Properties, agronomic uses and public perceptions of faecal sludge biochar

Larissa Nicholas

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SUMMARY

Since 2000 the proportion of the population in low and middle- income nations that use “unimproved” sanitation facilities is increasing, in 2020 3.5 billion people lacked access to safely managed sanitation facilities. Inadequate sanitation facilities and lack of clean water are key factors in the contraction of diarrheal disease which is responsible for the deaths of approximately 525,000 children every year (WHO, 2017). Faecal sludge collected from on-site sanitation facilities is often dumped into the local environment or reused untreated on farmland. The recycling and re-use of faecal sludge can improve sanitation in developing nations as well as playing a pivotal role in the development of a circular economy within the agriculture industry.

Here, biochars derived from faecal sludge were characterized with regards to a potential end-use in agriculture. All faecal sludge biochars were found to have high ash content which contributed to the high pH values measured. All biochars recorded relatively low carbon content and BET porosimetry indicated low specific surface areas. Fourier transform infrared spectroscopy revealed similar organic surface groups for each biochar. X-ray diffraction analysis differed slightly between biochars, but all displayed a high mineral content (Si, Ca, K and Mg).

Faecal sludge biochar was investigated as a soil amendment/fertilizer with acidic soil in two experiments; one conducted in an outdoor greenhouse in natural sunlight and one in a controlled temperature laboratory under a 24-hour photoperiod. It was found that faecal sludge biochar addition to acidic soil increased crop yield, fruit number, plant height and plant biomass and also reduced water runoff in Micro-Tom tomatoes. A combined biochar and fertilizer treatment together produced plants with greater plant height, and tomato yield. The high pH biochar initiated a liming effect which increased nutrient availability as evident in the combined biochar and fertilizer treatment. Under continuous light conditions biochar addition increased plant height, and tomato yield compared to control. However, biochar addition resulted in greater continuous light-induced leaf injury compared to the combined biochar and fertilizer treatment. The combined fertilizer and biochar treatment with a lower rate of biochar plus the addition of nutrients significantly reduced continuous light-induced leaf injury.

A survey investigating the public perception of biochar as a soil enhancer in agriculture focusing on faecal sludge derived biochar was conducted. This revealed the “disgust effect” – a “squeamishness” associated with the use of faecal sludge biochar by members of the public. Also, gender differences, issue awareness, and age need to be taken into consideration when enforcing management and policy decisions regarding the land application of faecal sludge biochar.

Declarations

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed: [redacted]

Date: 8th December 2023

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

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I hereby give consent for my thesis, if accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to outside organisations.

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The University's ethical procedures have been followed and, where appropriate, that ethical approval has been granted.

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Date: 8th December 2023

Authorship declarations

Paper 1: *Faecal sludge pyrolysis as a circular economic approach to waste management and nutrient recovery*

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Candidate contributed: The candidate's contributions to the submitted paper for publication include leading the design of the work, the analysis of the data, drafting the manuscript and corresponding with the reviewer.

Co-authors contributed:

Aisling Devine: Revised the manuscript.

Dr Iain Robertson: Revised the manuscript.

Dr Ian Mabbett: Revised the manuscript.

All authors approved the final manuscript before publication. We the undersigned agree with the above stated 'proportion of work undertaken' for the published manuscript presented in Chapter 2 of this thesis:

Signed Candidate: [redacted]

Co-author 1: …[redacted]

Co-author 2: … [redacted]

Co-author 3: … [redacted]

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Dr Ian Mabbett: Contributed to the design of the project and revised the manuscript.

Henry Apsey: Contributed to the acquisition and the interpretation of the data and revised the manuscript.

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Signed Candidate: [redacted]

Co-author 1: … [redacted]

Co-author 2: … [redacted]

Co-author 3: … [redacted]

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Signed Candidate: [redacted]

Co-author 1: … [redacted]

Co-author 2: … [redacted]

Co-author 3: … [redacted]

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Co-author 1: …[redacted]

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"*In other words, changing the earth's climate in ways that will be chaotic and disastrous is easier to accept than the prospect of changing the fundamental, growth-based, profit-seeking logic of capitalism."* - Naomi Klein

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ABBREVIATIONS

ABA: Abscisic acid

ACC: 1-aminocyclopropane-1-carboxylic acid

AIC: Akaike's information criterion

BET: Brunauer, Emmett, and Teller

CAT: Catalase

CEC: Cation exchange capacity

CL: Continuous lighting

DFT: Density functional theory

DS: Dry solids

EC: Electrical conductivity

EDX: Energy dispersive Xray

EU: European Union

Fm: Maximum fluorescence

FS: Faecal sludge

FTIR: Fourier transform infrared

Fv: Variable fluorescence

GCMC: Grand Canonical Monte Carlo

GLM: Generalized Linear Model

IAA: Indole-3-acetic acid

JA: Jasmonic acid

LED: Light emitting diode

POD: Peroxidase

PS I: Photosystem I

PS II: Photosystem II

PTEs: Potentially toxic elements

PV: Pore volume

SA: Salicylic acid

SEM: Scanning electron microscopy

SOD: Superoxide dismutase

SS: Sewage sludge

SSA: Specific surface area

TS: Total solids

TPV: Total pore volume

WHC: Water holding capacity

XRD: Xray crystal diffraction

1 GENERAL INTRODUCTION

BACKGROUND INFORMATION

"*No single measure would do more to reduce disease and save lives in the developing world than bringing safe water and adequate sanitation to all*" - Kofi Annan.

Sanitation is defined by the World Health Organization as "the provision of facilities and services for the safe disposal of human urine and feces." Inadequate sanitation facilities and lack of clean water are key factors in the contraction of diarrheal disease which is responsible for the deaths of approximately 525,000 children every year (WHO, 2017). Approximately 90% of all diarrhea-related deaths occur in children under five years old in low-and-middle income countries (WHO, 2020a).

To combat this, the international community set out 17 new Sustainable Development Goals including Goal 6, to "ensure availability and sustainable management of water and sanitation for all" (UN, 2015). The Joint Monitoring Program WHO/UNICEF reports that since 2000 the proportion of the population in low and middle- income nations that use "unimproved" sanitation facilities is increasing (UNICEF & WHO, 2017), and in 2022 a total of 3.5 billion people globally still lacked access to safely managed services (WHO and UNICEF, 2023). However, in the last 23 years 2.5 billion people have gained access to safely managed sanitation amenities (WHO and UNICEF, 2023).

Approximately 2 billion people depend on onsite sanitation facilities that generate faecal sludge (UNICEF & WHO, 2020). Faecal sludge collected from on-site sanitation facilities is often dumped into the local environment or disposed of within the household compound (Jiménez et al., 2009a). Untreated faecal sludge is also used directly in nearby agricultural fields as a soil conditioner (Chandana & Rao, 2021)with the potential to cause significant faecal coliform contamination of soil, water, and crops (Graham & Polizzotto, 2013; Lalander et al., 2013). In developing countries, faecal sludge (FS) collected from onsite sanitation facilities has been poorly managed, which has led to negative public and environmental health outcomes from eutrophication of surface water bodies, and contamination of groundwater and soils (Gwenzi & Munondo, 2008), and poor social and economic development (Haller et al., 2007; Mara et al., 2010).

Improving sanitation provision in developing nations is challenging due to the economic cost as well as the land area, water, and energy requirements. Sewer-based facilities in developed nations are more viable as water is far more readily available and large-scale infrastructure projects are more readily funded by the governments in these countries. In developing countries faecal sludge management emerged as a long-term and more sustainable approach to store, collect, transport, treat and safely disposal of faecal sludge without the need for expensive, water and energy intensive sewer systems. (Strande et al., 2014a).

Treatment technologies are an integral part of faecal sludge management to lessen the negative effect on public and environmental health (Strande et al., 2014b; Tayler, 2018). Different treatment technologies for faecal sludge include thermal drying and pelletizing, waste stabilization ponds, co-composting and vermicomposting and pyrolysis. Pyrolysis is the thermal conversion of biomass into biochar and is defined as "*a process whereby organic substances are broken down at temperatures ranging from 350°C to 1000 °C in a low-oxygen process*" (European Biochar Foundation, 2016). The thermochemical treatment of faecal sludge via pyrolysis has gained prominence in recent years (Andriessen et al., 2019; Krueger et al., 2020; Woldetsadik et al., 2018).

1.1 BIOCHAR

Pyrolysis fully eliminates harmful pathogenic organisms within the sludge and creates biochar, a porous, recalcitrant carbonaceous material. Biochar has many diverse uses including in soil remediation to remove environmental contaminants such as heavy metals from aqueous media (Cairns et al., 2022), as media in biofilters to remove faecal indicator bacteria from stormwater (Nabiul Afrooz & Boehm, 2017; Ulrich et al., 2017) and as a carbon sequestering additive in building material (Gupta et al., 2018) and in cattle feed to minimize enteric methane production from dairy cattle (Leng et al., 2012). One of the most significant uses of biochar, however, is as a soil amendment to improve soil fertility (Atkinson et al., 2010; Chan & Xu, 2009) whilst also sequestering carbon (Ippolito et al., 2012; Johannes Lehmann, 2007) and reducing anthropogenic CO_2, CH_4, and N_2O emissions (Woolf et al., 2010). Biochar has the potential to remove carbon equivalent to 3 % - 7% of current annual global anthropogenic CO_2 emissions (Karan et al., 2023). The properties of biochars can vary significantly depending on original feedstock source, pyrolysis temperature (i.e., the highest heating temperature), hold time, and heating rate (Chen et al., 2008; Crombie et al., 2015a; Lehmann & Joseph, 2012a; Tomczyk et al., 2020; Weber & Quicker, 2018a).

Sewage and faecal sludge biochars can have different characteristics compared to biochars derived from lignocellulose materials. This is due to the effect of the original feedstock source on biochar properties. Generally, sewage and faecal sludge biochars contain higher levels of essential plant nutrients (Singh et al., 2010) such as potassium, phosphorus (Hossain et al., 2010) and calcium (Hossain et al., 2011; Sousa & Figueiredo, 2016) leading to higher ash contents (Xu et al., 2014). The high ash content of sludge biochars contribute to the very alkaline pH values of these biochars (Hossain et al., 2011; X. Liu et al., 2014). Sewage sludge biochars also tend to have comparatively lower surface areas (Agrafioti et al., 2013; Bagreev et al., 2001; Schimmelpfennig & Glaser, 2012) compared to lignocellulosic biochars due to the high ash content reducing the surface area by filling or blocking access to the biochar micropores (Song and Guo, 2012).

Pyrolysis temperature also significantly impacts the characteristics of sewage and faecal sludge biochar (Gascó et al., 2005). Increasing pyrolysis temperature leads to a higher ash content, increased CEC, increased alkalinity (Koetlisi & Muchaonyerwa, 2017) and decreased biochar yield (Hossain et al., 2011; Xu et al., 2015). The total C, H, N and S content of sewage sludge biochars tend to decrease with increasing pyrolysis temperature (Lu et al., 2013).

1.2 BIOCHAR AS A SOIL AMENDMENT

The use of biochar to improve soil fertility and increase crop yield arose from analysis of Amazonian Black Earth (*Terra preta*), a very dark, fertile soil with higher nutrient levels and higher organic carbon content than the surrounding soils (Glaser et al., 2001).

There are several mechanisms by which biochar can improve soils and hence increase agricultural productivity:

- The porous structure of biochar improves water holding capacity of soils (Gaskin et al., 2007; Laird et al., 2010a)
- High biochar cation exchange capacity (CEC) increases the CEC of the soil (Glaser et al., 2001)

- The high CEC of biochars and larger surface areas can also limit nutrient leaching in soils (Lehmann & Joseph, 2012b) and improve nutrient retention (Song & Guo, 2012a)
- High ash content biochars are generally alkaline so can increase pH of acidic soil (Smider & Singh, 2014; Yuan, et al., 2011)
- Biochar promotes microbial, fungal and mycorrhizal growth (Steinbeiss et al., 2009)

In many developing nations such as in Sub-Saharan Africa subsistence farming and small-scale agricultural settings are widespread, however, the soils in these regions are degraded, (Gwenzi et al., 2015), with low pH, low fertility and low water holding capacity (Nyamapfene, 1991). Also, the majority of the increase in world food demand will occur in these developing countries, with an increase of approximately 30% in Asia and approximately 60% in Sub-Saharan Africa (World Bank, 2015).

