7.5	11	110	55	0.643333333	1.13	113.3333333	98	373.3333333	1200
WT-BC-600	7.133333333	153.3333333	9.666666667	20.33333333	160	64.33333333	0.696666667	0.048	92.66666667	126.6666667	476.6666667	1533.333333
WT-BC-700	9.066666667	163.3333333	11	21.66666667	130	63.33333333	0.79	0.068666667	45.33333333	150	536.6666667	263.3333333
WT-BC-800	8.7	136.6666667	11.33333333	21.33333333	153.3333333	59.33333333	0.446666667	0.022666667	24.33333333	150	583.3333333	108
DSL 500	45.66666667	48.33333333	8.133333333	30.33333333	233.3333333	3.166666667	16.66666667	0.743333333	22	103.3333333	150	690
DSL 600	47	50.33333333	8.6	31.33333333	243.3333333	2.866666667	16.33333333	0.196666667	21	110	156.6666667	706.666667
DSL 700	54	53.33333333	9.966666667	34.66666667	276.6666667	3.133333333	19	0.029	25.33333333	120	176.6666667	796.666667
DSL 800	56.33333333	62	11	39.33333333	290	3.5	19.66666667	0.026333333	24	130	180	796.666667
MOVAR 500	35.33333333	110	7.166666667	64	243.3333333	3.8	12	0.743333333	25.66666667	97	196.6666667	723.333333
MOVAR 600	39.33333333	52.33333333	7.4	34	220	4.133333333	11.66666667	0.087333333	15.66666667	103.3333333	210	620
MOVAR 700	39.33333333	50.66666667	7.7	34.33333333	223.3333333	4.166666667	11.66666667	0.024	16	110	216.6666667	630
MOVAR 800	40	51.33333333	7.4	34	230	4.366666667	12.33333333	0.0085	13	110	220	640

	Standard Deviations (SD) of trace elements in biochar											
Name	sd.V	sd.Cr	sd.Co	sd.Ni	sd.Cu	sd.As	sd.Mo	sd.Cd	sd.Pb	sd.Sr	sd.Ba	sd.Zn
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
CWC-BC-500	0.02178	2.5697	0.05774	1.50444	4.07308	0.01044	0.05686	0.0027	0.08893	0.00173	0.01155	3.511885
CWC-BC-600	0.0085	2.55774	0.02517	1.40475	0.35119	0.0048	0.04365	0.000208	0.00854	0.00252	0.02082	0.57735
CWC-BC-700	0.01637	1.22415	0.02646	0.64291	0.60277	0.00297	0.02194	0.0011	0.306	0.00208	0.00577	0.556776
CWC-BC-750	0.01473	0.8779	0.00577	0.3	0.20817	0.00416	0.0197	0.00015	0.3944	0.00153	0.00577	0
WT-BC-500	0.2	5.773502692	0.173205081	0	0	1.732050808	0.02081666	1.273146	5.773503	1.732051	5.773503	0
WT-BC-600	0.404145188	25.16611478	0.4163332	6.806859286	26.45751311	3.511884584	0.037859389	0.007211	7.505553	5.773503	25.16611	493.2883
WT-BC-700	0.907377173	11.54700538	0	5.686240703	10	4.932882862	0.026457513	0.005686	9.237604	0	11.54701	23.09401
WT-BC-800	0.458257569	15.27525232	0.577350269	5.131601439	25.16611478	2.081665999	0.005773503	0.002082	6.806859	0	15.27525	62.35383
DSL 500	2.081665999	3.511884584	0.351188458	0.577350269	5.773502692	0.230940108	0.577350269	0.075056	1.732051	5.773503	0	10
DSL 600	1	4.932882862	0.1	1.527525232	5.773502692	0.2081666	0.577350269	0.005774	0	0	5.773503	20.81666
DSL 700	1	1.527525232	0.057735027	0.577350269	5.773502692	0.2081666	0	0.002646	4.041452	0	5.773503	5.773503
DSL 800	1.154700538	1	0	0.577350269	0	0.346410162	0.577350269	0.002082	1	0	0	15.27525
MOVAR 500	1.154700538	0	0.2081666	2	15.27525232	0.1	0	0.023094	3.05505	2.645751	5.773503	51.31601
MOVAR 600	0.577350269	0.577350269	0.1	0	0	0.057735027	0.577350269	0.004726	0.57735	5.773503	0	10
MOVAR 700	1.154700538	1.154700538	0.3	0.577350269	5.773502692	0.057735027	0.577350269	0.003464	0	0	5.773503	10
MOVAR 800	1	2.309401077	0.173205081	1.732050808	0	0.057735027	0.577350269	0.001664	0	0	0	10

Appendix E Means of concentrations of main and trace elements in eluates

Elemental composition of eluates from batch leaching tests. The displayed values are means (n=3) of ICP-OES/MS analysis of eluates from biochar solution. CWC = clean wood chips, WT = waste wood, MOVAR = digested sludge from MOVAR waste handling company, DSL = digested sludge from Lindum waste handling company. The standard deviation depicts a measure of variation in the set of values

$$SD = \sqrt{\frac{\sum (X - \bar{X})^2}{n-1}}$$

Where SD = Standard deviation, X is a value in the dataset, $\bar{x}$ *is the average and* n *is the sample size.*

V. Liquid (mL)	pH		ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES
		LOD	0.000886	0.137229	0.003311	0.080727	0.139775	0.004866	0.004748	0.001101	0.016008	0.000	0.015	0.000	0.08449	0.000	0.000	0.000	0.016898	0.015	0.000	0.001669
		LOQ	0.002954	0.457429	0.011037	0.26909	0.465916	0.016221	0.015826	0.00367	0.053359	0.000	0.05	0.000	0.281634	0.000	0.000	0.000	0.056327	0.050	0.000	0.005565
			V	Cr	Co	Ni	Cu	As	Mo	Cd	Pb	Ba	Ca	Fe	K	Mg	Na	P	S	Si	Sr	Zn
		Sample Name	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
		Lab Blank	<LD	<0,38	<LD	<0,27	<0,47	<LD	<LD	<LD	0.059	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<0,05	<LD	<LD
		Lab Blank	<LD	<LD	<LD	<LD	<0,47	<LD	<LD	<LD	0.071	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<0,05	<LD	<LD
		Lab Blank	<LD	<LD	<LD	<LD	<0,47	<LD	<LD	<LD	0.061	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<0,05	<LD	<LD
		Lab Blank	<LD	<LD	<LD	<0.27	<0.47	<LD	<LD	<LD	0.061	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<0.05	<LD	<LD

Limit of Detection and Limit of Quantification values of elements analyzed in eluates. In instances where the measured value of element was less than LOQ, half the value of LOQ was used.

					Means of Main Elements in Eluates						
Biochar	Pyr. Temp	pH in Leachate	Target pH	Si	P	S	Fe	Ca	Mg	Na	K
				mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
CWC-BC	500	8.82	ambient	4.0661636	3.80605	3.5771	0.23888	67.987	17.289	7.1549	1844.7
CWC-BC	500	6.93	7	5.679697	4.58157	3.8006	0.39096	624.04	31.354	8.4877	1917.7
CWC-BC	500	4.5	5.5	8.5533896	6.70995	3.5231	124.674	1615.7	45.527	10.792	2056.2
CWC-BC	500	3.1	4	11.017994	23.2379	2.6933	784.469	2062.7	53.79	16.277	2208.6
CWC-BC	600	9.13	ambient	5.5320878	5.01919	3.6	0.19258	57.617	19.967	15.505	2304.2
CWC-BC	600	7.07	7	6.6907983	7.48814	3.3933	0.40306	744.73	33.615	19.489	2338.2
CWC-BC	600	4.86	5.5	10.295544	18.2301	3.8713	613.701	1673.3	49.481	20.935	2363.3
CWC-BC	600	3.66	4	13.160012	23.7008	3.4171	1034.11	2141	64.268	17.629	2551.7
CWC-BC	700	9.54	ambient	9.7017469	7.35274	7.5279	21.8456	54.527	36.714	15.7	2424.9
CWC-BC	700	6.02	7	17.004544	18.8805	7.8556	0.32991	2047.7	118.52	21.259	2778.2
CWC-BC	700	5.47	5.5	24.105011	44.9472	5.429	68.5247	2841	147.44	25.883	2804
CWC-BC	700	3.58	4	27.392391	55.4849	5.3991	131.48	2993.9	149.62	22.628	2700.9
CWC-BC	750	9.81	ambient	12.743207	4.59415	11.865	2.22233	57.548	72.151	22.37	2738.5
CWC-BC	750	6.81	7	21.609782	20.9862	11.998	1.52086	2555.5	208.7	26.88	2792
CWC-BC	750	5.88	5.5	29.43121	53.8086	10.036	17.4813	3670.6	232.6	29.802	2725.9
CWC-BC	750	3.39	4	37.513696	105.929	8.8123	113.841	4245.3	261.53	33.365	2916.4
WT-BC	500	9.21	ambient	20.769772	3.21213	725.75	0.37517	521.67	49.914	636.02	1103.1
WT-BC	500	6.66	7	35.827972	6.52085	728.67	0.19782	1331.3	73.507	681.16	1298.8
WT-BC	500	4.96	5.5	91.273728	36.5756	715.73	620.041	3276	286.24	823.81	1558.7
WT-BC	500	4.03	4	111.3386	52.1729	693.42	1049.65	3531	334.02	846.13	1590.5
WT-BC	600	10.23	ambient	41.434744	1.32275	185.64	0.62305	65.193	19.167	338.65	1080.1
WT-BC	600	6.69	7	71.330415	0.08215	143.48	3.72763	2077.6	366.71	427.49	1404.6
WT-BC	600	5.13	5.5	214.48787	0.09197	101.93	1662.82	4577	595.29	569.59	1633.1
WT-BC	600	4.26	4	755.40259	71.4233	76.894	1204.85	5623.5	718.96	740.11	1714
WT-BC	700	11.64	ambient	61.031558	0.07943	359.86	0.50297	153.88	0.3296	289.05	1107.3
WT-BC	700	7.04	7	150.8538	0.3741	208.12	11.9966	3921	552	428.29	1719.3
WT-BC	700	4.7	5.5	671.61568	17.5811	117.92	844.209	5835.3	722.67	595.78	1875.1
WT-BC	700	3.57	4	1017.756	77.895	111.03	1895.36	6660.3	857.29	761.58	2035.5
WT-BC	800	11.98	ambient	34.483883	0.05592	493.7	0.2289	765.97	0.1758	192.53	910.16
WT-BC	800	6.76	7	359.8564	0.05584	403.06	86.5006	7412.4	787.78	356.71	1768.4
WT-BC	800	4.64	5.5	644.4552	1.01383	346.87	554.312	8641.7	885.97	427.44	1952.1
WT-BC	800	3.7	4	1437.8316	98.6999	286.77	1592.21	9170.6	1030.3	618.04	1996.9

				Means of Main Elements in Eluates							
Biochar	Pyr. Temp	pH in Leachate	Target pH	Si	P	S	Fe	Ca	Mg	Na	K
				mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
DSL - BC	500	6.97	ambient	19.464149	0.54668	2120	0.26998	2025.4	306.91	354.42	226.32
DSL - BC	500	5.24	5.5	119.12083	0.54743	1649.9	17.4897	5719.3	653.27	463.85	369.06
DSL - BC	500	3.77	4	371.15575	10.1111	878.79	616.973	8627.7	878.79	569.5	553.47
DSL - BC	600	6.71	ambient	36.146041	0.57232	2389.1	0.20712	2005.4	408.14	329.73	338.49
DSL - BC	600	5.24	5.5	165.65741	0.63776	1965.7	0.95044	4502	655.7	400.22	484.86
DSL - BC	600	4.26	4	308.84845	0.54788	1459.3	76.665	6302.1	845.61	481.05	630.21
DSL - BC	700	9.68	ambient	121.04627	11.6988	45.191	0.58537	4.7505	3.3614	138.65	213.71
DSL - BC	700	6.44	7	759.59277	1814.43	157.36	43032.9	9830.4	1651.7	1106.4	2052.3
DSL - BC	700	5.53	5.5	234.10139	15.6192	152.26	15614.7	5898.5	972.1	842.27	1494.4
DSL - BC	700	3.84	4	1074.3988	2668.9	176.34	56775.5	11196	1655.6	842.79	1363.7
DSL - BC	800	9.04	ambient	7.5824788	43.1611	51.08	2.57147	2.6693	1.6965	245.6	357.71
DSL - BC	800	6.63	7	33.575704	0.53671	24.263	2196.55	1977.3	470.5	564.96	964.02
DSL - BC	800	5.44	5.5	497.35119	148.55	88.044	32054.9	8470.8	1229.5	714.07	1029.3
DSL - BC	800	4.05	4	909.3032	2323.49	123.33	63287.5	12332	1704	827.61	1119.7
MOVAR BC	500	8.38	ambient	6.3622476	1.0072	166.18	5.30088	108.62	30.798	270.37	625
MOVAR BC	500	6.8	7	16.632608	0.4925	68.015	118.004	1906.5	280.63	363.76	898.15
MOVAR BC	500	5.17	5.5	85.26033	1.91542	11.763	3187.1	6045.2	644	462.74	1201.1
MOVAR BC	500	3.8	4	246.39399	135.624	11.302	8137.45	8815.6	813.74	517.66	1356.2
MOVAR BC	600	8.41	ambient	4.5954252	0.86068	45.306	0.75731	20.842	7.2277	219.08	478.52
MOVAR BC	600	7.18	7	15.279742	0.53231	11.621	820.801	2123.6	451.47	382.99	999.32
MOVAR BC	600	5.53	5.5	72.441078	0.99077	4.4048	9056.11	5907.4	761.57	442.48	1173.1
MOVAR BC	600	3.35	4	324.25253	338.08	4.7856	20358.4	9162.6	977.34	502.94	1364.2
MOVAR BC	700	8.48	ambient	7.1821276	1.33914	38.408	0.55449	30.597	16.013	189.02	414.96
MOVAR BC	700	6.79	7	13.877239	0.53862	31.318	0.26153	652.93	224.75	269.42	693.12
MOVAR BC	700	3.97	5.5	226.90959	24.7978	16.137	11345	4269.2	587.97	301.15	804.49
MOVAR BC	700	3.76	4	520.84183	831.653	11.555	22488	8104.7	992.85	504.47	1276.6
MOVAR BC	800	8.58	ambient	19.574391	27.0196	14.859	4.5186	20.993	12.668	146.45	312.6
MOVAR BC	800	6.54	7	31.133164	0.54472	15.459	4.50231	337.66	164.75	229.91	571.75
MOVAR BC	800	5.5	5.5	472.79044	5.68361	18.226	9829.24	4525.2	777.84	460.69	1167.2
MOVAR BC	800	4	4	1332.2387	1557.34	37.904	19262.5	8810.1	1004	594.3	1557.3

				Means of Trace Elements in Eluates											
Biochar	Pyr. Temp	pH in Leachat	Target pH	V	Cr	Co	Ni	Cu	As	Mo	Cd	Pb	Sr	Ba	Zn
				µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg
CWC-BC	500	8.82	ambient	1.3083902	1.3355633	0.2229532	1.977374	3.3752666	1.9302554	9.7183214	0.1447403	35.97081	0.4846303	1.6486867	0.1983571
CWC-BC	500	6.93	7	0.7445248	1.1729404	5.9979688	129.11478	5.8142505	1.8018868	9.3688215	0.0477829	39.871922	2.0675802	8.0072834	0.8634022
CWC-BC	500	4.5	5.5	0.4036112	13.32891	24.233592	1057.3223	20.251164	3.3366328	1.1608539	0.5141028	55.055592	4.1488485	14.317922	4.4418987
CWC-BC	500	3.1	4	3.0394323	82.920573	40.185027	1952.6879	78.23235	7.0937956	0.0939749	0.4311429	179.73731	5.6732964	19.900571	6.3760765
CWC-BC	600	9.13	ambient	1.8915303	0	0.2427184	1.9241031	5.0021722	2.4812884	10.509073	0.0467115	66.203508	0.4782642	1.9593685	0.1219464
CWC-BC	600	7.07	7	0.8706331	0	7.8597012	227.54973	3.2672983	2.1365215	7.8671881	0.2430461	52.086927	2.1623566	9.1739752	0.6352406
CWC-BC	600	4.86	5.5	2.6517238	50.223443	33.743183	1379.9462	40.988956	3.7304731	0.1635045	0.1364498	78.788131	4.2199132	16.733172	2.58161
CWC-BC	600	3.66	4	5.6406697	91.779929	45.036113	1912.1477	56.074789	4.673907	0.0834651	0.3907357	92.054513	5.7870546	22.173317	3.1952746
CWC-BC	700	9.54	ambient	4.9996857	0	0.4765945	0	8.4225474	4.3473571	24.976854	0.0454876	38.690293	0.4241037	1.0049349	0.081965
CWC-BC	700	6.02	7	1.3610334	0	29.194831	606.24831	6.1325235	2.2713364	11.342805	0.1426753	47.904597	6.299629	21.259499	0.5292858
CWC-BC	700	5.47	5.5	4.7639204	104.11803	57.897891	1511.684	20.091627	4.0916482	0.2278329	0.4519585	66.494439	8.5588115	33.065437	1.2575114
CWC-BC	700	3.58	4	7.0499079	156.94631	72.674842	1863.034	20.795121	5.1106496	0.195617	0.3307941	76.923553	9.0540319	39.769456	1.460544
CWC-BC	750	9.81	ambient	6.4319698	0	0.1798375	0	5.0102364	3.1000473	25.046332	0.0475647	32.165944	0.5101547	1.0944319	0.0071839
CWC-BC	750	6.81	7	1.497802	0	17.100946	300.14806	1.3343089	3.6667891	13.118076	0	26.017359	8.2273365	26.29492	0.1025265
CWC-BC	750	5.88	5.5	1.2673488	33.80402	48.712446	1305.4018	10.637142	4.5830448	0.1910798	0.2346477	49.354841	10.757825	41.804683	0.941331
CWC-BC	750	3.39	4	7.7577141	135.78218	69.205647	1965.6319	15.532612	7.6421314	0.0705842	0.2364158	58.068081	12.892026	52.644566	1.4398324
WT-BC	500	9.21	ambient	23.83026	7.5183859	2.1926245	0.400641	4.5467677	1138.2616	32.183493	0.3226975	19.216795	7.0507025	0.8976439	0.2288778
WT-BC	500	6.66	7	11.711068	0	70.207263	21.322412	8.2972923	1363.8562	30.378547	4.2553851	17.66831	21.246014	1.8082274	16.904331
WT-BC	500	4.96	5.5	28.297254	103.65299	349.86402	356.00645	384.85166	2958.1659	0.1178254	54.071812	3720.3171	42.626147	2.0991352	219.45559
WT-BC	500	4.03	4	60.7646	168.62874	397.64307	302.22043	642.50024	3435.5806	0.1681401	69.039436	6967.6806	44.531783	2.004241	264.01482
WT-BC	600	10.23	ambient	99.007155	0	0.8916191	0	3.9585656	530.80119	102.05966	0.0391604	44.797816	1.913508	2.6922382	0.0212145
WT-BC	600	6.69	7	2.1038901	0	125.05696	219.53405	8.7488371	271.686	78.099691	0.4811512	39.383137	29.952104	20.175015	29.402103
WT-BC	600	5.13	5.5	0.2356444	3.4332085	592.26348	1726.2783	61.164633	80.587296	0.2315444	4.401465	258.85822	55.357095	22.382797	214.46467
WT-BC	600	4.26	4	446.04737	696.07325	1022.6172	3068.1152	292.21408	4455.1955	0.8853076	13.505594	12947.768	61.70218	34.082502	432.6477
WT-BC	700	11.64	ambient	110.75811	0.6972455	0.0729572	0.2415564	1.7531597	114.34575	289.01803	0.0405318	23.646163	9.551507	8.3188778	0.0060168
WT-BC	700	7.04	7	0.4932897	0.0324851	370.80407	831.96292	11.666795	235.36824	96.539453	1.0436782	27.159814	53.062927	18.105389	21.565131
WT-BC	700	4.7	5.5	227.15898	463.03628	1269.8763	2993.7111	205.94286	2571.9226	0.6136789	6.6811473	1696.7326	70.785473	31.15724	52.351077
WT-BC	700	3.57	4	554.83891	1017.756	1851.969	3920.6806	240.85016	5638.237	1.0038138	10.78362	4188.1677	79.283125	38.266537	66.898114
WT-BC	800	11.98	ambient	37.625016	2.6500639	0.0718391	0	1.770794	11.270866	384.7944	0	25.569766	24.447772	9.7152519	0.0095785
WT-BC	800	6.76	7	0.1556955	1.0377358	672.97063	1487.3082	24.731206	359.1714	61.319921	0.7138246	29.921217	78.838779	12.717851	7.5160878
WT-BC	800	4.64	5.5	2.5701766	57.359722	1177.4779	2477.7409	105.1802	763.13103	1.5206787	1.9889045	81.552541	84.505896	11.470643	14.247869
WT-BC	800	3.7	4	611.30034	1407.7473	1840.2533	3520.9708	185.83283	5665.1223	1.0934327	5.2732722	4843.8173	92.012663	18.811998	23.65224