Phosphorus is an irreplaceable plant limiting nutrient (Steen, 1998), and a crucial component in fertilizer however, it is a finite resource and estimated that the depletion of all remaining natural phosphorus reserves will occur within the next 100 – 400 years (Cisse et al., 2004; Günther, 1997; Van Vuuren et al., 2010). Almost 100% of phosphorus consumed in food is excreted (Jonsson et al., 2004), consequently the collection and thermochemical treatment of faecal sludge would recapture phosphorus from the food system and help to close the nutrient loop.

1.3 THE WATER-ENERGY-FOOD NEXUS

Biochar can play a pivotal role in developing a circular economy with the agriculture industry as it can be combined with current fertilization practices (Jindo et al., 2020). Many see the implementation of a circular economy as a fundamental step to achieve sustainable development (Drechsel et al., 2015b; Ellen MacArthur Foundation, 2015; European Commission, 2018b, 2018a). Pivotal to achieving sustainable development is the water-food-energy-nexus. The nexus approach underlines the interconnection between water, energy and food security and our natural resources (Belmonte et al., 2017). Demand for water, soil and land is rising, driven by rapid population and economic growth, increased urbanization, and changing diets (Drechsel et al., 2015b;

WWAP, 2018). Agriculture is the biggest consumer of the world's freshwater resources (UN-Water, 2021) and 30% of total global energy consumption is expended on food production and supply (FAO, 2011). It is predicted nearly 6 billion people will experience clean water scarcity by 2050 due to a rising demand for water, declining water resources, and increasing water pollution, driven by rapid economic and population growth (WWAP, 2018). The interdependence of these key domains requires an integrated systems-based approach. Faecal sludge biochar can play a pivotal role in the water-energy-food nexus through its potential to improve soil health resulting in increased agricultural productivity.

Benefits also include:

- A reduced demand for fertilizer and the recapture of essential plant nutrients from waste
- An increased crop yield which would alleviate food insecurity.
- A reduced demand for water, along with preventing the contamination of fresh water sources from untreated faecal sludge.
- the sequestration of carbon with the potential to reduce anthropogenic greenhouse gas emissions.

1.4 AIMS AND OBJECTIVES

The main goal of this research was to investigate several aspects relating to faecal sludge biochar produced from three full-scale faecal sludge treatment plants operating in India. These aspects include the determination of faecal sludge biochar properties, the application of these biochars to soil and the public perception of faecal sludge biochar as an amendment for growing crops.

Towards these ends Chapter 3 aims to summarize the literature regarding both faecal sludge and sewage sludge biochar including specifically:

- Composition of faecal and sewage sludge
- Properties of faecal sludge and sewage sludge
- Physico - chemical characteristics of sewage sludge and faecal sludge biochars
- The effect of transport conditions, treatment processes and holding times on sludge biochar properties

There is a considerable amount of research investigating characteristics of sewage sludge derived biochar but less on faecal sludge biochar (Gold et al., 2018).
Most of the research into faecal sludge – derived biochar has been focused on characterization of small-scale laboratory produced biochar (Bleuler et al., 2021; Gold et al., 2018; Liu et al., 2014; Woldetsadik et al., 2018) while data from full-scale operations are very limited (Krueger et al., 2020). It is becoming increasingly important to investigate the feasibility of resource recovery of operational up-scaled sludge treatment technologies (Andriessen et al., 2019). Processing conditions such as highest heating temperature, residence times, as well as the various pyrolysis technologies employed have a significant impact on biochar properties and thus its potential end-use (Ronsse et al., 2013). Large-scale production of FS biochar with consistent properties that is economically valuable and functional is imperative to alleviate the sanitation crisis (Strande et al., 2014a).

It was the focus of Chapter 4 to:

- assess the uniformity of biochar properties produced from three full-scale faecal sludge treatment plants in India.
- investigate agronomic biochar properties, including identifying organic surface groups, investigating surface charge, mineral content, pore volume, specific surface area, and determining pH, and ash content.

It is widely known that biochar addition to soil increases crop yield (Jeffery et al., 2011; Lehmann & Joseph, 2015). There are multiple benefits to biochar addition to soil including improving carbon content and nutrient levels (Glaser et al., 2001), increasing the cation exchange capacity of the soil (Glaser et al., 2001), increasing the water holding capacity of the soil (Gaskin et al., 2007; Herath et al., 2013), increasing pH levels in acidic soil (Novak et al., 2009)), as well as reducing and immobilizing toxic metals such as arsenic, cadmium and zinc (Park et al., 2011). There are more studies evaluating the benefits of sewage sludge biochar on soil fertility and crop yield (Gwenzi et al., 2016; Hossain et al., 2015; Khan et al., 2013; T. Liu et al., 2014; Sousa & Figueiredo, 2016; Tian et al., 2019; Waqas et al., 2015; You et al., 2019; Y. Zhang et al., 2016), compared to studies on faecal sludge biochar (X. Bai et al., 2018; Woldetsadik et al., 2018).

Until recently only laboratory - scale FS biochars have been studied (Krueger et al., 2020); there is currently very little research on the effect of large-scale commercially produced faecal sludge biochar on soil fertility and crop yield.
Specifically, Chapter 5 aimed to investigate:

- the effect of faecal sludge biochar with and without fertilizer on soil properties and plant parameters, including fruit yield and water runoff, of a dwarf cultivar of tomato (*Solanum lycopersicum L.*)
- Contextualize these findings with respect to the treatment used, and the control soil properties.
- Comment upon the significance of the results with regards to improved crop yield amidst climate change-induced food insecurity and water scarcity in developing nations.

Providing enough food for the rapidly expanding global population is one of the most pressing challenges of the 21st century (FAO et al., 2021). In 2020 nearly one in three people in the world did not have access to adequate food, an increase of almost 320 million from the previous year (FAO et al., 2021). Increasing agricultural production requires overcoming several significant obstacles such as water scarcity, degraded agricultural soils, climate change, and inadequate light for photosynthesis.
Industrial greenhouses are widely used to grow specific crops in all seasons during the year and especially used in high latitude nations to produce food and alleviate food insecurity (Mahdavian & Wattanapongsakorn, 2017). Greenhouses offer the ability to control conditions such as temperature, humidity, and lighting. Supplemental lighting has been widely used to increase the growth and yield of greenhouse vegetables (Demers & Gosselin, 1991; Hurd & Thornley, 1974; Logendra et al., 1990; McAvoy & Janes, 1984). Continuous light is photoperiods of up to 24 hours of supplemental light and has the potential to increase plant growth and fruit yield in greenhouse production (Velez-Ramirez et al., 2011).
Tomato plants exposed to continuous light develop inter-vascular chlorosis (Hillman, 1956), a leaf injury which eventually leads to necrosis (Arthur et al., 1930; Demers et al., 1998a; Hillman, 1956; Logendra et al., 1990). Continuous light leaf injury was first discovered in the 1920s (Arthur et al., 1930), however the underlying mechanisms of chlorosis from exposure to continuous lighting is still not understood.

Biochar has been shown to benefit the management of stress in plants under various abiotic conditions such as drought stress (e.g., Akhtar et al., 2014; Artiola et al., 2012; Batool et al., 2015), salt stress (e.g., Kul et al., 2021; Sun et al., 2016), high temperature stress (Fahad et al., 2015) and heavy metal toxicity (Abbas et al., 2017; Kamran et al., 2020).

To date there has been no research conducted to study the effect of biochar on tomato plants grown under continuous light stress.

The aims of Chapter 6 were:

- To investigate the influence of FS biochar, with and without fertilizer on the growth of (*Solanum lycopersicum L.*) cultivar Micro-Tom under continuous light stress
- To study the effect of FS biochar on other plant and soil parameters such as fruit yield, water runoff, and root mass
- Comment upon the potential mechanisms behind leaf chlorosis from exposure to continuous lighting in tomato plants

Faecal sludge biochar has the potential to improve soil health and crop yield in developing nations more at risk of climate change and food insecurity. However, few studies have been carried out investigating the public acceptance of faecal sludge-derived biochar as a soil amendment in agriculture.

There are many benefits to the reuse of faecal sludge in agriculture, however it is crucial that socio-economic constraints including negative perceptions and attitudes from public consumers is addressed. Improving the public's understanding and knowledge of faecal sludge biochar and biosolids, and highlighting the benefits is crucial for its acceptance by the public and ultimately the mass production of sludge biochar.

The aims of Chapter 7 were to:

- Determine if gender differences, age differences, residential area and issue awareness impacts affected public attitudes towards faecal sludge biochar, wood biochar and biosolids land application.
- Collect valuable information on public perceptions of exposure and risks towards consuming crops grown in faecal sludge biochar.

Structure of the thesis – Larissa Nicholas

'Properties, agronomic uses and public perceptions of faecal sludge biochar'

This thesis is comprised of the following chapters in the table below. These have been organised as standalone sections due to the multidisciplinary nature of the research. Some chapters have been published as journal articles, and some are yet to be submitted. A statement of authorship contribution, with respect to the candidate's involvement in experimentation, data collection and analysis and writing of the manuscript, is included for the chapters under review in journals. Further information is listed in the table below.

Chapter	Chapter/Paper title and status	Data collection/analysis and writing contribution
3	Agronomic properties of biochar from slow pyrolysis of human waste - A Review **Published in: Intech Open Book "Sustainable Use of Biochar"**	Literature review was undertaken primarily by Larissa Nicholas – first author. Review and editing being provided by co-authors Dr. Ian Mabbett, Aisling Devine and Dr. Iain Robertson
4	Agronomic properties of waste derived biochar from community scale faecal sludge treatment plants **Published in: Gates Open Research**	Characterization and data processing was undertaken by Larissa Nicholas and Henry Apsey (u/g student). XRD analysis was conducted by Tom Dunlop. Elemental analysis by Gabriel Sigmund, University of Vienna, and CEC measurements by Maria Santiso Taboada, University of Santiago de Compostela. Writing undertaken primarily by Larissa Nicholas – first author. Review being provided by co-author Dr. Ian Mabbett, Henry Apsey and Dr. Iain Robertson
5	The effect of faecal sludge biochar on the growth and fruit yield of tomato (*Solanum lycopersicum L.*) cultivar Micro-Tom **Published in: MDPI Agronomy**	Experimental work was undertaken by Larissa Nicholas. Soil CEC and pH was measured by Maria Santiso Taboada, University of Santiago de Compostela. The data processing and statistical analysis, as presented, was undertaken by Larissa Nicholas and Aisling Devine Writing undertaken primarily by Larissa Nicholas – first author. Review being provided by co-authors Dr. Aisling Devine, Dr. Ian Mabbett and Dr. Iain Robertson
6	The effect of biochar on the growth and fruit yield of tomato (*Solanum lycopersicum L.*) cultivar Micro-Tom under continuous light **In preparation for Journal of Soil Science and Plant Nutrition**	Experimental work was undertaken by Larissa Nicholas. Soil CEC and pH was measured by Maria Santiso Taboada, University of Santiago de Compostela. The data processing, as presented, was undertaken by Larissa Nicholas. Writing undertaken primarily by Larissa Nicholas – first author. Review being provided by co-authors Dr. Aisling Devine, Dr. Ian Mabbett and Dr. Iain Robertson
7	Public Perceptions on Faecal Sludge Biochar and Biosolids Use in Agriculture **Published in: MDPI Sustainability**	Experimental work was undertaken by Larissa Nicholas. The data processing, as presented, was undertaken by Larissa Nicholas under the guidance of Dr. Keith Hafacree. Writing undertaken primarily by Larissa Nicholas – first author. Review being provided by co-author Dr. Keith Hafacree

2 LITERATURE REVIEW: POTENTIAL AGRICULTURAL PROPERTIES OF BIOCHAR FROM SLOW PYROLYSIS OF HUMAN WASTE

Chapter Overview

The treatment and safe disposal of sanitation waste is crucial to human health and the environment. In developed countries the emphasis is on recovering phosphorus from municipal sewage sludge (SS) and the reduction of landfilling. The focus in developing countries, is on long-term mechanisms to deal with the faecal sludge (FS) generated from non-sewered onsite sanitation facilities.