							Means of Trace Elements in Eluates								
Biochar	Pyr. Temp	pH in Leachate	Target pH	V	Cr	Co	Ni	Cu	As	Mo	Cd	Pb	Sr	Ba	Zn
				µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg
DSL - BC	500	6.97	ambient	0.46308288	12.2679093	1.28150921	16.323041	27.8692733	0.484446	118.721439	0.10960839	22.84030913	2.07290407	0.09494856	0.034194
DSL - BC	500	5.24	5.5	0.09820829	4.16494553	84.6554371	45.238424	30.8429121	0.6752226	1.49355406	7.14783538	30.30462478	9.79984546	1.10677736	6.36214
DSL - BC	500	3.77	4	13.1012994	37.3993628	439.496448	418.743	160.886784	2.8915789	1.29294729	60.2316882	46.13675532	21.3249533	4.62267406	56.975685
DSL - BC	600	6.71	ambient	0.37838655	1.48513313	2.72742703	1.773764	28.4934118	0.5948672	35.655003	0.08011015	25.19890459	1.91778226	0.06951188	0.0264205
DSL - BC	600	5.24	5.5	0.15604772	3.63392218	100.094054	122.70953	42.3529461	0.5099177	0.36981408	1.41689182	42.56608511	7.59191488	0.7598804	2.1923666
DSL - BC	600	4.26	4	0.16452884	3.31052883	345.29361	388.44768	156.186968	0.7128393	0.18044713	6.49507953	41.43544685	14.2641936	2.20994704	11.480585
DSL - BC	700	9.68	ambient	0.51696338	3.44798357	0.03539805	8.5013354	28.2151833	4.761607	105.28949	0.06307962	10.63887554	0.00737463	0.17080419	0.0204538
DSL - BC	700	6.44	7	0.87382426	5.65390396	72.3547271	78.841001	41.0204679	1.6323723	0.26205357	0.12774467	45.8578404	33.8431534	3.32337523	3.8235066
DSL - BC	700	5.53	5.5	0.39387034	1.29655843	13.8765751	30.348539	70.1947435	2.1546793	146.520265	0.16834922	44.85436438	21.0397834	6.38458585	1.4344831
DSL - BC	700	3.84	4	1.54156386	6.11240684	92.0749736	101.68407	24.3373754	1.5373745	0.17774518	0.07373073	29.57061064	40.6198179	1.59760067	5.2176737
DSL - BC	800	9.04	ambient	0.4712308	0.94030312	0.01638602	0.9512139	27.8019746	1.5062086	202.929901	0.04557917	13.08196889	0	0.04948964	0.0138571
DSL - BC	800	6.63	7	0.00544298	1.89539025	1.54494858	2.8706465	27.0981739	0.0242731	0.23788075	0.05489641	37.35163283	5.47986764	1.73985362	0.216582
DSL - BC	800	5.44	5.5	1.15717727	4.43159242	43.1943123	128.95863	80.0638109	5.7645012	0.30440139	0.1231021	37.30741766	31.0677168	2.20850274	2.8914099
DSL - BC	800	4.05	4	1.75038919	8.13476124	29.5783618	60.207294	21.9081248	1.6530539	0.27867356	0.04384442	29.62748393	43.9761985	1.34497606	5.355093
MOVAR BC	500	8.38	ambient	1.19734855	8.45026128	0.4714505	0.5368398	2153.03661	1.8423258	1440.49182	0.31691719	68.23170224	0.33250326	0.15552383	1.6188976
MOVAR BC	500	6.8	7	0.03576525	7.45257674	21.7080648	37.22596	1862.7122	0.9841246	20.4351035	0.82921353	70.14340203	4.9095052	1.72887758	2.2698501
MOVAR BC	500	5.17	5.5	1.95192502	29.8995388	161.582866	574.74922	1920.47967	16.181387	1.28039658	22.5040605	146.878744	17.2382127	14.8464926	31.030093
MOVAR BC	500	3.8	4	144.712747	257.691911	375.224608	1537.0321	2034.42274	57.19225	2.34997889	60.5828522	1001.740407	27.5771032	29.385629	66.682868
MOVAR BC	600	8.41	ambient	3.11602844	6.18992073	0.0751345	0.6294618	31.968958	0.3857887	1616.70252	0.32755286	22.31381583	0.06382635	0.02104377	0.0691106
MOVAR BC	600	7.18	7	0.03481981	2.64351446	18.7305548	47.057549	43.6255757	0.1842032	0.05544186	0.17333079	24.14564345	5.39394213	1.88013477	0.4387209
MOVAR BC	600	5.53	5.5	0.47405586	2.85503892	148.300253	613.57511	120.672171	2.5295479	0.25976711	1.09191012	63.15261556	17.4969533	10.8999551	10.97738
MOVAR BC	600	3.35	4	154.31973	209.831823	324.004789	1201.9481	56.4761133	34.898664	22.9079971	3.80448259	161.9100623	29.9250685	26.4717224	39.951211
MOVAR BC	700	8.48	ambient	1.76745071	3.04960541	0.02041227	3.8966587	17.4778236	0.0364634	476.551894	0.14167237	14.37285316	0.06164988	0.02099076	0.0508422
MOVAR BC	700	6.79	7	0.21215188	2.24912725	3.81510569	7.2436572	22.2722683	0.6342131	12.9827361	0.13649487	17.35742823	1.28588563	0.20474172	0.052552
MOVAR BC	700	3.97	5.5	31.2008984	19.0495722	158.715735	618.33637	136.211108	3.2438261	1.479894	0.349987	92.85824493	12.1681974	8.45960219	8.0448827
MOVAR BC	700	3.76	4	196.726539	113.561273	330.392968	1277.6157	55.5021341	6.8939039	15.599141	0.40958357	56.03691485	24.3117984	22.7022409	12.665301
MOVAR BC	800	8.58	ambient	5.29372099	0.91721553	0.09788586	1.9597258	22.7309221	1.0841706	1210.60533	0.22665775	12.66004323	0.03969694	0.05935103	0.0557016
MOVAR BC	800	6.54	7	0.01411906	8.29147144	2.32071808	16.725921	28.3610966	0.029703	9.21614482	0.06624596	24.77794806	0.48833513	0.08151691	0.0711238
MOVAR BC	800	5.5	5.5	0.67589747	1.77401844	26.0285992	72.483741	43.1214078	2.844032	0.30632067	0.11706295	32.8354555	10.2357543	1.57591537	1.9652933
MOVAR BC	800	4	4	206.985691	202.859874	133.183022	442.54632	81.9305635	0.4989097	0.82054302	0.13853518	38.39163335	27.4578019	21.9241782	9.4249714

Appendix F Comparison of Concentrations of Trace Elements Leached from Waste Biochar with Reference Biochar

Trace elements leached from waste biochar i.e waste timber (WT), digested sludge from Lindum (DSL) and digested sludge from MOVAR (MOVAR) were compared with leaching from the reference biochar, clean wood chips biochar (CWC). The values displayed are means of concentrations of elements (n=3). Number attached to biochar is pyrolysis temperature, pH displayed is the measured pH of leachate. Blue highlight are concentrations of elements in reference biochar, green highlight are concentrations of elements =/< concentrations in reference biochar, unhighlighted values are concentrations of elements higher than concentrations in leachate of reference biochar.

Cu and Zn Concentrations were particularly high for all waste biochar at all pHs except (WT-600, WT 700 and WT-800 leached at ambient pH)

Trace Element		Cr														
Eluate of **Reference** Biochar and pH	CWC-BC-500 pH 8.82	CWC-BC-500 pH 6.93	CWC-BC-500 pH 4.5	CWC-BC-500 pH 3.1	CWC-BC-600 pH 9.13	CWC-BC-600 pH 7.07	CWC-BC-600 pH 4.86	CWC-BC-600 pH 3.66	CWC-BC-700 pH 9.54	CWC-BC-700 pH 6.02	CWC-BC-700 pH 5.47	CWC-BC-700 pH 3.58	CWC-BC-750 pH 9.81	CWC-BC-750 pH 6.81	CWC-BC-750 pH 5.88	CWC-BC-750 pH 3.39
Ref. Conc (µg/kg)	1.34	1.17	13.33	82.92	0.00	0.00	50.22	91.78	0.00	0.00	104.12	156.95	0.00	0.00	33.80	135.78
Eluate of biochar and pH	WT-BC-500 pH 9.21	WT-BC-500 pH 6.66	WT-BC-500 pH 4.96	WT-BC-500 pH 4.03	WT-BC-600 pH 10.23	WT-BC-600 pH 6.69	WT-BC-600 pH 5.13	WT-BC-600 pH 4.26	WT-BC-700 pH 11.64	WT-BC-700 pH 7.04	WT-BC-700 pH 4.7	WT-BC-700 pH 3.57	WT-BC-800 pH 11.98	WT-BC-800 pH 6.76	WT-BC-800 pH 4.64	WT-BC-800 pH 3.7
Conc of Element(µg/kg)	7.52	0.00	103.65	168.63	0.00	0.00	3.43	696.07	0.70	0.03	463.04	1017.76	2.65	1.04	57.36	1407.75
Eluate of biochar and pH	DSL 500 pH 6.97	DSL 500 pH 5.24	DSL 500 pH 3.77	N/A	DSL 600 pH 6.71	DSL 600 pH 5.24	DSL 600 pH 4.26	N/A	DSL 700 pH 9.68	DSL 700 pH 6.44	DSL 700 pH 5.53	DSL 700 pH 3.84	DSL 800 pH 9.04	DSL 800 pH 6.63	DSL 800 pH 5.44	DSL 800 pH 4.05
Conc of Element(µg/kg)	12.27	4.16	37.40	N/A	1.49	3.63	3.31	N/A	3.45	5.65	1.30	6.11	0.94	1.90	4.43	8.13
Eluate of biochar and pH	MOVAR 500 pH 8.38	MOVAR 500 pH 6.8	MOVAR 500 pH 5.17	MOVAR 500 pH 3.8	MOVAR 600 pH 8.41	MOVAR 600 pH 7.18	MOVAR 600 pH 5.53	MOVAR 600 pH 3.35	MOVAR 700 pH 8.48	MOVAR 700 pH 6.79	MOVAR 700 pH 3.97	MOVAR 700 pH 3.76	MOVAR 800 pH 8.58	MOVAR 800 pH 6.54	MOVAR 800 pH 5.5	MOVAR 800 pH 4.0
Conc of Element(µg/kg)	8.45	7.45	29.90	257.69	6.19	2.64	2.86	209.83	3.05	2.25	19.05	113.56	0.92	8.29	1.77	202.86

Trace Element	Co															
Eluate of **Reference** Biochar and pH	CWC-BC-500 pH 8.82	CWC-BC-500 pH 6.93	CWC-BC-500 pH 4.5	CWC-BC-500 pH 3.1	CWC-BC-600 pH 9.13	CWC-BC-600 pH 7.07	CWC-BC-600 pH 4.86	CWC-BC-600 pH 3.66	CWC-BC-700 pH 9.54	CWC-BC-700 pH 6.02	CWC-BC-700 pH 5.47	CWC-BC-700 pH 3.58	CWC-BC-750 pH 9.81	CWC-BC-750 pH 6.81	CWC-BC-750 pH 5.88	CWC-BC-750 pH 3.39
Ref. Conc (µg/kg)	0.22	6.00	24.23	40.19	0.24	7.86	33.74	45.04	0.48	29.19	57.90	72.67	0.18	17.10	48.71	69.21
Eluate of biochar and pH	WT-BC-500 pH 9.21	WT-BC-500 pH 6.66	WT-BC-500 pH 4.96	WT-BC-500 pH 4.03	WT-BC-600 pH 10.23	WT-BC-600 pH 6.69	WT-BC-600 pH 5.13	WT-BC-600 pH 4.26	WT-BC-700 pH 11.64	WT-BC-700 pH 7.04	WT-BC-700 pH 4.7	WT-BC-700 pH 3.57	WT-BC-800 pH 11.98	WT-BC-800 pH 6.76	WT-BC-800 pH 4.64	WT-BC-800 pH 3.7
Conc of Element(µg/kg)	2.19	70.21	349.86	397.64	0.89	125.06	592.26	1022.62	0.07	370.80	1269.88	1851.97	0.07	672.97	1177.48	1840.25
Eluate of biochar and pH	DSL 500 pH 6.97	DSL 500 pH 5.24	DSL 500 pH 3.77	N/A	DSL 600 pH 6.71	DSL 600 pH 5.24	DSL 600 pH 4.26	N/A	DSL 700 pH 9.68	DSL 700 pH 6.44	DSL 700 pH 5.53	DSL 700 pH 3.84	DSL 800 pH 9.04	DSL 800 pH 6.63	DSL 800 pH 5.44	DSL 800 pH 4.05
Conc of Element(µg/kg)	12.27	4.16	37.40	N/A	1.49	3.63	3.31	N/A	3.45	5.65	1.30	6.11	0.94	1.90	4.43	8.13
Eluate of biochar and pH	MOVAR 500 pH 8.38	MOVAR 500 pH 6.8	MOVAR 500 pH 5.17	MOVAR 500 pH 3.8	MOVAR 600 pH 8.41	MOVAR 600 pH 7.18	MOVAR 600 pH 5.53	MOVAR 600 pH 3.35	MOVAR 700 pH 8.48	MOVAR 700 pH 6.79	MOVAR 700 pH 3.97	MOVAR 700 pH 3.76	MOVAR 800 pH 8.58	MOVAR 800 pH 6.54	MOVAR 800 pH 5.5	MOVAR 800 pH 4.0
Conc of Element(µg/kg)	0.47	21.71	161.58	375.22	0.08	18.73	148.30	324.00	0.02	3.82	158.72	330.39	0.10	2.32	26.03	133.18

Trace Element	Ni															
Eluate of Reference Biochar and pH	CWC-BC-500 pH 8.82	CWC-BC-500 pH 6.93	CWC-BC-500 pH 4.5	CWC-BC-500 pH 3.1	CWC-BC-600 pH 9.13	CWC-BC-600 pH 7.07	CWC-BC-600 pH 4.86	CWC-BC-600 pH 3.66	CWC-BC-700 pH 9.54	CWC-BC-700 pH 6.02	CWC-BC-700 pH 5.47	CWC-BC-700 pH 3.58	CWC-BC-750 pH 9.81	CWC-BC-750 pH 6.81	CWC-BC-750 pH 5.88	CWC-BC-750 pH 3.39
Ref. Conc (µg/kg)	1.98	129.11	1057.32	1952.69	1.92	227.55	1379.95	1912.15	0.00	606.25	1511.68	1863.03	0.00	300.15	1305.40	1965.63
Eluate of biochar and pH	WT-BC-500 pH 9.21	WT-BC-500 pH 6.66	WT-BC-500 pH 4.96	WT-BC-500 pH 4.03	WT-BC-600 pH 10.23	WT-BC-600 pH 6.69	WT-BC-600 pH 5.13	WT-BC-600 pH 4.26	WT-BC-700 pH 11.64	WT-BC-700 pH 7.04	WT-BC-700 pH 4.7	WT-BC-700 pH 3.57	WT-BC-800 pH 11.98	WT-BC-800 pH 6.76	WT-BC-800 pH 4.64	WT-BC-800 pH 3.7
Conc of Element(µg/kg)	0.40	21.32	356.01	302.22	0.00	219.53	1726.28	3068.12	0.24	831.96	2993.71	3920.68	0.00	1487.31	2477.74	3520.97
Eluate of biochar and pH	DSL 500 pH 6.97	DSL 500 pH 5.24	DSL 500 pH 3.77	N/A	DSL 600 pH 6.71	DSL 600 pH 5.24	DSL 600 pH 4.26	N/A	DSL 700 pH 9.68	DSL 700 pH 6.44	DSL 700 pH 5.53	DSL 700 pH 3.84	DSL 800 pH 9.04	DSL 800 pH 6.63	DSL 800 pH 5.44	DSL 800 pH 4.05
Conc of Element(µg/kg)	16.32	45.24	418.74	N/A	1.77	122.71	388.45	N/A	8.50	78.84	30.35	101.68	0.95	2.87	128.96	60.21
Eluate of biochar and pH	MOVAR 500 pH 8.38	MOVAR 500 pH 6.8	MOVAR 500 pH 5.17	MOVAR 500 pH 3.8	MOVAR 600 pH 8.41	MOVAR 600 pH 7.18	MOVAR 600 pH 5.53	MOVAR 600 pH 3.35	MOVAR 700 pH 8.48	MOVAR 700 pH 6.79	MOVAR 700 pH 3.97	MOVAR 700 pH 3.76	MOVAR 800 pH 8.58	MOVAR 800 pH 6.54	MOVAR 800 pH 5.5	MOVAR 800 pH 4.0
Conc of Element(µg/kg)	0.54	37.23	574.75	1537.03	0.63	47.06	613.58	1201.95	3.90	7.24	618.34	1277.62	1.96	16.73	72.48	442.55
Trace Element	Cu															
Eluate of Reference Biochar and pH	CWC-BC-500 pH 8.82	CWC-BC-500 pH 6.93	CWC-BC-500 pH 4.5	CWC-BC-500 pH 3.1	CWC-BC-600 pH 9.13	CWC-BC-600 pH 7.07	CWC-BC-600 pH 4.86	CWC-BC-600 pH 3.66	CWC-BC-700 pH 9.54	CWC-BC-700 pH 6.02	CWC-BC-700 pH 5.47	CWC-BC-700 pH 3.58	CWC-BC-750 pH 9.81	CWC-BC-750 pH 6.81	CWC-BC-750 pH 5.88	CWC-BC-750 pH 3.39
Ref. Conc (µg/kg)	3.38	5.81	20.25	78.23	5.00	3.27	40.99	56.07	8.42	6.13	20.09	20.80	5.01	1.33	10.64	15.53
Eluate of biochar and pH	WT-BC-500 pH 9.21	WT-BC-500 pH 6.66	WT-BC-500 pH 4.96	WT-BC-500 pH 4.03	WT-BC-600 pH 10.23	WT-BC-600 pH 6.69	WT-BC-600 pH 5.13	WT-BC-600 pH 4.26	WT-BC-700 pH 11.64	WT-BC-700 pH 7.04	WT-BC-700 pH 4.7	WT-BC-700 pH 3.57	WT-BC-800 pH 11.98	WT-BC-800 pH 6.76	WT-BC-800 pH 4.64	WT-BC-800 pH 3.7
Conc of Element(µg/kg)	4.55	8.30	384.85	642.50	3.96	8.75	61.16	292.21	1.75	11.67	205.94	240.85	1.77	24.73	105.18	185.83
Eluate of biochar and pH	DSL 500 pH 6.97	DSL 500 pH 5.24	DSL 500 pH 3.77	N/A	DSL 600 pH 6.71	DSL 600 pH 5.24	DSL 600 pH 4.26	N/A	DSL 700 pH 9.68	DSL 700 pH 6.44	DSL 700 pH 5.53	DSL 700 pH 3.84	DSL 800 pH 9.04	DSL 800 pH 6.63	DSL 800 pH 5.44	DSL 800 pH 4.05
Conc of Element(µg/kg)	27.87	30.84	160.89	N/A	28.49	42.35	156.19	N/A	28.22	41.02	70.19	24.34	27.80	27.10	80.06	21.91
Eluate of biochar and pH	MOVAR 500 pH 8.38	MOVAR 500 pH 6.8	MOVAR 500 pH 5.17	MOVAR 500 pH 3.8	MOVAR 600 pH 8.41	MOVAR 600 pH 7.18	MOVAR 600 pH 5.53	MOVAR 600 pH 3.35	MOVAR 700 pH 8.48	MOVAR 700 pH 6.79	MOVAR 700 pH 3.97	MOVAR 700 pH 3.76	MOVAR 800 pH 8.58	MOVAR 800 pH 6.54	MOVAR 800 pH 5.5	MOVAR 800 pH 4.0
Conc of Element(µg/kg)	2153.04	1862.71	1920.48	2034.42	31.97	43.63	120.67	56.48	17.48	22.27	136.21	55.50	22.73	28.36	43.12	81.93