The principal aim of this review is to summarize the knowledge on the properties of both sewage sludge (SS) and faecal sludge (FS), the thermal treatment via slow pyrolysis of SS and FS, and the resultant characterization of SS and FS - derived biochar with an emphasis on the end-use of biochar as a soil amendment. The characteristics of both sewage and faecal sludges and the resulting biochars produced from these slightly different feedstocks are examined to determine the similarities and differences between them.

The description of analyses includes determination of pH, ash content, CEC, heavy metal content, P and N content, surface area and porosity and both macro-and micronutrient content. In conclusion, the slow pyrolysis of FS and SS to produce biochar can play a pivotal role in a circular economy through the recovery and re-use of waste. Waste-derived biochar provides an opportunity to utilize an integrated systems-based approach in the water-energy-food nexus through its potential to improve soil health, increase crop yield, and improve water retention.

2.1 INTRODUCTION

In developed countries there are sewer systems and wastewater treatment plants that transport and safely treat sewage sludge, however, dramatic population growth, as well as stringent requirements for the treatment of sewage effluent have resulted in a steady increase in the volume of sewage sludge produced (Agrafioti et al., 2013). Conventionally the methods for disposing of treated sewage sludge include three main routes: reuse (land application), incineration or landfilling (Paz-Ferreiro et al., 2018). However, these options are becoming less desirable due to the accumulation of heavy metals and pathogens in sludge which effect its use in agriculture (Fytili & Zabaniotou, 2008). The impact of EU Directive 2018/851/EC resulted in a ban on landfilling, limited land application of sewage sludge and a focus on sustainable material management and a transition to a circular economy (European Parliament & European Council, 2018).

The focus in developing countries, is on long-term mechanisms to deal with the faecal sludge generated from non-sewered onsite sanitation facilities. Goal 6 of the UNs 17 Sustainable Development Goals is to "*ensure availability and sustainable management of water and sanitation for all*" (UN, 2015). Since 2000 the proportion of the population in low and middle- income nations that use "unimproved" sanitation facilities has increased (WHO & UNICEF, 2017). Globally a total of 3.5 billion people still have no access to adequate sanitation facilities (WHO, 2020b). Worldwide 2 billion people use onsite sanitation facilities that generate significant quantities of untreated faecal sludge (UNICEF & WHO, 2017). Untreated faecal sludge from these facilities is generally discarded straight into the local environment, or reused on agricultural land (Jiménez et al., 2009).

The poor management of faecal sludge (FS) collected from these onsite sanitation facilities has contributed to worsening public health outcomes and environmental pollution in the form of eutrophication of neighboring lakes and streams, and contamination of groundwater (Gwenzi & Munondo, 2008).

Improving sanitation provision in developing nations is challenging due to the economic cost as well as the land area, water, and energy requirements. The approach used to deal with these challenges is termed faecal sludge management and is based around 5 main principles which include the storage, collection, transport, treatment and safe disposal of faecal sludge (Strande et al., 2014a).

Recent research has focused on thermochemical treatment by pyrolysis as a safe method of disposing of both sewage and faecal sludge. The pyrolysis (thermal treatment) of biomass generates a recalcitrant carbon rich product, biochar, which can be used for improving soil health and soil carbon sequestration. Physico-chemical properties of biochar are related to the composition of the original feedstock and the pyrolysis conditions such as the highest treatment temperature (HTT) and residence time. This process also yields other by-products including bio-oil, tar and syngas.

Biochar been produced and used as a soil amendment to improve soil health and sequester carbon for thousands of years (Weber & Quicker, 2018b). It has received considerable attention in recent years due the potential benefits of its use in mitigating climate change, increasing soil fertility, increasing crop yields and wastewater treatment (Yu et al., 2019).

Biochar as a soil amendment produces many known benefits including improving carbon content and nutrient levels (Glaser et al., 2001), increasing the cation exchange capacity of the soil (CEC) (Glaser et al., 2001), increasing the water holding capacity of the soil (Gaskin et al., 2007; Herath et al., 2013), increasing pH levels in acidic soil (Novak et al., 2009), as well as reducing and immobilizing toxic metals such as arsenic, cadmium and zinc (Park et al., 2011). Biochar application to soil can also provide long-term carbon sequestration due to the recalcitrant nature of biochar and reduce yearly greenhouse emissions and therefore is an important tool in achieving net zero targets (Woolf et al., 2010).

Far more research has focused on evaluating the benefits of sewage sludge biochar on soil fertility and crop yield (Gwenzi et al., 2016; Hossain et al., 2015; Khan et al., 2013; T. Liu et al., 2014; Sousa & Figueiredo, 2016; Tian et al., 2019; Waqas et al., 2015; You et al., 2019; Zhang et al., 2016), compared to faecal sludge biochar (Bai et al., 2018; Woldetsadik et al., 2018). A google scholar search using the terms "*sewage sludge biochar*" brings up 44,400 results, however "*faecal sludge biochar* "returns only 2,390 results. Using an alternate spelling of faecal as in "*fecal sludge biochar*" still only produces about 4,300 results.   This review compares the properties of both raw faecal sludge and sewage sludge and their resulting biochars, noting any similarities and differences between the two.

The composition of biochar is largely dependent on two conditions; the feedstock and the temperature at which the feedstock is pyrolyzed (Downie et al., 2009). Sewage sludge and faecal sludge have different physico - chemical characteristics due to the different transport conditions, treatment processes and holding times.

There are similarities and differences between the three types of human waste discussed in this review. The characteristics of each type of waste can vary significantly, depending on several factors outlined below. In general human – waste is a complex heterogeneous mixture which can contain microorganisms, water, oils, nutrients, inorganic material and can be rich in organic matter.

Definitions

Sewage sludge: sludge generated during primary and secondary treatment of wastewater via sewer systems.

Biosolids: sewage sludge that has been treated at centralized treatment plant and meets land application standards (NRC, 2002). Treatment is usually comprised of biochemical processes such as anaerobic fermentation or a thermochemical process such as addition of alkaline materials.

Faecal sludge: sludge that has not been transported through a waterborne sewer system and originates from septic tanks, dry toilets and pit latrines.

Septage: is a specific type of faecal sludge in that it is limited to septic tank contents whereas faecal sludge is a broader term that encompasses contents from all types of onsite sanitation facilities.

Sewage sludge characteristics can vary with time, type of wastewater treatment facility, the operational method and the sources of the sewage. Wastewater treatment plants receive discharges from industry as well as residential areas. The high concentrations of metals and organic compounds found in sewage sludge can vary greatly depending on industrial activities (Alloway & Jackson, 1991; Baveye et al., 1999).

Undigested inorganic matter is usually higher than 50% in sewage sludge (Chorazy et al., 2020). The undigested organic matter of sewage sludge consists of a mixture of hydrocarbon compounds such as proteins, polycyclic aromatic hydrocarbons, peptides, lipids, polysaccharides, etc. (Fonts et al., 2012). Different forms of nitrogen and phosphorus exist within dry sewage sludge as well as environmentally harmful substances such as heavy metals, microplastics, and xenobiotic pharmaceutical trace chemicals (Chorazy et al., 2020).

Biosolids characteristics vary depending on the retention time, the treatment process and the stabilization technologies used (H. Wang et al., 2008). Stabilization technologies include anaerobic digestion, thermal treatment, composting and the addition of alkaline materials such as lime or fly ash, to reduce pathogen content and immobilize heavy metals (Kajitvichyanukul et al., 2008; H. Wang et al., 2008).

Faecal sludge quantities and characteristics can vary greatly depending on several important factors including location, climate, age of the sludge, type of sludge collection and the types of onsite sanitation facilities (Strande et al., 2014a). These onsite sanitation technologies include septic tanks, aqua privies, pit latrines (including ventilated improved pit latrines VIPs), public ablution blocks and dry toilets. Another difficulty in quantifying faecal sludge is that in cities different types of these facilities can be found side-by-side.

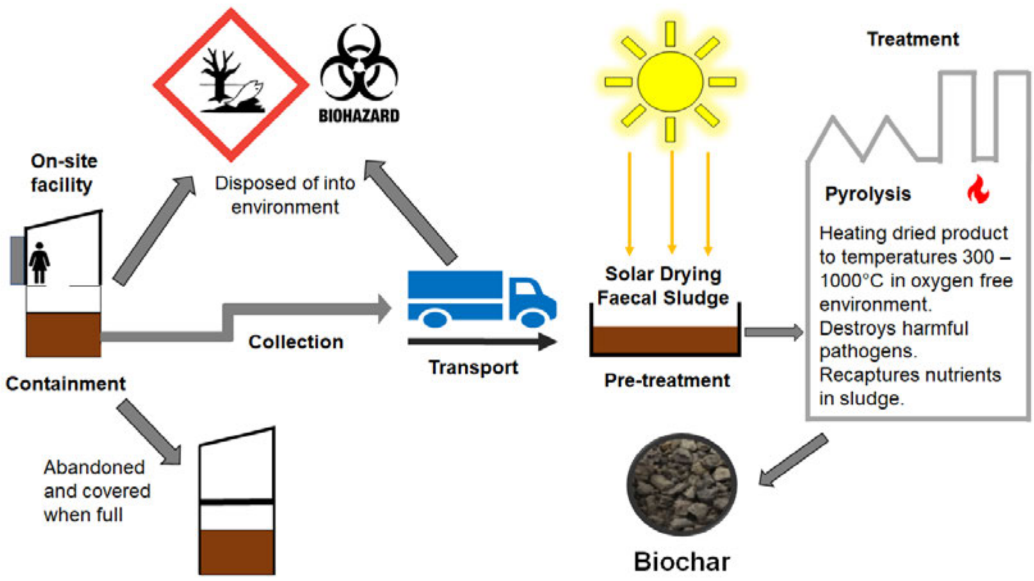


Figure 2.1 *Simplified overview of faecal sludge management with faecal sludge biochar as end product.*

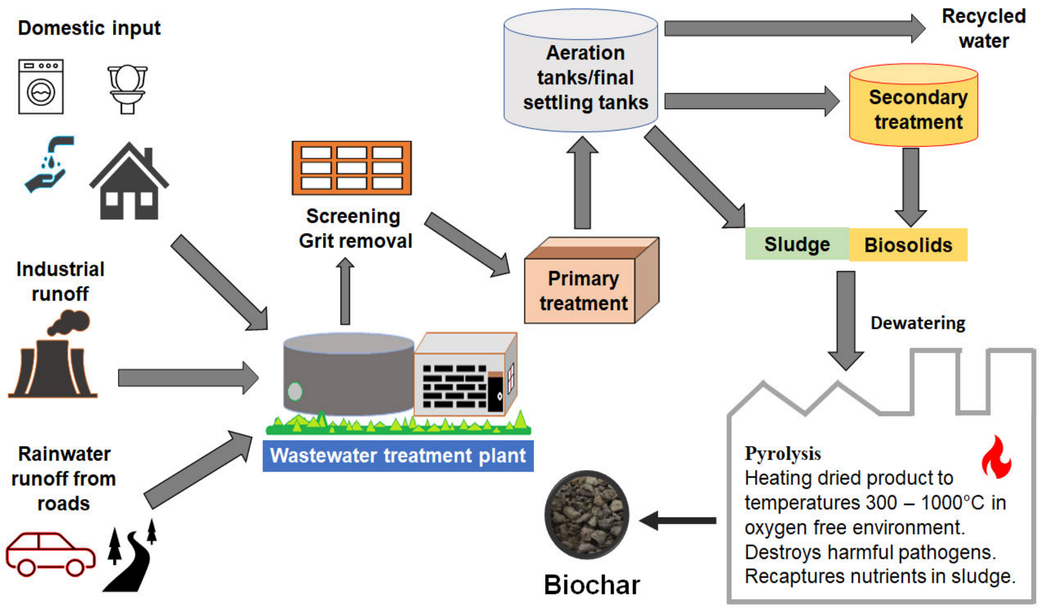


Figure 2.2 *Simplified overview of sewered waste treatment processes with sewage sludge and biosolids biochar as end products.*

2.2 COMPOSITION OF HUMAN WASTE

2.2.1 *pH*

Untreated primary sewage sludge can have pH values ranging from 5.0 – 8.0, with values of digested primary sludge in the range 6.5 – 7.5 (Metcalf et al., 2004).