Trace Element	As															
Eluate of Reference Biochar and pH	CWC-BC-500 pH 8.82	CWC-BC-500 pH 6.93	CWC-BC-500 pH 4.5	CWC-BC-500 pH 3.1	CWC-BC-600 pH 9.13	CWC-BC-600 pH 7.07	CWC-BC-600 pH 4.86	CWC-BC-600 pH 3.66	CWC-BC-700 pH 9.54	CWC-BC-700 pH 6.02	CWC-BC-700 pH 5.47	CWC-BC-700 pH 3.58	CWC-BC-750 pH 9.81	CWC-BC-750 pH 6.81	CWC-BC-750 pH 5.88	CWC-BC-750 pH 3.39
Ref. Conc (µg/kg)	1.93	1.80	3.34	7.09	2.48	2.14	3.73	4.67	4.35	2.27	4.09	5.11	3.10	3.67	4.58	7.64
Eluate of biochar and pH	WT-BC-500 pH 9.21	WT-BC-500 pH 6.66	WT-BC-500 pH 4.96	WT-BC-500 pH 4.03	WT-BC-600 pH 10.23	WT-BC-600 pH 6.69	WT-BC-600 pH 5.13	WT-BC-600 pH 4.26	WT-BC-700 pH 11.64	WT-BC-700 pH 7.04	WT-BC-700 pH 4.7	WT-BC-700 pH 3.57	WT-BC-800 pH 11.98	WT-BC-800 pH 6.76	WT-BC-800 pH 4.64	WT-BC-800 pH 3.7
Conc of Element(µg/kg)	1138.26	1363.86	2958.17	3435.58	530.80	271.69	80.59	4455.20	114.35	235.37	2571.92	5638.24	11.27	359.17	763.13	5665.12
Eluate of biochar and pH	DSL 500 pH 6.97	DSL 500 pH 5.24	DSL 500 pH 3.77	N/A	DSL 600 pH 6.71	DSL 600 pH 5.24	DSL 600 pH 4.26	N/A	DSL 700 pH 9.68	DSL 700 pH 6.44	DSL 700 pH 5.53	DSL 700 pH 3.84	DSL 800 pH 9.04	DSL 800 pH 6.63	DSL 800 pH 5.44	DSL 800 pH 4.05
Conc of Element(µg/kg)	0.48	0.68	2.89	N/A	0.59	0.51	0.71	N/A	4.76	1.63	2.15	1.54	1.51	0.02	5.76	1.65
Eluate of biochar and pH	MOVAR 500 pH 8.38	MOVAR 500 pH 6.8	MOVAR 500 pH 5.17	MOVAR 500 pH 3.8	MOVAR 600 pH 8.41	MOVAR 600 pH 7.18	MOVAR 600 pH 5.53	MOVAR 600 pH 3.35	MOVAR 700 pH 8.48	MOVAR 700 pH 6.79	MOVAR 700 pH 3.97	MOVAR 700 pH 3.76	MOVAR 800 pH 8.58	MOVAR 800 pH 6.54	MOVAR 800 pH 5.5	MOVAR 800 pH 4.0
Conc of Element(µg/kg)	1.84	0.98	16.18	57.19	0.39	0.18	2.53	34.90	0.04	0.63	3.24	6.89	1.08	0.03	2.84	0.50
Trace Element	Cd															
Eluate of Reference Biochar and pH	CWC-BC-500 pH 8.82	CWC-BC-500 pH 6.93	CWC-BC-500 pH 4.5	CWC-BC-500 pH 3.1	CWC-BC-600 pH 9.13	CWC-BC-600 pH 7.07	CWC-BC-600 pH 4.86	CWC-BC-600 pH 3.66	CWC-BC-700 pH 9.54	CWC-BC-700 pH 6.02	CWC-BC-700 pH 5.47	CWC-BC-700 pH 3.58	CWC-BC-750 pH 9.81	CWC-BC-750 pH 6.81	CWC-BC-750 pH 5.88	CWC-BC-750 pH 3.39
Ref. Conc (µg/kg)	0.14	0.05	0.51	0.43	0.05	0.24	0.14	0.39	0.05	0.14	0.45	0.33	0.05	0.00	0.23	0.24
Eluate of biochar and pH	WT-BC-500 pH 9.21	WT-BC-500 pH 6.66	WT-BC-500 pH 4.96	WT-BC-500 pH 4.03	WT-BC-600 pH 10.23	WT-BC-600 pH 6.69	WT-BC-600 pH 5.13	WT-BC-600 pH 4.26	WT-BC-700 pH 11.64	WT-BC-700 pH 7.04	WT-BC-700 pH 4.7	WT-BC-700 pH 3.57	WT-BC-800 pH 11.98	WT-BC-800 pH 6.76	WT-BC-800 pH 4.64	WT-BC-800 pH 3.7
Conc of Element(µg/kg)	0.32	4.26	54.07	69.04	0.04	0.48	4.40	13.51	0.04	1.04	6.68	10.78	0.00	0.71	1.99	5.27
Eluate of biochar and pH	DSL 500 pH 6.97	DSL 500 pH 5.24	DSL 500 pH 3.77	N/A	DSL 600 pH 6.71	DSL 600 pH 5.24	DSL 600 pH 4.26	N/A	DSL 700 pH 9.68	DSL 700 pH 6.44	DSL 700 pH 5.53	DSL 700 pH 3.84	DSL 800 pH 9.04	DSL 800 pH 6.63	DSL 800 pH 5.44	DSL 800 pH 4.05
Conc of Element(µg/kg)	0.11	7.15	60.23	N/A	0.08	1.42	6.50	N/A	0.06	0.13	0.17	0.07	0.05	0.05	0.12	0.04
Eluate of biochar and pH	MOVAR 500 pH 8.38	MOVAR 500 pH 6.8	MOVAR 500 pH 5.17	MOVAR 500 pH 3.8	MOVAR 600 pH 8.41	MOVAR 600 pH 7.18	MOVAR 600 pH 5.53	MOVAR 600 pH 3.35	MOVAR 700 pH 8.48	MOVAR 700 pH 6.79	MOVAR 700 pH 3.97	MOVAR 700 pH 3.76	MOVAR 800 pH 8.58	MOVAR 800 pH 6.54	MOVAR 800 pH 5.5	MOVAR 800 pH 4.0
Conc of Element(µg/kg)	0.32	0.83	22.50	60.58	0.33	0.17	1.09	3.80	0.14	0.14	0.35	0.41	0.23	0.07	0.12	0.14

Trace Element	**Pb**															
Eluate of Reference Biochar and pH	CWC-BC-500 pH 8.82	CWC-BC-500 pH 6.93	CWC-BC-500 pH 4.5	CWC-BC-500 pH 3.1	CWC-BC-600 pH 9.13	CWC-BC-600 pH 7.07	CWC-BC-600 pH 4.86	CWC-BC-600 pH 3.66	CWC-BC-700 pH 9.54	CWC-BC-700 pH 6.02	CWC-BC-700 pH 5.47	CWC-BC-700 pH 3.58	CWC-BC-750 pH 9.81	CWC-BC-750 pH 6.81	CWC-BC-750 pH 5.88	CWC-BC-750 pH 3.39
Ref. Conc (µg/kg)	35.97	39.87	55.06	179.74	66.20	52.09	78.79	92.05	38.69	47.90	66.49	76.92	32.17	26.02	49.35	58.07
Eluate of biochar and pH	WT-BC-500 pH 9.21	WT-BC-500 pH 6.66	WT-BC-500 pH 4.96	WT-BC-500 pH 4.03	WT-BC-600 pH 10.23	WT-BC-600 pH 6.69	WT-BC-600 pH 5.13	WT-BC-600 pH 4.26	WT-BC-700 pH 11.64	WT-BC-700 pH 7.04	WT-BC-700 pH 4.7	WT-BC-700 pH 3.57	WT-BC-800 pH 11.98	WT-BC-800 pH 6.76	WT-BC-800 pH 4.64	WT-BC-800 pH 3.7
Conc of Element(µg/kg)	19.22	17.67	3720.32	6967.68	44.80	39.38	258.86	12947.77	23.65	27.16	1696.73	4188.17	25.57	29.92	81.55	4843.82
Eluate of biochar and pH	DSL 500 pH 6.97	DSL 500 pH 5.24	DSL 500 pH 3.77	N/A	DSL 600 pH 6.71	DSL 600 pH 5.24	DSL 600 pH 4.26	N/A	DSL 700 pH 9.68	DSL 700 pH 6.44	DSL 700 pH 5.53	DSL 700 pH 3.84	DSL 800 pH 9.04	DSL 800 pH 6.63	DSL 800 pH 5.44	DSL 800 pH 4.05
Conc of Element(µg/kg)	22.84	30.30	46.14	N/A	25.20	42.57	41.44	N/A	10.64	45.86	44.85	29.57	13.08	37.35	37.31	29.63
Eluate of biochar and pH	MOVAR 500 pH 8.38	MOVAR 500 pH 6.8	MOVAR 500 pH 5.17	MOVAR 500 pH 3.8	MOVAR 600 pH 8.41	MOVAR 600 pH 7.18	MOVAR 600 pH 5.53	MOVAR 600 pH 3.35	MOVAR 700 pH 8.48	MOVAR 700 pH 6.79	MOVAR 700 pH 3.97	MOVAR 700 pH 3.76	MOVAR 800 pH 8.58	MOVAR 800 pH 6.54	MOVAR 800 pH 5.5	MOVAR 800 pH 4.0
Conc of Element(µg/kg)	68.23	70.14	146.88	1001.74	22.31	24.15	63.15	161.91	14.37	17.36	92.86	56.04	12.66	24.78	32.84	38.39
Trace Element	**Zn**															
Eluate of Reference Biochar and pH	CWC-BC-500 pH 8.82	CWC-BC-500 pH 6.93	CWC-BC-500 pH 4.5	CWC-BC-500 pH 3.1	CWC-BC-600 pH 9.13	CWC-BC-600 pH 7.07	CWC-BC-600 pH 4.86	CWC-BC-600 pH 3.66	CWC-BC-700 pH 9.54	CWC-BC-700 pH 6.02	CWC-BC-700 pH 5.47	CWC-BC-700 pH 3.58	CWC-BC-750 pH 9.81	CWC-BC-750 pH 6.81	CWC-BC-750 pH 5.88	CWC-BC-750 pH 3.39
Ref. Conc (µg/kg)	0.20	0.86	4.44	6.38	0.12	0.64	2.58	3.20	0.08	0.53	1.26	1.46	0.01	0.10	0.94	1.44
Eluate of biochar and pH	WT-BC-500 pH 9.21	WT-BC-500 pH 6.66	WT-BC-500 pH 4.96	WT-BC-500 pH 4.03	WT-BC-600 pH 10.23	WT-BC-600 pH 6.69	WT-BC-600 pH 5.13	WT-BC-600 pH 4.26	WT-BC-700 pH 11.64	WT-BC-700 pH 7.04	WT-BC-700 pH 4.7	WT-BC-700 pH 3.57	WT-BC-800 pH 11.98	WT-BC-800 pH 6.76	WT-BC-800 pH 4.64	WT-BC-800 pH 3.7
Conc of Element(µg/kg)	0.23	16.90	219.46	264.01	0.02	29.40	214.46	432.65	0.01	21.57	52.35	66.90	0.01	7.52	14.25	23.65
Eluate of biochar and pH	DSL 500 pH 6.97	DSL 500 pH 5.24	DSL 500 pH 3.77	N/A	DSL 600 pH 6.71	DSL 600 pH 5.24	DSL 600 pH 4.26	N/A	DSL 700 pH 9.68	DSL 700 pH 6.44	DSL 700 pH 5.53	DSL 700 pH 3.84	DSL 800 pH 9.04	DSL 800 pH 6.63	DSL 800 pH 5.44	DSL 800 pH 4.05
Conc of Element(µg/kg)	34.19	6362.14	56975.68	N/A	26.42	2192.37	11480.59	N/A	20.45	3823.51	1434.48	5217.67	13.86	216.58	2891.41	5355.09
Eluate of biochar and pH	MOVAR 500 pH 8.38	MOVAR 500 pH 6.8	MOVAR 500 pH 5.17	MOVAR 500 pH 3.8	MOVAR 600 pH 8.41	MOVAR 600 pH 7.18	MOVAR 600 pH 5.53	MOVAR 600 pH 3.35	MOVAR 700 pH 8.48	MOVAR 700 pH 6.79	MOVAR 700 pH 3.97	MOVAR 700 pH 3.76	MOVAR 800 pH 8.58	MOVAR 800 pH 6.54	MOVAR 800 pH 5.5	MOVAR 800 pH 4.0
Conc of Element(µg/kg)	1618.90	2269.85	31030.09	66682.87	69.11	438.72	10977.38	39951.21	50.84	52.55	8044.88	12665.30	55.70	71.12	1965.29	9424.97

N/A = Not Applicable

Appendix G

Comparison of concentrations of trace elements leached from biochar with threshold values for leaching from waste deposited to "inert landfills" in Norway, and acceptable Leaching for natural/clean materials . L e a c h a t e s w i t h ó a c c e p t a b l e of trace elements based on this comparison are shown in table 3. Values highlighted red = leaching concentrations higher than the threshold values, pink highlighted values = leaching concentrations higher ácceptable leaching limits ô Values not highlighted are leaching concentrations that are within both threshold and acceptable leaching limits.

Acceptable leaching limits = threshold concentrations/ 10

Source of threshold values (Forskrift om gjenvinning og behandling av avfall (avfallsforskriften) - Kapittel 9. Deponering av avfall - Lovdata , Accessed 2nd April 2022)

	Pyr. Temp	pH	Trace Elements							
	˚C		Cr	Co	Ni	Cu	As	Cd	Pb	Zn
Threshold values for shake test particle size <4 mm µg/kg dry matter			500		400	2000	500	40	500	4000
Acceptable Leaching Values for Biochar (ug/kg) (Threshold values divided by 10)			50		40	200	50	4	50	400
Biochar		Concentrations of trace elements ((ug/kg)								
WT-BC	500	9.21	7.5184	2.1926	0.4006	4.5468	1138.3	0.3227	19.217	0.2289
WT-BC	500	6.66	0	70.207	21.322	8.2973	1363.9	4.2554	17.668	16.904
WT-BC	500	4.96	103.65	349.86	356.01	384.85	2958.2	54.072	3720.3	219.46
WT-BC	500	4.03	168.63	397.64	302.22	642.5	3435.6	69.039	6967.7	264.01
WT-BC	600	10.23	0	0.8916	0	3.9586	530.8	0.0392	44.798	0.0212
WT-BC	600	6.69	0	125.06	219.53	8.7488	271.69	0.4812	39.383	29.402
WT-BC	600	5.13	3.4332	592.26	1726.3	61.165	80.587	4.4015	258.86	214.46
WT-BC	600	4.26	696.07	1022.6	3068.1	292.21	4455.2	13.506	12948	432.65
WT-BC	700	11.64	0.6972	0.073	0.2416	1.7532	114.35	0.0405	23.646	0.006
WT-BC	700	7.04	0.0325	370.8	831.96	11.667	235.37	1.0437	27.16	21.565
WT-BC	700	4.7	463.04	1269.9	2993.7	205.94	2571.9	6.6811	1696.7	52.351
WT-BC	700	3.57	1017.8	1852	3920.7	240.85	5638.2	10.784	4188.2	66.898
WT-BC	800	11.98	2.6501	0.0718	0	1.7708	11.271	0	25.57	0.0096
WT-BC	800	6.76	1.0377	672.97	1487.3	24.731	359.17	0.7138	29.921	7.5161
WT-BC	800	4.64	57.36	1177.5	2477.7	105.18	763.13	1.9889	81.553	14.248
WT-BC	800	3.7	1407.7	1840.3	3521	185.83	5665.1	5.2733	4843.8	23.652
DSL - BC	500	6.97	12.268	1.2815	16.323	27.869	0.4844	0.1096	22.84	34.194
DSL - BC	500	5.24	4.1649	84.655	45.238	30.843	0.6752	7.1478	30.305	6362.1
DSL - BC	500	3.77	37.399	439.5	418.74	160.89	2.8916	60.232	46.137	56976
DSL - BC	600	6.71	1.4851	2.7274	1.7738	28.493	0.5949	0.0801	25.199	26.42
DSL - BC	600	5.24	3.6339	100.09	122.71	42.353	0.5099	1.4169	42.566	2192.4
DSL - BC	600	4.26	3.3105	345.29	388.45	156.19	0.7128	6.4951	41.435	11481
DSL - BC	700	9.68	3.448	0.0354	8.5013	28.215	4.7616	0.0631	10.639	20.454
DSL - BC	700	6.44	5.6539	72.355	78.841	41.02	1.6324	0.1277	45.858	3823.5

DSL - BC	700	5.53	1.2966	13.877	30.349	70.195	2.1547	0.1683	44.854	1434.5
DSL - BC	700	3.84	6.1124	92.075	101.68	24.337	1.5374	0.0737	29.571	5217.7
DSL - BC	800	9.04	0.9403	0.0164	0.9512	27.802	1.5062	0.0456	13.082	13.857
DSL - BC	800	6.63	1.8954	1.5449	2.8706	27.098	0.0243	0.0549	37.352	216.58
DSL - BC	800	5.44	4.4316	43.194	128.96	80.064	5.7645	0.1231	37.307	2891.4
DSL - BC	800	4.05	8.1348	29.578	60.207	21.908	1.6531	0.0438	29.627	5355.1
MOVAR BC	500	8.38	8.4503	0.4715	0.5368	2153	1.8423	0.3169	68.232	1618.9
MOVAR BC	500	6.8	7.4526	21.708	37.226	1862.7	0.9841	0.8292	70.143	2269.9
MOVAR BC	500	5.17	29.9	161.58	574.75	1920.5	16.181	22.504	146.88	31030
MOVAR BC	500	3.8	257.69	375.22	1537	2034.4	57.192	60.583	1001.7	66683
MOVAR BC	600	8.41	6.1899	0.0751	0.6295	31.969	0.3858	0.3276	22.314	69.111
MOVAR BC	600	7.18	2.6435	18.731	47.058	43.626	0.1842	0.1733	24.146	438.72
MOVAR BC	600	5.53	2.855	148.3	613.58	120.67	2.5295	1.0919	63.153	10977
MOVAR BC	600	3.35	209.83	324	1201.9	56.476	34.899	3.8045	161.91	39951
MOVAR BC	700	8.48	3.0496	0.0204	3.8967	17.478	0.0365	0.1417	14.373	50.842
MOVAR BC	700	6.79	2.2491	3.8151	7.2437	22.272	0.6342	0.1365	17.357	52.552
MOVAR BC	700	3.97	19.05	158.72	618.34	136.21	3.2438	0.35	92.858	8044.9
MOVAR BC	700	3.76	113.56	330.39	1277.6	55.502	6.8939	0.4096	56.037	12665
MOVAR BC	800	8.58	0.9172	0.0979	1.9597	22.731	1.0842	0.2267	12.66	55.702
MOVAR BC	800	6.54	8.2915	2.3207	16.726	28.361	0.0297	0.0662	24.778	71.124
MOVAR BC	800	5.5	1.774	26.029	72.484	43.121	2.844	0.1171	32.835	1965.3
MOVAR BC	800	4	202.86	133.18	442.55	81.931	0.4989	0.1385	38.392	9425

Appendix H Percentages (Concentrations) of Trace Elements Leached from Biochar

CWC = clean wood chips, WT = waste wood, MOVAR = digested sludge from MOVAR, DSL = digested sludge from Lindum , BC=biochar (ambient pH is pH of biochar + only deionized water). Leaching increased as pH decreased for a specific pyrolysis temperature (ref to results and discussion)