Biosolids can be stabilized by adding alkaline materials to raise the pH level in order to remove pathogens from the product. In the EU, the pH of biosolids must be raised to greater than 12.0 and ensure that the pH is greater than 12 for a minimum period of 2 hours. The biosolids can then be used directly as a soil amendment (Carrington, 2001).

The range of pH of faecal sludge has been reported between 6.55 and 9.34 (Kengne et al., 2011). A difference in pH of FS between peri-urban areas and rural areas was reported by Appiah-Effah et al. (2014) with a mean pH of 6.7 in rural areas and 7.3 in peri-urban areas in the Ashanti Region of Ghana (Appiah-Effah et al., 2014).

2.2.2 *Total Solids*

Total solids characterization of FS is important to be able to design and implement FS treatment solutions. The total solids present in FS comprises of both organic (vaporizes readily) and inorganic matter. FS total solids concentration have been measured at a range of 12,000 – 35000 mg/l (Koné & Strauss, 2004) and volatile solids in faecal sludge measured at 0.45 - 4.3 g VS/g ash (Zuma et al., 2015). Total dry solids of untreated primary sludge and digested primary sludge have been reported at 5-9% and 2-5% respectively (Metcalf et al., 2004). Total solids of liquid, dewatered, and dried, biosolids have been reported at 2–12%, 12–30%, and 50% TS, respectively (H. Wang et al., 2008).

2.2.3 *Nutrient content*

The main nitrogen form found in untreated wastewater is ammonium nitrogen (NH_4-N), with other forms such as, nitrate nitrogen (NO_3^--N), nitrite nitrogen (NO_2^-N) and organic nitrogen present to a lesser degree (Li et al., 2017). Both ammonium nitrogen

(NH_4-N) and nitrate nitrogen (NO_3-N) are bioavailable forms for plant uptake and are crucial in evaluating faecal sludge as a soil fertilizer.

Nitrogen in FS can be found as nitrate, nitrite, organic forms (amino acids), and ammonium with the latter mainly arising from the urine component (Fidjeland, 2015). Ammoniacal-nitrogen concentration in FS from septic tanks has been measured at 150 -1200 mg/l (Koné & Strauss, 2004) and < 1,000 to 2, - 5,000 to mg/l in studies from Ghana, Thailand and Philippines (Heinss et al., 1998). A value of 30-70 mg/l for typical municipal sewage in tropical countries was also reported by Heinss et al., (1998). Dad et al., (2019) reported a NH_4-N range of 0.67 -8743 mg/kg for thermally hydrolyzed Mesophilic Anaerobically Digested (MAD) biosolids and dewatered MAD biosolids respectively. In general, ammoniacal-nitrogen concentration is higher in faecal sludge and septage than biosolids and sewage sludge.

The levels of nitrates in FS from septic tanks have been measured at 0.2-21 mg N/L (Koottatep et al., 2005). Biosolids had varying ranges of nitrates depending on treatment. Dewatered MAD, thermally dried MAD and lime stabilized biosolids have very low levels of nitrates <0.01 mg/kg DS. Thermally dried raw biosolids and composted biosolids had the highest levels of 7.49 mg/kg DS and 1,073 mg/kg DS respectively (Dad et al., 2019). In sewage sludge a significant quantity of nitrogen is organically bound and therefore it is not in a readily bioavailable form for plant uptake (Haynes et al., 2009). Dewatered anaerobically stabilized primary sewage sludge has a reported Nitrate-N content of 0.253 mg/g ± 0.015 dried sludge (Zorpas et al., 2000).

Total phosphorus levels found in FS can be very high, it is usually present in phosphate form (e.g., H_3PO_4/PO_4-P) or in the organic phosphate form that is present in plant tissue such as nucleic acids, phosphoproteins and adenosine triphosphate (Niwagaba et al., 2014). The form that phosphorus takes in the faecal sludge depends on various factors such as pH, sedimentation, precipitation, and redox potential (Niwagaba et al., 2014). Dad et al., (2019) reported highest phosphorus contents in liquid biosolids (2.35% phosphorous). Both the lowest total nitrogen and phosphorus content was recorded in the lime stabilized biosolids at 1.03% and 0.38% respectively.

The content of phosphorus in SS has been reported at 20.1–28.4 g/kg (Zielińska et al., 2015) with phosphorus in sludge mainly present in an inorganic form (R. Li et al., 2015; Pokhrel et al., 2018).

2.2.4 Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD)

COD indicates the amount of oxygen needed to chemically oxidize organic matter present in FS. It provides an index to measure the effect that discharged FS can have in the environment. Levels of COD in FS have been measured at 1200 mg/l – 7800 mg/l (Koné & Strauss, 2004) 20–50,000 and < 10,000 mg/l (Heinss & Strauss, 1999) and at 43,844 mg/l in raw, untreated sewage sludge (Montusiewicz et al., 2010). Biosolids generally have lower COD values due to the extra treatment processes.

BOD indicates the amount of oxygen required by aerobic microorganisms to break down organic matter. High BOD levels can lead to a decrease in the oxygen content in water bodies causing death to aquatic lifeforms (Bhateria & Jain, 2016). BOD concentrations in FS are much higher than in wastewater where a BOD5 >750 mg/L is considered to be very strong (Mara, 2013). Levels of BOD in FS have been measured at 840-2,600 mg/l (Koné & Strauss, 2004).

2.2.5 Pathogens

Human waste contains many different types of pathogens. Generally, only particular indicators of pathogenic activity are measured rather than all types of pathogens. This is less costly and less time-consuming and provides a reliable guide to the effectiveness of the treatment for pathogen removal. The generally used indicator organisms for human waste include helminths, bacteriophage, and the coliform bacteria (Snel & Shordt, 2005). Helminth eggs in FS from public toilets have been measured at 20000 – 60000 (Numbers/L) (Heinss et al., 1998), 458 egg/gTS (Appiah-Effah et al., 2020) and 4000 (Numbers/L) from septic tanks (Heinss et al., 1998). Coliform bacteria measurements on FS have been recorded at 128×10^6 cfu/100 mL from public toilets and 100, 000 cfu/100 ml from septic tanks and public toilets (Heinss et al., 1998). However, properties of faecal sludges differ greatly due to the type of the onsite sanitation system (e.g., septic tank systems, aqua privy, pit latrines), the retention time in the site, any groundwater infiltration into the sanitation site, and consumer habits (Appiah-effah et al., 2014).

Sewage sludge and biosolids generally contain less pathogens (Numbers/L) than faecal sludge. SS contains less pathogens per litre as it contains wastewater via sewer systems and different levels of treatment processes i.e., secondary treatment can lower the number of pathogens than that in primary treatment. Helminth egg concentrations in

FS are reported to be higher by a factor of ten or a hundred in comparison with wastewater sludge (Strauss et al., 2002). SS can contain 300-2000 (Numbers/L) helminth eggs (Heinss & Strauss, 1999).

There is no universal standard for pathogenic microorganisms in biosolids. Several countries in the EU have very stringent standards on pathogen concentration, France, for example has a maximum limit of 3 helminth eggs per 10 g of dry matter (European Commission, 2001) In the US biosolids are divided into two classes determined by their pathogen content. Class A has no detectable levels of pathogens with limits set at fecal coliforms <1000 MPN (most probable number) per g and helminth eggs <1 per 4 g total solids. Class B, in comparison, generally contain bacterial, parasitic, and viral pathogens due to a lower-level treatment and the only limit is set at faecal coliform density <2,000,000 MPN per g total solids (Pepper et al., 2006).

2.2.6 Heavy Metals

Heavy metals that are found in sewage and faecal sludge are toxic and harmful to the environment and humans if they enter the food chain. These include cadmium, zinc, nickel, chromium, mercury, lead and copper. Arsenic whilst not technically classed as a heavy metal is often included in this group as it is carcinogenic and a plant toxin (Moreno-Jiménez et al., 2012). Heavy metals in sewage sludge and biosolids arise from industry wastewater as well as rainwater runoff (Fijalkowski et al., 2020). The concentration of heavy metals in sewage sludge can affect its suitability as a soil amendment/fertilizer.

It is thought that heavy metals are at lower levels in faecal sludge than sewage sludge however, there is still large variation in concentrations depending on factors such as season and location. The majority of HMs found in SS and BS come from point sources such as households and businesses and diffuse sources such as rainwater runoff from roofs, galvanized materials, traffic, and agricultural areas (Bergbäck et al., 2001; Sörme & Lagerkvist, 2002).

The terms biosolids and sewage sludge are at times used interchangeably in the literature therefore it is not always possible to differentiate between them especially due to a lack of supporting information regarding the treatment processes and operating conditions of the wastewater treatment plants.

Table 2.1 *Ranges of heavy metal concentrations in sewage sludge (SS) and faecal sludge (FS), where* ***n/a*** *indicates no data was available.*

Type of sludge	**Cd**	**Pb**	**Cu**	**Zn**	**Cr**	**Ni**	**Hg**	**Fe**	**As**
SS dewatered (mg/kg dry weight)[1]	1 – 3.5	<5.6 – 167.8	140.8 – 216.4	690-1477.6	<5.6 - 260	22.6-54.6	0.8 - <1.3	n/a	n/a
FS Dry season (mg/l)[2]	n/a	0.7	1.2	8.0	n/a	n/a	n/a	21.0	n/a
FS Rainy season (mg/l)[2]	n/a	1.0	1.8	10.1	n/a	n/a	n/a	155.0	n/a
FS Peri-urban (mg/l)[3]	0.05	0.16	3.98	2.24	n/a	n/a	n/a	2.49	0.15
FS Rural (mg/l)[3]	0.01	0.05	0.34	1.29	n/a	n/a	n/a	0.93	0.025
BS (mg/kg DM) limit values EU directive[4]	20-40	750-1200	1000-1750	2500-4000	n/a	300-400	16-25	n/a	n/a
BS -3 WWTPs in Spain (mg/kg DM)[5]	1.4 – 2.6	59-172	309-649	482-1117	29-70	23-47	1.0-1.7	9,792-16717	5.6-18

[1] (Alvarenga et al., 2016; Moretti et al., 2016; Tüfenkçi et al., 2006)

[2] (Bassan et al., 2013)

[3] (Appiah-Effah et al., 2014)

[4] (European Commission, 1986)

[5] (Galvín et al., 2009)

2.3 PYROLYSIS

2.3.1 Pre-Treatment of sludge for pyrolysis

Sewage sludge needs to be dewatered and dried before pyrolysis can occur. Sewage sludge is transported through a waterborne sewer system, so it contains a higher liquid content than faecal sludge. Wang et al., (2008) reported that total solids of liquid, dewatered and dried biosolids increased from 2–12%, 12–30%, and 50% TS. A pelletizing process is sometimes used after the drying step to produce dried pellets of SS which is safer for handling.

Dewatering faecal sludge is usually achieved using drying beds (Tchobanoglous et al., 2003).

FS total solids concentration have been measured at a range of 12– 35 g/l (Koné and Strauss; 2004), and 20–50 g/l (Cofie et al., 2009; Kuffour et al., 2009)

Collection, drying and pyrolysis methods of sewage and faecal sludge can vary considerably.

Tables 2.2 and 2.3 below identify some of the different collection, drying and pyrolysis conditions reported in the literature.