Biochar	Pyrolysis Temp (°C)	Target pH	pH in Leachate	Trace Element							
				Cr	Co	Ni	Cu	As	Cd	Pb	Zn
CWC-BC	500	ambient	8.82	0.029246	0.073502	0.054424	0.046237	9.191692	22.61568	24.25053	0.000773
CWC-BC	500	7	6.93	0.025685	1.977374	3.55365	0.079647	8.580413	7.466074	26.88055	0.003364
CWC-BC	500	5.5	4.5	0.291874	7.989184	29.10088	0.277413	15.88873	80.32857	37.11696	0.017306
CWC-BC	500	4	3.1	1.815778	13.24796	53.7442	1.071676	33.77998	67.36608	121.17	0.024842
CWC-BC	600	ambient	9.13	0	0.074301	0.073067	0.102784	17.5567	14.59735	10.3443	0.000963
CWC-BC	600	7	7.07	0	2.406006	8.64114	0.067136	15.11725	75.95192	8.138582	0.005015
CWC-BC	600	5.5	4.86	1.621855	10.32944	52.40308	0.842238	26.39548	42.64056	12.31065	0.020381
CWC-BC	600	4	3.66	2.963829	13.78642	72.6133	1.152221	33.07088	122.1049	14.38352	0.025226
CWC-BC	700	ambient	9.54	0	0.158865	0	0.163017	40.50459	10.3381	48.16419	0.002561
CWC-BC	700	7	6.02	0	9.73161	34.31594	0.118694	21.16218	32.42621	59.63475	0.01654
CWC-BC	700	5.5	5.47	6.173005	19.2993	85.567	0.38887	38.12213	102.7178	82.77659	0.039297
CWC-BC	700	4	3.58	9.305115	24.22495	105.4547	0.402486	47.61623	75.18049	95.75943	0.045642
CWC-BC	750	ambient	9.81	0	0.05562	0	0.098886	21.13621	4.324063	10.51175	0.000257
CWC-BC	750	7	6.81	0	5.289007	15.79727	0.026335	25.00027	0	8.502405	0.003662
CWC-BC	750	5.5	5.88	2.073866	15.06586	68.70536	0.209943	31.24732	21.33161	16.12903	0.033619
CWC-BC	750	4	3.39	8.330195	21.40403	103.4543	0.306565	52.10426	21.49234	18.9765	0.051423

Biochar	Pyrolysis Temp (°C)	Target pH	pH in Leachate	Trace Element							
				Cr	Co	Ni	Cu	As	Cd	Pb	Zn
WT-BC	500	ambient	9.21	0.007048	0.029235	0.003642	0.004133	2.069567	0.028557	0.016956	1.91E-05
WT-BC	500	7	6.66	0	0.936097	0.19384	0.007543	2.479739	0.376583	0.01559	0.001409
WT-BC	500	5.5	4.96	0.097175	4.664854	3.236422	0.349865	5.378483	4.785116	3.282633	0.018288
WT-BC	500	4	4.03	0.158089	5.301908	2.747458	0.584091	6.24651	6.109685	6.147953	0.022001
WT-BC	600	ambient	10.23	0	0.009224	0	0.002474	0.82508	0.081584	0.048343	1.38E-06
WT-BC	600	7	6.69	0	1.293693	1.079676	0.005468	0.42231	0.000748	0.0425	0.001918
WT-BC	600	5.5	5.13	0.002239	6.126864	8.489893	0.038228	0.125265	0.006842	0.279343	0.013987
WT-BC	600	4	4.26	0.453961	10.5788	15.08909	0.182634	6.925174	0.020993	13.97241	0.028216
WT-BC	700	ambient	11.64	0.000427	0.000663	0.001115	0.001349	0.180546	0.059027	0.052161	2.28E-06
WT-BC	700	7	7.04	1.99E-05	3.370946	3.839829	0.008974	0.371634	1.51992	0.059911	0.008189
WT-BC	700	5.5	4.7	0.283492	11.54433	13.81713	0.158418	4.06093	9.729826	3.742792	0.01988
WT-BC	700	4	3.57	0.623116	16.83608	18.09545	0.185269	8.902479	15.7043	9.238605	0.025404
WT-BC	800	ambient	11.98	0.001939	0.000634	0	0.001155	0.018996	0	0.105081	8.87E-06
WT-BC	800	7	6.76	0.000759	5.937976	6.971757	0.016129	0.605345	3.149226	0.122964	0.006959
WT-BC	800	5.5	4.64	0.041971	10.38951	11.61441	0.068596	1.286176	8.774578	0.335147	0.013192
WT-BC	800	4	3.7	1.030059	16.23753	16.50455	0.121195	9.547959	23.26444	19.9061	0.0219

Biochar	Pyrolysis Temp (°C)	Target pH	pH in Leachate	Trace Element							
				Cr	Co	Ni	Cu	As	Cd	Pb	Zn
DSL	500	ambient	6.97	0.025382	0.015756	0.053812	0.011944	0.015298	0.014746	0.10382	0.004956
DSL	500	5.5	5.24	0.008617	1.040846	0.149138	0.013218	0.021323	0.961592	0.137748	0.922049
DSL	500	4	3.77	0.077378	5.403645	1.380471	0.068951	0.091313	8.102918	0.209713	8.257346
DSL	600	ambient	6.71	0.002951	0.031714	0.005661	0.01171	0.020751	0.040734	0.119995	0.003739
DSL	600	5.5	5.24	0.00722	1.163884	0.391626	0.017405	0.017788	0.720453	0.202696	0.310241
DSL	600	4	4.26	0.006577	4.015042	1.239727	0.064186	0.024866	3.302583	0.197312	1.624611
DSL	700	ambient	9.68	0.006465	0.000355	0.024523	0.010198	0.151966	0.217516	0.041996	0.002567
DSL	700	7	6.44	0.010601	0.725967	0.227426	0.014827	0.052097	0.440499	0.181018	0.479938
DSL	700	5.5	5.53	0.002431	0.13923	0.087544	0.025372	0.068766	0.580515	0.177057	0.180061
DSL	700	4	3.84	0.011461	0.923829	0.293319	0.008797	0.049065	0.254244	0.116726	0.654938
DSL	800	ambient	9.04	0.001517	0.000149	0.002418	0.009587	0.043035	0.173085	0.054508	0.001739
DSL	800	7	6.63	0.003057	0.014045	0.007298	0.009344	0.000694	0.208467	0.155632	0.027186
DSL	800	5.5	5.44	0.007148	0.392676	0.327861	0.027608	0.1647	0.467476	0.155448	0.362938
DSL	800	4	4.05	0.013121	0.268894	0.153069	0.007555	0.04723	0.166498	0.123448	0.672187

Biochar	Pyrolysis Temp (°C)	Target pH	pH in Leachate	Trace Element							
				Cr	Co	Ni	Cu	As	Cd	Pb	Zn
MOVAR	500	ambient	8.38	0.007682	0.006578	0.000839	0.88481	0.048482	0.042635	0.265838	0.223811
MOVAR	500	7	6.8	0.006775	0.302903	0.058166	0.765498	0.025898	0.111553	0.273286	0.313804
MOVAR	500	5.5	5.17	0.027181	2.254645	0.898046	0.789238	0.425826	3.027452	0.572255	4.289875
MOVAR	500	4	3.8	0.234265	5.235692	2.401613	0.836064	1.505059	8.150159	3.902885	9.21883
MOVAR	600	ambient	8.41	0.011828	0.001015	0.001851	0.014531	0.009334	0.375061	0.142429	0.011147
MOVAR	600	7	7.18	0.005051	0.253116	0.138405	0.01983	0.004457	0.19847	0.154121	0.070761
MOVAR	600	5.5	5.53	0.005455	2.004057	1.804633	0.054851	0.061199	1.250279	0.403102	1.770545
MOVAR	600	4	3.35	0.400953	4.378443	3.535142	0.025671	0.844323	4.356278	1.033468	6.443744
MOVAR	700	ambient	8.48	0.006019	0.000265	0.011349	0.007826	0.000875	0.590302	0.08983	0.00807
MOVAR	700	7	6.79	0.004439	0.049547	0.021098	0.009973	0.015221	0.568729	0.108484	0.008342
MOVAR	700	5.5	3.97	0.037598	2.061243	1.80098	0.06099	0.077852	1.458279	0.580364	1.276966
MOVAR	700	4	3.76	0.224134	4.290818	3.721211	0.024852	0.165454	1.706598	0.350231	2.010365
MOVAR	800	ambient	8.58	0.001787	0.001323	0.005764	0.009883	0.024828	2.666562	0.097385	0.008703
MOVAR	800	7	6.54	0.016152	0.031361	0.049194	0.012331	0.00068	0.779364	0.1906	0.011113
MOVAR	800	5.5	5.5	0.003456	0.351738	0.213187	0.018748	0.065131	1.377211	0.25258	0.307077
MOVAR	800	4	4	0.395182	1.799771	1.301607	0.035622	0.011425	1.629826	0.29532	1.472652

Appendix J Biochar yield data

Biochar yield decreased as pyrolysis temperature decreased due to evaporation of moisture and volatilization of compounds

Feedstock	Sample name	Pyr temp (°C)	Residence time (min)	Feedstock (kg/h)	Biochar (kg/h)	Condensate (kg/h)	Gass by diff (kg/h)	Feedstock C (%)	Biochar C (%)	Yield, %				Biochar C yield (%)	Relative Biochar yield (%)
										Biochar	Condensate	Gas	Sum		
Clean wood chips (CWC)	CWC-550-181220	500	20	5.2	1.0	1.92	2.3	50.3 %	91.4 %	20.0 %	36.7 %	43.2 %	100.0 %	36.47%	100.0%
Clean wood chips (CWC)	CWC-600-070121	600	20	4.9	1.1	1.74	2.1	50.3 %	92.5 %	21.5 %	35.3 %	43.2 %	100.0 %	39.49%	107.0%
Clean wood chips (CWC)	CWC-700-080121	700	20	4.8	1.0	1.41	2.4	50.3 %	91.4 %	21.0 %	29.4 %	49.6 %	100.0 %	38.27%	104.9%
Clean wood chips (CWC)	CWC-750-120121	750	20	5.1	0.8	0.79	3.4	50.3 %	89.9 %	16.5 %	15.5 %	68.0 %	100.0 %	29.49%	82.2%
Waste timber (WT)	WT-BC-500	500	20	10.46	2.70	5.97	1.8	48.1 %	85.0 %	25.8 %	57.1 %	17.1 %	100.0 %	45.60%	100.0%
Waste timber (WT)	WT-BC-600	600	20	4.94	1.15	2.25	1.5	48.1 %	79.6 %	23.3 %	45.5 %	31.2 %	100.0 %	38.50%	90.2%
Waste timber (WT)	WT-BC-700	700	20	4.78	1.00	1.95	1.8	48.1 %	85.4 %	20.9 %	40.8 %	38.3 %	100.0 %	37.13%	81.0%
Waste timber (WT)	WT-BC-800	800	20	4.78	0.90	1.87	2.0	48.1 %	85.1 %	18.8 %	39.1 %	42.1 %	100.0 %	33.29%	72.9%
Digested Sludge Lindum (DSL)	DSL-BC-500	500	20	8.50	4.60	2.60	1.3	20.5 %	13.2 %	54.1 %	30.6 %	15.3 %	100.0 %	34.91%	100.0%
Digested Sludge Lindum (DSL)	DSL-BC-600	600	20	8.50	4.30	2.58	1.6	20.5 %	13.1 %	50.6 %	30.4 %	19.1 %	100.0 %	32.39%	93.5%
Digested Sludge Lindum (DSL)	DSL-BC-700	700	20	8.19	4.40	2.69	1.1	20.5 %	13.5 %	53.7 %	32.8 %	13.4 %	100.0 %	35.45%	99.3%
Digested Sludge Lindum (DSL)	DSL-BC-750	750	20	8.19	4.40	2.69	1.1	20.5 %	13.1 %	53.7 %	32.8 %	13.4 %	100.0 %	34.40%	99.3%
Digested Sludge Movar (MOVAR)	MS-BC-500	500	20	5.56	2.24	2.05	1.3	31.6 %	30.3 %	40.3 %	36.9 %	22.8 %	100.0 %	38.62%	100.0%
Digested Sludge Movar (MOVAR)	MS-BC-600	600	20	6.35	2.37	2.34	1.6	31.6 %	28.0 %	37.3 %	36.9 %	25.8 %	100.0 %	33.06%	92.6%
Digested Sludge Movar (MOVAR)	MS-BC-700	700	20	5.97	2.30	3.00	0.7	31.6 %	28.1 %	38.5 %	50.3 %	11.2 %	100.0 %	34.25%	95.6%
Digested Sludge Movar (MOVAR)	MS-BC-800	800	20	6.35	2.21	2.80	1.3	31.6 %	27.7 %	34.8 %	44.1 %	21.1 %	100.0 %	30.50%	86.4%

Appendix K Models tested for factors affecting leaching of trace elements

A stepwise regression analysis used to estimate the factors affecting leaching of Cu and Zn in biochar using the AIC (Akaike information criterion) as the selection criteria. Leaching data of trace elements was used. Cu/Zn leached were the response variables and feedstock, pyrolysis temperature, pH of leachate, concentrations of Fe and Al were run as the predictor variables. The best model using AIC showed that pyrolysis temperature, leachate pH, feedstock as well as concentrations of Fe and Al significantly impact leaching of Cu and Zn(Ref to section 6.4)

```
#MODELS TO TEST FACTORS AFFECTING Cu LEACHING IN BIOCHAR#
my.lm1 = lm (Cu~ Feedstock+ Temp+ ph, data=leaching)
my.lm2 = lm(Cu~ Feedstock* Temp* ph, data=leaching)
my.lm3 = lm(Cu~ Feedstock* Temp+ ph*Temp, data=leaching)
my.lm4 = lm(Cu~ Feedstock+ Temp* ph, data=leaching)
my.lm5 = lm(Cu~ Feedstock* Temp+ ph, data=leaching)
my.lm6 = lm(Cu~ Temp + ph, data=leaching)
my.lm7 = lm(Cu~ Temp* ph, data=leaching)
my.lm8 = lm(Cu~ ph, data=leaching)
my.lm9 = lm(Cu~ Temp, data=leaching)
my.lm10 = lm(Cu~ Feedstock * ph, data=leaching)
my.lm11 = lm(Cu~ Feedstock + ph, data=leaching)
my.lm12 = lm(Cu~ Feedstock+Temp+ph+Al+Fe, data=leaching)
my.lm13 = lm(Cu~ Feedstock+Temp*ph*Al+ph*Fe, data=leaching)
my.lm14 = lm(Cu~ Feedstock+Temp+ph+Al, data=leaching)
my.lm15 = lm(Cu~ Feedstock*Temp+ph*Al, data=leaching)
my.lm16 = lm(Cu~ Feedstock+Temp+ph+Fe, data=leaching)
my.lm17 = lm(Cu~ Feedstock*Temp+ph*Fe, data=leaching)
my.lm18 = lm(Cu~ Temp+ph+Fe+Al, data=leaching)
my.lm19 = lm(Cu~ Temp+ph+Fe, data=leaching)
my.lm20 = lm(Cu~ Temp+ph+Al, data=leaching)
my.lm21 = lm(Cu~ Temp+ph*Fe, data=leaching)
my.lm22 = lm(Cu~ Temp+ph*Al, data=leaching)
my.lm23 = lm(Cu~ Temp+ph*Fe+ph*Al, data=leaching)
my.lm24 = lm(Cu~ Feedstock+Temp+ph*Al+ph*Fe, data=leaching)
my.lm25 = lm(Cu~ Feedstock+Temp*ph*Al+Temp*ph*Fe, data=leaching)
my.lm26 = lm(Cu~ Feedstock+Temp*ph*Fe, data=leaching)
my.lm27 = lm(Cu~ Feedstock+Temp*ph*Al, data=leaching)
my.lm28 = lm(Cu~ Feedstock+ph*Al+Temp*ph*Fe, data=leaching)
my.lm29 = lm(Cu~ ph*Fe+Temp*ph*Al, data=leaching)
my.lm30 = lm(Cu~ Temp + ph*Fe+Temp*ph*Al, data=leaching)
my.lm31 = lm(Cu~ Feedstock+Temp*ph*Al+Fe, data=leaching)
```

```r
##MODELS TO TEST FACTORS AFFECTING zn LEACHING IN BIOCHAR##
my.lm32 = lm (Zn~ Feedstock+ Temp+ ph, data=leaching)
my.lm33= lm(Zn~ Feedstock* Temp* ph, data=leaching)
my.lm34= lm(Zn~ Feedstock* Temp+ ph*Temp, data=leaching)
my.lm35= lm(Zn~ Feedstock+ Temp* ph, data=leaching)
my.lm36= lm(Zn~ Feedstock* Temp+ ph, data=leaching)
my.lm37= lm(Zn~ Temp + ph, data=leaching)
my.lm38= lm(Zn~ Temp* ph, data=leaching)
my.lm39= lm(Zn~ ph, data=leaching)
my.lm40= lm(Zn~ Temp, data=leaching)
my.lm41 = lm(Zn~ Feedstock * ph, data=leaching)
my.lm42 = lm(Zn~ Feedstock + ph, data=leaching)
my.lm43 = lm(Zn~ Feedstock+Temp+ph+Al+Fe, data=leaching)
my.lm44 = lm(Zn~ Feedstock+Temp*ph*Al+ph*Fe, data=leaching)
my.lm45 = lm(Zn~ Feedstock+Temp+ph+Al, data=leaching)
my.lm46= lm(Zn~ Feedstock*Temp+ph*Al, data=leaching)
my.lm47 = lm(Zn~ Feedstock+Temp+ph+Fe, data=leaching)
my.lm48 = lm(Zn~ Feedstock*Temp+ph*Fe, data=leaching)
my.lm49 = lm(Zn~ Temp+ph+Fe+Al, data=leaching)
my.lm50 = lm(Zn~ Temp+ph+Fe, data=leaching)
my.lm51 = lm(Zn~ Temp+ph+Al, data=leaching)
my.lm52 = lm(Zn~ Temp+ph*Fe, data=leaching)
my.lm53 = lm(Zn~ Temp+ph*Al, data=leaching)
my.lm54 = lm(Zn~ Temp+ph*Fe+ph*Al, data=leaching)
my.lm55 = lm(Zn~ Feedstock+Temp+ph*Al+ph*Fe, data=leaching)
my.lm56 = lm(Zn~ Feedstock+Temp*ph*Al+Temp*ph*Fe, data=leaching)
my.lm57 = lm(Zn~ Feedstock+Temp*ph*Fe, data=leaching)
my.lm58 = lm(Zn~ Feedstock+Temp*ph*Al, data=leaching)
my.lm59 = lm(Zn~ Feedstock+ph*Al+Temp*ph*Fe, data=leaching)
my.lm60 = lm(Zn~ ph*Fe+Temp*ph*Al, data=leaching)
my.lm61 = lm(Zn~ Temp + ph*Fe+Temp*ph*Al, data=leaching)
my.lm62 = lm(Zn~ Feedstock+Temp*ph*Al+Fe, data=leaching)
```

Appendix L Concentration (g/kg)of Iron (Fe) and Aluminium (Al) in biochar.

Values displayed are means (n=3) of concentrations of elements in biochar. LOD and LOQ values for both Al and Fe are 0.00 and 0.00 respectively.

Biochar	Feedstock	Temp (°C)	Conc. of Al	Conc. Of Fe
CWC-BC	Clean wood chips	500	0	0.33
CWC-BC	Clean wood chips	600	0	0.21
CWC-BC	Clean wood chips	700	0	0.13
CWC-BC	Clean wood chips	750	0	0.14
WT-BC	Waste timber	500	2.8	3.6
WT-BC	Waste timber	600	3.33	4.3
WT-BC	Waste timber	700	3.9	5.1
WT-BC	Waste timber	800	4	5
DSL	Digested sludge from Lindum	500	55.3	166.7
DSL	Digested sludge from Lindum	600	57	166.7
DSL	Digested sludge from Lindum	700	63	180
DSL	Digested sludge from Lindum	800	64	180
MOVAR	Digested sludge from MOVAR	500	120	66
MOVAR	Digested sludge from MOVAR	600	136.7	74.3
MOVAR	Digested sludge from MOVAR	700	140	76
MOVAR	Digested sludge from MOVAR	800	150	81.3

Appendix M Threshold values for trace element concentrations in an organic soil improver according to the European Union (EU) fertilizer framework directive

'A soil improver shall be an EU fertilising product the function of which is to maintain, improve or protect the physical or chemical properties, the structure or the biological activity of the soil to which it is added'.

Contaminants in an organic soil improver must not exceed the following limit values:

(a) cadmium (Cd): 2 mg/kg dry matter,

(b) hexavalent chromium (Cr VI): 2 mg/kg dry matter,

(c) mercury (Hg): 1 mg/kg dry matter,

(d) nickel (Ni):: 50 mg/kg dry matter,

(e) lead (Pb): 120 mg/kg dry matter, and

(f) inorganic arsenic (As): 40 mg/kg dry matter.

The copper (Cu) content in an organic soil improver must not exceed 300 mg/kg dry matter, and the zinc (Zn) content in an organic soil improver must not exceed 800 mg/kg dry matter.

(Source: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L:2019:170:FULL&from=NL, Accessed 12th july,2022)

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