Table 2.2 *Collection, drying and pyrolysis conditions of sewage sludge reported in the selected literature, n/a denotes that no data was available.*

Source of sewage sludge	Pyrolysis apparatus	HHT (°C)	Heating rates (°C/min)	Residence time (min)	Gas	Reference
Bulk portions of spray-dried sludge (<2 mm) were obtained from the Gaobeidian Wastewater Treatment Plant in Beijing	Sludge was tightly filled into steel cylinders.	200 300 500 700	10	n/a	n/a	Tian et al., (2019)
Four sewage sludges were obtained from municipal (mechanical–biological) (WWTPs) located in Koszalin, Kalisz, Chełm, and Suwałki, Poland. All the WWTPs used an anaerobic digestion process and dewatering. Samples were air-dried, ground and passed through a 2 mm sieve	Pyrolysis occurred in a pre-heated quartz tube and placed into an already heated furnace.	500 600 700	25 °C min^{-1}	300	N_2	Zielińska et al., (2015)
The sewage feedstocks were sourced from three different WWTPs, Xilang, Liede, and Datansha located in Guangzhou, China. The SS was belt filtered or centrifuged for dewatering without any anaerobic digestion pretreatment.	Pyrolysis was performed in a fixed bed reactor. The SS was dried during pyrolysis at a temperature between 100 and 127 °C.	300 400 500 600	10 °C min^{-1}	120	N_2	Lu et al., (2013)
Sewage sludge was obtained from the Chania (Crete) municipal WWTP. SS was treated via anaerobic digestion and belt-filter-press dewatering. Dewatered sludge was dried in an oven at 103 °C for 24 h, it was then crushed, and sieved.	Raw sludge and distilled water were stirred and heated at 250 °C until a thick paste was obtained. Then pyrolysis was conducted in a muffle furnace.	300 400 500	17 °C/min	30 60 90	N_2	Agrafioti et al., (2013)

Digested wastewater sludge sample was collected from an urban WWTP in Sydney, Australia. The sludge was dried at room temperature, then separated from other physical impurities and dried at 36 °C for two days	Pyrolysis was carried out using a fixed bed horizontal tubular reactor	300 400 500 700	10 °C min	n/a	N_2	Hossain et al., (2011)
SS was obtained from a sewage treatment plant in Harare that uses conventional biological trickling filtration system and the biological nutrient removal system. sludge was air-dried before pyrolysis.	Pyrolysis undertaken in a 0.2 m^3 drum pyrolysis reactor. fired using coal.	300-500	n/a	360	n/a	Gwenzi et al., (2016)
A mixture of activated sludge and primary sludge were sourced from Greenway WWTP in Ontario. This mixed sludge was mixed with polymer and dewatered to 72 wt.% moisture and dried in an oven at 105 °C.	Pyrolysis was performed in a batch Mechanically Fluidized Reactor (MFR) The reactor was cylindrical and constructed of stainless steel.	300 400 500	10	30	n/a	Barry et al., (2019)
SS samples were collected from the Gama municipal WWTP, in Brazil. In this plant, municipal wastewater receives secondary treatment in which the sludge is treated in digesters which function to stabilize the organic material. The sludge used was stored in a drying yard	Pyrolysis carried out in a pyrolysis furnace. The samples were placed in a metal container adapted to the furnace inner space, with mechanism to prevent the flow of oxygen.	300	11	30	n/a	Sousa and Figueiredo, (2016)
Sewage sludge was sampled from Xinzhuang Urban WWTP(Guiyang), in which municipal wastewater was subjected to secondary treatment by an activated sludge system. Activated sludge was dewatered by anaerobic	The sewage sludge sample was pyrolyzed in a fixed bed laboratory pyrolyzer.	450	5	30	n/a	T. Liu et al., (2014)

digestion and belt-filter press, air-dried, crushed, and passed through a 2-mm sieve.						
SS collected from a WWTP located in Shanghai city, China. After being dried at 105 °C for 48 h, the waste solids were ground to less than 2 mm.	Pyrolysis undertaken in a self-made stainless-steel reactor and heated in a Muffle Furnace	500	n/a	240	n/a	Xu et al., (2014)

***Table 2.3** Collection, drying and pyrolysis conditions of faecal sludge reported in the selected literature.*

Source of faecal sludge	Pyrolysis apparatus	HHT (°C)	Heating rates (°C/min)	Residence time (min)	Gas	Literature
Fecal sludge was obtained from a septic tank in the University of Science and Technology in Beijing. Fecal sludge was crushed to 2–6 mm after it was dried in natural air.	Fecal sludge was packed tightly in a ceramic crucible with a cover and heated in a tube furnace.	600	15	70	n/a	Bai et al., (2018)
12 locations from the top 10 cm of the septage drying area of a sewage disposal facility were collected in Ethiopia and mixed into one sample.	Sample was placed in Aluminium electric furnace. The air-inlet was covered to ensure a low oxygen condition.	450	14	60	n/a	Woldetsadik et al., (2018)
The biochar samples were taken at the FS treatment plants in Warangal, Telangana and Narsapur, Andhra Pradesh, India. Before treatment the FS was stored in holding tanks and then dewatered and thermally dried. The FS was co-	Pyrolysis occurred at full scale. The process treats 360 kg FS/day (dry basis). The chamber receives a limited supply of oxygen fan to	500-700	n/a	n/a	n/a	Krueger et al., (2020)

treated with pellet fuel (PF) derived from agricultural waste (0.3 kg PF/kg FS dry basis).	allow for partial oxidation enabling autothermal operation.					
FS collected from vacuum trucks at the National Water & Sewerage Corporation (NWSC) Lubigi WWTP in Kampala, Uganda. Samples were dewatered with a 0.3-mm mesh polyester fabric and then dried in a laboratory oven at 105 C	Pyrolysis conducted in a laboratory tunnel furnace; the tube was flushed with nitrogen gas at 50 L h1 to maintain an oxygen-free environment.	350 450 600	25 ± 3	10 20 40	N_2	Gold et al., (2018)
FS obtained from a sedimentation chamber of a septic tank system in Beijing, China. Samples were dried outdoors under solar heat and then dried in an oven at 75 °C.	Pyrolysis was carried out in a reactor consisting of a quartz tube	300 400 500 600 700	15	40	N_2	X. Liu et al., (2014)
Latrine waste was obtained from emptying of Ventilated and Improved Pit latrine (VIP) toilets in the eThekwini Municipality, South Africa. The fecal wastes were pelletized by the latrine dehydration and pasteurization process at 200°C for eight minutes. The feed stocks were dried at 70°C for 24 h and milled to <5 mm	Pyrolysis occurred in a muffle furnace. The furnace temperature was raised to set levels of 350, 550 or 650°C at a rate of 10°C for 2 hours.	350 550 650	10	120	n/a	Koetlisi and Muchaonyerwa, (2017)

Pyrolysis involves the thermal decomposition of carbonaceous material when heated under relatively high temperatures in an oxygen -free environment, producing three main products: bio-oil, syngas, and biochar (Wei et al., 2022). Bio-oil is mainly composed of low volatile organic compounds mixed with water, syngas comprises gases such as methane, hydrogen, and carbon dioxide and biochar is the carbonaceous solid by-product (Karaca et al., 2018). Pyrolysis can be divided into different classes based on the residence time of the biomass and the operating temperature (Perkins, 2018).

Slow pyrolysis: uses a low heating rate and a long solid and vapour residence time at a low temperature of approximately 400°C (Brownsort & Mašek, 2009). Slow pyrolysis maximizes the solid biochar yield, but liquid and gas products are still generally recovered in this process.

Intermediate pyrolysis: represents biomass pyrolysis in a specific type of commercial screw-pyrolyser called the Haloclean reactor (Hornung & Seifert, 2006). This Haloclean reactor uses pyrolysis as a method of waste disposal of electronic component residues. It is similar to the slow pyrolysis method just slightly faster.

Fast pyrolysis: uses high heating rates and shorter vapour residence times and usually depends on a feedstock of finely ground biomass. This method maximizes the liquid bio-oil yield and uses a temperature of around 500°C (Brownsort & Mašek, 2009). Fast pyrolysis is generally performed in circulating fluidized bed reactors or utilizing bubbling fluidized beds (Amenaghawon et al., 2021).

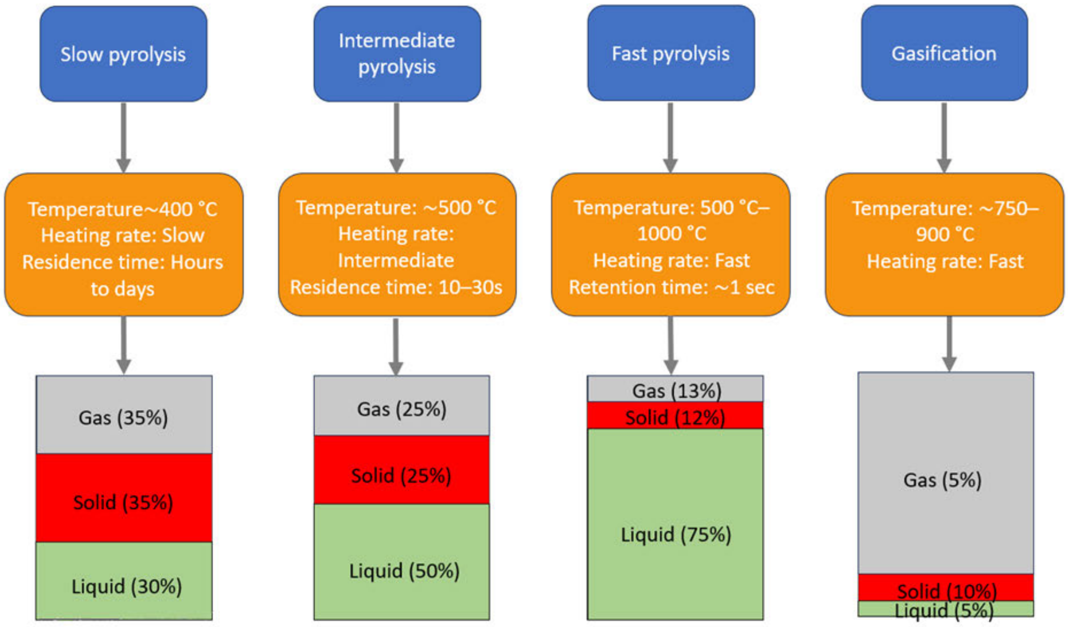


Figure 2.3 *Typical pyrolysis conditions including pyrolysis temperature, heating rate and residence times with product weight yields (dry wood basis) for different pyrolysis methods of wood* (Bridgwater, 2012).

Slow Pyrolysis

In this chapter we focus on the most common method of producing biochar: slow pyrolysis. Slow pyrolysis is defined by slow heating rates between 1 and 30 °C min^{-1} (Lua et al., 2004) with highest heating temperatures of 400°C – 900°C in the absence of oxygen. Slow pyrolysis is often deemed the most practical process for agronomic biochar production (W. Song & Guo, 2012b). Slow pyrolysis is generally undertaken at atmospheric pressure, with the process heat supplied from an external energy source. This source can be from combustion of the produced syngas or by partial combustion of the biomass feedstock (Laird et al., 2009).

2.4 Properties of Biochar

Pyrolysis involves heating of biomass to temperatures of 350°C - 1000°C in the absence of oxygen (European Biochar Foundation, 2016) to produce biochar.

Physico-chemical properties and yield of biochar are related to the composition of the original feedstock and the pyrolysis conditions such as the highest treatment temperature (HTT), vapour residence times and heating rate (Kramer et al., 2004).

Studies have shown that the HTT is the main parameter in determining final biochar characteristics (Antal & Grønli, 2003; Lua et al., 2004).

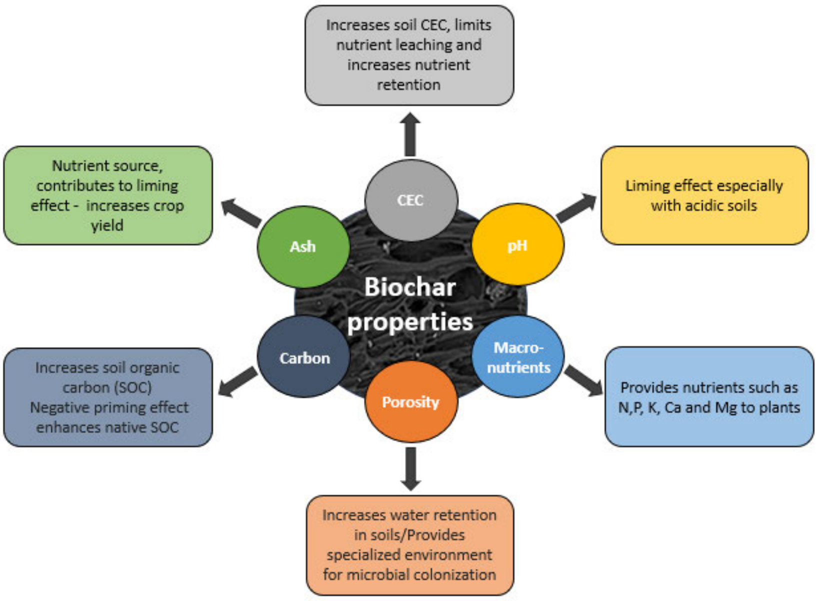


Figure 2.4 *Biochar properties relating to its use a soil amendment (CEC = cation exchange capacity, SOC = soil organic carbon, N (nitrogen), P (phosphorus), K (potassium), Ca (calcium), Mg (magnesium))*

2.4.1 pH

Biochar derived from both faecal and sewage sludge generally tend to have high pH values with increasing pyrolysis temperatures leading to an increase in pH (Hossain et al., 2011; X. Liu et al., 2014). Examples of pH for SS biochars and FS biochars are presented in tables 2.4 and 2.5. It has been proposed that the general alkaline character of biochar results from the carbonate content and the release of alkaline elements such as Na, K, Ca, and Mg during pyrolysis (Singh et al., 2010b). Altering soil pH is one of several mechanisms by which biochar can improve soils and increase agricultural productivity. Acidic soils are responsible for the severe limitation of crop agriculture worldwide. Up to 50% of soils globally which are suited to arable agriculture are acidic (von Uexküll & Mutert, 1995). Acidic soils are not just responsible for reduced crop yield but also affect the types of crops that can be grown, maize for example a staple food crop is adversely affected by acidic soils (Ngoune Tandzi et al., 2018).

The pH of biochar is generally neutral to high and so can increase the pH of soil, this liming effect of biochar can increase plant growth especially in acidic soils. In fact, the liming effect is one of the main processes influencing the enhanced plant growth seen on biochar addition to soils (Jeffery et al., 2011).

The liming effect can enhance several soil- plant interactions including:

- Increase phosphorus availability and N, Ca, Mg and Mo availability.
- Reduce the available level of aluminium, which is toxic to plant growth (Hammes, K. and Schmidt, 2009)
- Improvement of N_2 fixation in legumes
- Enhance microbial activity (DeLuca et al., 2012)

Sewage sludge derived biochar produced at low temperatures (300-400°C) tend to be acidic whereas biochar produced at temperatures ≥500° are generally alkaline (Hossain et al., 2011; Sousa & Figueiredo, 2016; Tian et al., 2019). Results of FS and SS derived biochars effect on soil pH are mixed (Tian et al., 2019).

Sewage sludge derived biochar has been shown to increase soil pH, available nutrients, and reduce the bioavailable forms of As, Cr, Co, Ni and Pb (Khan et al., 2013) and faecal sludge biochar has been shown to increase the pH and CEC of soil (Bai et al., 2018). However, Tian et al., (2019) conversely showed SS derived biochar addition to soil decreased soil pH, despite the alkaline nature of the biochar used. In another study biochar treatments significantly increased soil pH relative to inorganic fertilizer, but both were similar to pH values of the raw sludge and unamended control soils (Gwenzi et al., 2016).

pH conditions can also affect both the adsorption and bioavailability of phosphorus. This effect is particularly evident in acidic soils due to the liming effect of biochar leading to an increase in P availability (Nigussie et al., 2012).

2.4.2 Ash

It is accepted that the concentration of ash in biochar is generally higher than in the original feedstock regardless of pyrolysis temperature. Furthermore, an increase in pyrolysis temperature leads to an increase in the ash content of biochar (Fuertes et al., 2010). Ash content also differs greatly depending on the feedstock used. Poultry litter biochar has been described as having an ash content of 30.7% (Cantrell et al., 2012) compared to pine wood chip biochar of only 1.5% (Spokas et al., 2012), with both pyrolyzed at 350°C. The initial feedstock of sewage sludge is high in ash. Sewage sludges have been found to contain very high concentrations of silica (19–58%), calcium (5.1–7.4%), and phosphorus (3.4–4.9%) (Zielińska et al., 2015). Ash content of faecal sludge is also high and has been measured at 17.0 wt.%, significantly higher than the measured ash content of sawdust at 0.8% (X. Liu et al., 2014). It is thought that digestion during storage in onsite sanitation technologies can also play a part in the high ash content of faecal sludge biochar (Gold et al., 2018), as well as contamination of FS by sand and grit caused by poorly lined containment structures (Niwagaba et al., 2014a).

Sewage sludge biochar has been reported to have ash concentrations of 52.8% at 300°C and 63.3% at 400°C (Hossain et al., 2011). A high ash content is a positive when viewing the applicability of biochar as a soil amendment as the soil benefits from the minerals such as calcium carbonate, silicates and potassium found in ash (Nicholas et al., 2023). The high ash content of SS and FS biochars is related to the pH values. Increasing pyrolysis temperatures leads to an increase in pH due to an increase in ash in biochars derived from sewage sludge feedstocks (Hossain et al., 2011; X. Liu et al., 2014).

Table 2.4 *pH, ash content, and surface area values from selected sewage sludge biochars in reported literature, n/a denotes that no data was available.*

Pyrolysis Temperature °C	pH	Ash content %	S_{BET} Surface area (m^2g^{-1})	Reference
200	6.54	68.62	n/a	Tian et al., (2019)
300	7.20	70.14	n/a	
500	8.70	79.00	n/a	
700	11.15	85.75	n/a	
500[1]	7.13	73.56	31.8	Zielińska et al., (2015)
600[1]	11.03	77.77	24	
700[1]	12.23	79.08	54.1	
500[2]	7.08	68.09	16.3	
600[2]	11.45	70.27	9	
700[2]	12.38	74.28	29.9	
500[3]	7.17	68.98	34.2	
600[3]	11.33	70.22	16.4	
700[3]	12.44	71.99	9.2	
500[4]	7.25	64.1	35.7	
600[4]	8.05	63.86	19.2	
700[4]	13.1	67.98	18.1	
300	7.2-7.5	n/a	4.0 -6.7	Lu et al., (2013)
400	7.1-7.5	n/a	8.7-17.7	
500	7.6-7.7	n/a	10.2 – 26.5	

600	8.1-8.5	n/a	6.3 – 18.2	
300	6.0	n/a	4	Agrafioti et al., (2013)
500	n/a	n/a	18	
300	5.32	52.8	n/a	Hossain et al., (2011)
400	4.87	63.3	n/a	
500	7.27	68.2	n/a	
600	12.00	72.5	n/a	
300-500	8.54±0.08	n/a	n/a	Gwenzi et al., (2016)
300	n/a	38.3	n/a	Barry et al., (2019)
400	n/a	44.0	n/a	
500	n/a	50.4	n/a	
300	6.0* (Cacl2 method)	n/a	n/a	Sousa and Figueiredo, (2016)
450	8.6	n/a	n/a	T. Liu et al., (2014)
500	8.9	61.4	71.6	Xu et al., (2014)

**In* Zielińska et al., (2015) *the sewage sludge samples were characterized by moisture content before pyrolysis, the superscript numbers indicate the moisture content of the sewage sludge samples: [1]4.9 %, [2]4.3 %, [3]4.6 % and [4]4.4%.*

Table 2.5 *pH, ash, surface area and CEC (cation exchange capacity) values of selected faecal sludge biochars from selected literature (hold times are in brackets), n/a denotes that no data was available.*

Pyrolysis Temperature °C	pH	Ash content %	S_{BET} Surface area (m^2g^{-1})	CEC cmol $_{(+)}$ kg^{-1}	Reference
600	10.4	n/a	690.8* (<74µm and demineralized with HCl 2M)	n/a	Bai et al., (2018)
450	8.23	n/a	3.36	23.2	Woldetsadik et al., (2018)
500-700	10.5 ± 0.5	45.6 ± 4.2	n/a	n/a	Krueger et al., (2020)
500-700	10.8 ± 1.2	60.8 ± 5.5	n/a	n/a	
350 (10 min)	9.1	54.5	n/a	9.8	Gold et al., (2018)
350 (20 min)	9.2(± 0.02)	57.2(± 1.8)	n/a	13(± 0.7)	
350 (40 min)	9.3	57.5	n/a	9.8	
450 (10 min)	9.7	65.6	n/a	22.9	
450 (20 min)	9.7(±0.02)	66.9(± 1)	n/a	23.2(± 0.9)	
450 (40 min)	9.7	66.2	n/a	23.5	
600 (10 min)	11.0	68.1	n/a	24.6	
600 (20 min)	11.1(±0.01)	72.9(± 0.9)	n/a	26 (± 1.7)	
600 (40 min)	11.2	73.8	n/a	27.7	

300	7.3 ± 0.1	26.3 ± 0.8	n/a	n/a	X. Liu et al., (2014)
400	7.5 ± 0.1	31.3 ± 0.9	n/a	n/a	
500	10.3 ±0.2	45.5 ± 1.2	n/a	n/a	
600	10.7 ± 0.2	58.8 ± 0.6	n/a	n/a	
700	11.1 ± 0.2	62.5 ± 0.4	n/a	n/a	
350	6.94	84.60	7.5	5.09	Koetlisi and Muchaonyerwa, (2017)
550	7.02	90.23	23.7	4.91	
650	7.14	92.97	25.7	5.65	

2.4.3 *Surface area and porosity*

It is thought that the addition of biochar to soil can greatly improve soils water retention. A study by Glaser et al., (2002) showed that water retention in *Terra preta* was 18% greater than in adjacent soils containing little or no charcoal. One of the benefits of biochar is its recalcitrant nature making it generally stable in soil thus the benefits can be long-lasting. Biochar itself has highly variable water holding capacity and can even hold more than 10 x own weight in water (Kinney et al., 2012). This is due to its porous nature and large specific surface area. The porous structure of biochar results in greater water holding capacity of soil (Herath et al., 2013) and increases water availability (Blanco-Canqui, 2017; Omondi et al., 2016; Uzoma et al., 2011).

Increasing the pyrolysis temperature can enhance the BET surface area, the number of pores within the structure are increased due to the increase in volatile matter released. The fast pyrolysis of municipal sludge biochar at temperatures 500- 900 °C showed that increasing temperatures resulted in a greater yield of biochar and greater microporous network within the biochar (Chen et al., 2014). In a study by Bagreev et al., (2001) the biochar produced from sewage sludge-derived fertilizer mainly consisted of mesopores with some microporous structure present (Bagreev et al., 2001).

Surface area measured by N_2 is generally quite low for SS derived biochars, values have been reported ranging from 2.2 m^2g^{-1} (Gondek et al., 2019) to 54.1 m^2g^{-1} (Zielińska et al., 2015) (Table 2.4). Research has shown that sewage sludge biochars have low surface areas due to high ash content (Agrafioti et al., 2013; Bagreev et al., 2001; Schimmelpfennig & Glaser, 2012). It is thought that high ash contents reduce surface area by filling or blocking access to the biochar micropores (W. Song & Guo, 2012b). Bai et al., (2018) reported a specific surface area of faecal sludge biochar of

690.8 m^2g^{-1}, which was attained by measuring biochar <74µm and demineralizing with 2M HCl. Surface areas of other faecal sludge biochars without an acid wash pre-treatment have been reported at 3.7 m^2g^{-1} and 25.7 m^2g^{-1} (Koetlisi & Muchaonyerwa, 2017; Woldetsadik et al., 2018) (Table 2.5).

2.4.4 CEC

Biochars unique and varied surface chemistry plays a key role in nutrient leaching and retention in soils. Biochar is negatively charged, thus contributing to electrostatic adsorption of cations (Hale et al., 2013; Yao et al., 2011). The oxygen containing functional groups present on biochars surface such as C=O groups determine its cation exchange capacity (CEC) (Banik et al., 2018). It is this property that enables biochars to adsorb cationic nutrients such as NH^{4+}, Ca^{2+}, and K^{+}. This characteristic of biochar, results, predominantly from formation of carboxylic functional groups during oxidation (Cheng et al., 2006). These surface functional groups on the surface of biochar can lead to an increase in the CEC of the soil upon biochar addition (Glaser et al., 2001).

CEC is an indicator of a soil's nutrients-holding capacity and thus soils with high CEC values are generally fertile. The high CEC of biochars combined with large surface areas contribute to limit nutrient leaching in soils, (Lehmann & Joseph, 2012b) and improves nutrient retention (W. Song & Guo, 2012a). Additions of biochar to soil have shown increases in cation exchange capacity (CEC) and pH leading to its use as soil amendment (X. Bai et al., 2018; Glaser et al., 2001).

The determination of the cation exchange capacity (CEC) of biochar can be problematic in part because of the alkaline ash content and also the porous nature of biochars. It has been proposed that methodological problems are to blame for the variable and frequently unreproducible CEC values found in the literature (Munera-Echeverri et al., 2018). CEC values for biochar can range from from 6 $cmol_{(+)}\ kg^{-1}$ (Munera-Echeverri et al., 2018) to 36.3 $cmol_{(+)}\ kg^{-1}$ (W. Song & Guo, 2012b) to as high as 304 $cmol_{(+)}\ kg^{-1}$ (Yuan et al., 2011).

There are not many studies that have examined the CEC from SS and FS derived biochar. Méndez et al., (2013) looked at biochar pyrolyzed from sewage sludge co-composted with woody material and leaves from pine, elm and chestnut. They reported biochar CEC values of 30 $cmol_{(+)}\ kg^{-1}$ and 12 $cmol_{(+)}\ kg^{-1}$ pyrolyzed at 400°C and

600°C respectively. The cation exchange capacity of faecal sludge biochar has been reported at 23.2 $cmol_{(+)}$ kg^{-1} for biochar pyrolyzed at 450°C (Woldetsadik et al., 2018). Due to the lack of CEC values in the literature for sewage and faecal sludge biochar it is difficult to draw any conclusions about the affect feedstock and pyrolysis temperature has on CEC values. Previous research has shown inconsistent findings with CEC values of wood char decreasing with pyrolysis temperature (Crombie et al., 2015b), but increasing with pyrolysis temperature for cow manure char (Hossain et al., 2011) up to a pyrolysis temperature of 500-550°C, with a decrease above these pyrolysis temperatures. Gold et al., (2018) demonstrated that CEC value of FS char increased with pyrolysis temperature up to a temperature of 600°C (Gold et al., 2018). A study by Koetlisi and Muchaonyerwa (2017) investigated CEC values of biochar derived from faecal sludge (latrine waste) and sewage sludge. They reported a decrease in CEC values for both biochars with increasing pyrolysis temperature from 350°C to 550°C, however CEC values of both biochars increased when pyrolysis temperatures were increased to 650°C. The reported CEC values for these biochars are also very low, even lower than the CEC values of the original feedstock (11.7 - 17.8 $cmol_{(+)}$ kg^{-1}). Examples of CEC values for SS and FS biochars are given in tables 2.4 and 2.5.

2.4.5 Elemental Microanalysis C, H, N, and O

Yuan et al., (2016) showed that increasing pyrolysis temperature resulted in a decrease in nitrogen content of sewage sludge biochar. It is thought nitrogen exits in faecal sludge in mainly organic forms (Tian et al., 2013) and is volatilized at temperatures around 200°C (DeLuca et al., 2012), thus, the actual N content can be very low. Total N content in biochars can vary considerably across a large range (Bridle & Pritchard, 2004), with total N content of sewage sludge biochars reported as higher than biochars produced from green wastes. However, a measure of total nutrient content of biochars is not a measure of the bioavailable form of nutrients. Hossain et al., (2011) reported N content in wastewater sludge biochars increasing from between 1.2 to 3.32% with decreasing pyrolysis temperature.

FS and SS – derived biochars generally have low total C concentrations (11-40%) in comparison with cellulose derived biochars (Tomczyk et al., 2020). This is due to the high ash content in the original feedstock of FS and SS. The percentage of C in sewage sludge derived biochar has been measured at 21.6 to 26.2% with a low percentage of H also reported (3.8 to 5.1%) (Zielińska et al., 2015).

Pyrolysis generally concentrates carbon in the biochar with an increase in C content relative to the feedstock frequently reported, however most studies on sewage sludge –derived biochar show a decrease in the percentage of C in the final product relative to the feedstock (Agrafioti et al., 2013; Khan et al., 2013). An increase in pyrolysis temperature leads to a decrease in C and N and an increase in the ash content suggesting that as more ash is relatively accumulated, C and N are reduced. A study by Khan et al., (2013) observed that soils amended with sewage sludge biochar had increased total nitrogen, and organic carbon content. Examples of CHNO content for SS biochars and FS biochars are presented in tables 2.6 and 2.7.

Table 2.6 *Organic components, C, H, N, O and ratios of selected sewage sludge biochars, n/a denotes that no data was available.*

Pyrolysis temperature °	C	H	O	N	O/C	H/C	Reference
200	17.09	2.09	10.01	2.19	n/a	n/a	Tian et al., (2019)
300	19.72	1.97	5.76	2.59			
500	15.26	0.73	3.28	1.73			
700	11.33	0.31	1.90	0.71			
500[1]	18.92	0.72	4.0	2.72	0.16	0.46	Zielińska, et al (2015)
600[1]	18.43	0.38	1.19	2.2	0.05	0.25	
700[1]	8.12	0.24	0.68	1.88	0.03	0.16	
500[2]	23.16	0.77	4.42	3.57	0.14	0.4	
600[2]	23.72	0.44	2.29	3.29	0.07	0.22	
700[2]	22.84	0.33	0.3	2.25	0.01	0.17	
500[3]	22.41	0.67	4.94	3	0.17	0.36	
600[3]	22.47	0.63	4.02	2.67	0.13	0.34	
700[3]	21.71	0.56	3.34	2.4	0.12	0.31	
500[4]	26.59	1.08	4.29	3.95	0.12	0.49	
600[4]	27.68	0.82	3.89	3.76	0.11	0.36	
700[4]	27.84	0.48	0.79	2.92	0.02	0.21	

300[5]	31.5	3.3	n/a	5.4	n/a	n/a	Lu et al (2013)
400[5]	27.5	2		4.4			
500[5]	26.7	1.9		3.7			
600[5]	26	1.3		3.4			
300[6]	21.7	2.8		3.4			
400[6]	16.4	1.7		2.8			
500[6]	15.4	1.6		2.3			
600[6]	15.2	1		2			
300[7]	27.1	3		4.4			
400[7]	22.6	1.9		3.7			
500[7]	22.1	1.7		3.3			
600[7]	21.9	1.1		2.7			
300	39.7	4.1	n/a	7.1	n/a	n/a	Agrafioti et al., (2013)
500	9.8	0.4		2.1			
300	25.6	2.55	8.33	3.32	n/a	n/a	Hossain et al., (2011)
400	20.2	1.28	4.61	2.40			
500	20.3	0.88	0.65	2.13			
600	20.4	0.51	0.00	1.20			
300-500	n/a	n/a	n/a	0.69 ± 0.02	n/a	n/a	Gwenzi et al., (2016)
300	45.4	4.2	7.3	4.9	n/a	n/a	Barry et al., (2019)
400	42.1	3.2	5.6	4.6			
500	40.5	2.0	5.6	0.7			

300	23.4	n/a	n/a	3.3	n/a	n/a	Sousa and Figueiredo, (2016)
450	21.3	n/a	n/a	3.17	n/a	n/a	Liu., et al. (2014).
500	27.7	n/a	n/a	n/a	n/a	n/a	Xu, et al (2014).

**In* Zielińska et al., (2015) *the sewage sludge samples were characterized by moisture content before pyrolysis, the superscript numbers indicate the moisture content of the sewage sludge samples: [1]4.9 %, [2]4.3 %, [3]4.6 % and [4]4.4%. In Lu et al. (2014) the sewage feedstocks were sourced from three different WWTPs, the superscript number 5-7 indicate which WWTP the sewage was sourced from: [5] Xilang WWTP, [6] Liede WWTP), and [7] Datansha WWTP.*

Table 2.7 *Organic components, C, H, N, O and ratios of selected faecal sludge biochars, (pyrolysis hold times are in brackets), n/a denotes no data was available.*

Pyrolysis temperature °C	C	H	O	N	H/C	Reference
600	84.37	2.40	n/a	0.77	n/a	Bai et al., (2018)
450	19.5	n/a	n/a	2.02	n/a	Woldetsadik, et al (2018).
500-700 500-700	34.1 ± 3.9* 17.2 ± 5.2*	n/a	n/a	n/a	n/a	Krueger, et al (2020).
350 (10 min) 350 (20 min) 350 (40 min) 450 (10 min) 450 (20 min) 450 (40 min) 600 (10 min) 600 (20 min) 600 (40 min)	33.3(±2.7) 33.5(±2.4) 34.9(±2.8) 32.8(±1.2) 27.4(± 4.1) 31.5(±4.1) 29.8(±2.3) 28.2(± 2.2) 27.4(±2.7)	n/a	n/a	2.3(± 0.0) 2.3(± 0.0) 2.3(± 0.0) 2.0(±0.0) 1.6(± 0.0) 1.8(±0.0) 1.5(±0.0) 1.3(± 0.0) 1.3(±0.0)	n/a	Gold et al., (2018)
300 400 500 600 700	42.9 ± 1.2 42.0 ± 2.1 35.7 ± 3.9 37.9 ± 1.3 36.4 ± 4.3	6.7 ± 1.4 3.5 ± 0.4 1.9 ± 0.4 1.8 ± 0.2 1.8 ± 0.8	44.4 ± 1.9 50.1 ± 1.7 58.4 ± 3.3 56.4 ± 1.2 58.3 ± 2.3	4.8 ± 0.6 3.4 ± 0.6 2.9 ± 0.7 2.9 ± 0.9 2.4 ± 0.8	1.88 0.99 0.62 0.56 0.58	X. Liu et al., (2014)
350 550 650	11.14 8.73 6.45	1.01 0.36 0.35	n/a n/a n/a	1.04 0.71 0.44	1.1 0.3 0.4	Koetlisi and Muchaonyerwa, (2017)

2.4.6 Heavy metals

Heavy metals that are toxic and harmful to the environment include cadmium, zinc, nickel, chromium, mercury, lead and copper with arsenic often included in this group as it is carcinogenic and a plant toxin (Moreno-Jiménez et al., 2012). The heavy metal concentration is highly variable, both in sewage, and faecal sludge and this impacts the heavy metal content in the biochar. Biochar produced from sewage sludge contains higher concentrations of heavy metals than that found in soils (X. D. Song et al., 2014). This is because heavy metals do not volatilize, so their concentration within the biochar increases with pyrolysis temperature (Chanaka Udayanga et al., 2019; Hossain et al., 2010; Wang et al., 2021). Studies have shown that even though sewage sludge biochars contain high concentrations of HMs the pyrolysis process entraps the heavy metals in immobile and stable forms within the biochar, therefore the use of biochar as a soil amendment still has potential (Galvín et al., 2009; S. Sun et al., 2018; X. Wang et al., 2016).

Heavy metal concentration in biochars generally increase with pyrolytic temperature (Lu et al., 2013), however there are conflicting reports on the impact that increasing pyrolysis temperature has on heavy metal concentrations in sludge biochar. The general trend does seem to be an increase in HM concentration with an increase in pyrolysis temperature with some noticeable exceptions at higher temperatures. Studies have shown heavy metal concentrations in sludge biochar peaking at 450°C and then decreasing at higher temperatures of 500°C - 550°C (X. D. Song et al., 2014). Others have reported a decrease in all HM concentrations of sludge biochar pyrolyzed at 700°C except for cadmium (Hossain et al., 2011). Heavy metals in FS-biochar adhered to the general trend with an increase in HM concentrations with an increase in pyrolysis temperature (Gold et al., 2018).

Biochars pyrolyzed at higher temperatures can have beneficial qualities for use as a soil amendment including higher pH values and greater surface areas. Consideration needs to be paid to ensure that the higher temperatures do not increase HM concentration in biochars to greater than the recommended guidelines for HMs in soils. Heavy metals in most SS and FS derived biochars are below International Biochar Initiative (IBI) accepted upper thresholds (IBI, 2015). One exception to this is FS derived biochar studied by Woldetsadik, et al., 2018. This biochar pyrolyzed at 450°C contained Zinc and Pb in excess of the upper thresholds (IBI, 2015). No explanation for this was given but heavy metal concentrations in faecal sludge can vary considerably depending on season and location and industrial runoff.

Heavy metal concentrations in selected sewage and faecal sludge biochars are presented in tables 2.9 and 2.10.

Table 2.8 *Comparison of biochar heavy metal thresholds* (EBC, 2016)*;* (IBI, 2015)

European Biochar Certificate V4.8 Basic grade:	IBI Biochar Standards V2.0 B Maximum allowed thresholds
mg kg^{-1}	mg kg^{-1}
Cd < 1.5	Cd 1.4 – 39
Ni < 50	Ni 47 – 600
Zn < 400	Zn 200 – 7000
Pb < 150	Pb 70 – 500
Cu < 100	Cu 63 – 1500
Hg < mg kg^{-1}	Hg 1 – 17
Cr < 90	Cr 64 – 1200
	Co 40 – 150 Mo 5 – 20 mg Se 2 – 36 As 12 – 100

Studies looking at SS and FS biochar have also investigated the potential leaching of heavy metals from biochar.

The soluble and extractable fractions of heavy metals in biochar is significantly decreased when compared to the original feedstock and the total heavy metal concentrations in biochar (S. Sun et al., 2018).

There have been several reasons suggested for this trend:

- Amines and amides remaining at pyrolysis temperatures > 300°C behave as ligands for binding heavy metals in the sludge and entraining the metals within the carbon structure network (Jin et al., 2014)
- High phosphorus content can stabilize heavy metals through the formation of an insoluble phosphate precipitant (Lu et al., 2013)
- High pH values (commonly found in SS and FS chars) tend to restrain heavy metal release (Kistler et al., 1987)

Hossain et al., (2011) showed that DTPA-extractable concentrations of heavy metals decreased with increasing pyrolysis temperature from 300 - 700°C, however in another study extractable heavy metal concentrations in sewage sludge biochar increased with pyrolysis temperature in the range 300 - 500°C (Lu et al., 2013). There is limited research available on the effect of pyrolysis temperature on extractable heavy metal concentrations in faecal sludge biochar.

Table 2.9 *Heavy metal concentrations in selected sewage sludge biochars, n/a denotes no data was available.*

	mg kg 1	g kg-1					Reference
Pyrolysis temperature °C	**Zn**	**Cd**	**Ni**	**Cr**	**Pb**	**Cu**	
300[1]	1.49 ± 0.02	5.68 ± 0.06	n/a	n/a	241.8 ± 5.6	1034.3 ± 9.2	Lu et al. (2013)
400[1]	1.66 ± 0.03	5.97 ± 0.07	n/a	n/a	274.8 ± 6.1	1197.7 ± 19.8	
500[1]	1.80 ± 0.05	6.44 ± 0.09	n/a	n/a	299.2 ± 9.2	1267.3 ± 27.8	
300[2]	0.85 ± 0.03	3.30 ± 0.05	n/a	n/a	189.5 ± 4.2	479.9 ± 8.5	
400[2]	0.91 ± 0.03	3.76 ± 0.06	n/a	n/a	194.2 ± 4.4	548.6 ± 5.9	
500[2]	1.02 ± 0.04	4.25 ± 0.07	n/a	n/a	211.8 ± 5.0	564.9 ± 9.7	
300[3]	1.91 ± 0.05	7.45 ± 0.10	n/a	n/a	350.0 ± 5.8	686.9 ± 10.1	
400[3]	2.10 ± 0.06	9.82 ± 0.03	n/a	n/a	438.3 ± 6.3	690.8 ± 4.3	
500[3]	2.30 ± 0.07	8.85 ± 0.1	n/a	n/a	506.4 ± 9.1	692.1 ± 14.1	
300	1.675±0.025	2.62 ±0.04	182.5 ±18.42	107.5 ±2.50	115 ±2.88	1150 ±28.86	Hossain et al. (2011)
400	1.825±0.025	2.8±0.05	165 ±11.9	112.5 ±2.50	130±0.00	1125 ±25	
500	2100 ±0.000	3.17 ±0.12	292.5 ±34.24	112.5 ±2.50	140 ±0.00	1325 ±25	
600	2.175±0.025	3.22 ±0.06	195 ±6.45	83 ±3.36	132 ±2.5	1500±70.71	
300-500	548.8±10.7	n/a	41.67±2.7 a	n/a	112.7±3.7	307.8±12.6	Gwenzi et al, (2016).
500	n/a	n/a	n/a	n/a	n/a	n/a	Barry, et al. (2019)
300	0.005	n/a	n/a	n/a	n/a	1.4	Sousa & Figueiredo. (2016).
450	0.749	4.12	n/a	92.2	67.5	124.8	Liu., et al. (2014).
500	0.00152	n/a	n/a	n/a	n/a	0.38	Xu, et al (2014).

* *In Lu et al. (2014) the sewage feedstocks were sourced from three different WWTPs, the superscript number 1-3 indicate which WWTP the sewage was sourced from: [1] Xilang WWTP, [2] Liede WWTP), and [3] Datansha WWTP.*

Table 2.10 *Heavy metal concentrations in selected faecal sludge biochars, n/a denotes no data was available.*

Pyrolysis temperature °C	g kg^{-1}	mg kg^{-1}					Reference
	Zn	**Cd**	**Ni**	**Cr**	**Pb**	**Cu**	
450	28.4	1.23	84.4	39.5	502	214	Woldetsadik, et al (2018).
500-700	1. 5± 0.2	13.5 ± 2.7	122.7 ± 37.1	6.1 ± 5.8	395.3 ± 57.9	463.0 ± 61.1	Krueger, et al (2020).
500-700	1.1 ± 0.3	12.4 ± 2.0	164.1 ±48.8	54.3 ±16.5	241.7 ±50.9	310.3 ±37.0	
350 (10 min)	0.917 ±0.05	n/a	63.7±2.7	121.5 ±7.1	<5	90.4 ±3.9	Gold, et al (2018).
350 (20 min)	0.923 ±0.06	n/a	63.3± 5	124.9 ± 8.8	21.5	86.6 ± 9.4	
350 (40 min)	0.873±0.005	n/a	57.4 ±0.9	113.7 ±4.0	<5	81.8 ±1.9	
450 (10 min)	0.971 ±0.06	n/a	62.9±3.8	125.2 ±4.6	14.9 ± 1.4	96.7±9.2	
450 (20 min)	1.01 ±0.01	n/a	66.6 ± 1.9	129 ± 3.5	13.7 ± 2.4	101.7 ± 1.6	
450 (40 min)	0.948 ±0.01	n/a	76 ±1.9	152.6 ±3.5	<5	91.5 ±1.6	
600 (10 min)	1.06 ±0.02	n/a	89.8 ±3.1	180 ±4.8	<5	101.6 ±4.3	
600 (20 min)	1.09 ±0.08	n/a	78 ± 3.5	151.9 ± 6.1	<5	110. ± 8.0	
600 (40 min)	1.12 ±0.037	n/a	96.5 ±3.2	194.2 ±6.7	<5	113.2 ±7.9	

2.4.7 Available nitrogen

The nitrogen within biochar that is available for plant uptake is found in the forms NH_4-N (ammonium nitrogen) and NO_3-N (nitrate nitrogen). Along with phosphorus, nitrogen is a plant limiting nutrient and a significant agronomic property of sludge biochar. Concentrations of ammonium N is higher than nitrate in sludge biochars (Hossain et al., 2011; Tian et al., 2019).

Ammonium nitrogen concentrations decrease with increasing pyrolysis temperature whereas NO_3-N concentrations increase with higher pyrolysis temperatures (Hossain et al., 2011; Tian et al., 2013).

Table 2.11 *Ammonium nitrogen (NH_4^+ - N) and nitrate nitrogen (NO_3^- - N) concentrations of selected sewage sludge biochars (mg/kg)*

Pyrolysis temperature (°C)	NH_4^+ - N (mg/kg)	NO_3^- - N (mg/kg)	Reference
200	533.51	0.10	Tian et al., (2019)
300	119.28	1.97	
500	21.41	2.77	
700	17.72	2.72	
300	1175	<0.2	Hossain et al., (2011)
400	142.5	<0.2	
500	25	0.24	
600	1.34	0.32	
300	431.9	17.5	Sousa and Figueiredo, (2016)

2.4.8 Phosphorus

Sewage and faecal sludges are rich in mineral nutrients such as ammonium, nitrate, potassium, trace elements and phosphate, the latter of which is a finite resource and an irreplaceable plant limiting nutrient (Steen, 1998). Reported concentrations of phosphorus on a dry weight basis in sewage sludge can range from <0.1% to 14% (Sommers, 1977).

The phosphorus concentration in biochar is increased relative to the original feedstock due to volatilization of elements C, H, O and N during pyrolysis (Sousa & Figueiredo, 2016). The general trend observed with total phosphrous and pyrolysis temperature is increasing phosphorus content with increasing temperature. Chan and Xu, (2009) reported an increase in phosphorous from 5.6% at 250 °C to 12.8% at 800 °C in SS biochar.

It is thought that phosphorus within sewage sludge is mainly in inorganic form therefore is more susceptible to volatilization losses specifically at pyrolysis temperatures over 700 °C (Gaskin et al., 2008a). This effect has been recorded in studies of SS biochar (Lu et al., 2013; Zielińska et al., 2015) and FS biochar (Gold et al., 2018; X. Liu et al., 2014), however at pyrolysis temperatures of 700°C Liu et al., (2014) recorded a decrease in P content in FS biochar and Zielińska et al., (2015) observed an increase of P content in SS biochar. The conflicting trend of phosphorus content at pyrolysis temperatures of 700 °C may be caused by variations in the forms of phosphorus present in different types of sludge. Both the composition of raw sludge and differing chemical and biological treatment processes can alter the forms of P present (McLaughlin, 1984), and hence alter the resistance to volatilization losses at temperatures > 700 °C. Gold et al., (2018) reported an increase in Total P concentration in FS biochar with P content increasing from 3.2% at 350°C to 3.9% at 600°C and X. Liu et al., (2014) reported an increase from 5.4 at 300 to 8.1 wt.% at 600°C and then a slight decrease at 700°C.

Not all phosphorous within biochar is available to plants, the P available to plants within biochar is less than the total phosphorus in biochar.

Pyrolysis of sludge does increase the amount of available phosphorus within biochar relative to original sludge feedstock (T. Liu et al., 2014), in fact, Barry et al., (2019) states that the availability of phosphorous within biochar amended soils is the most significant impact of sewage sludge biochar application. Biochar-added soils have much higher organic available P compared to soil without biochar amendment but mechanisms leading to the release of nutrients from biochar are still not fully understood.

Added nutrients from the biochar itself is one cause however there are other mechanisms such an increased nutrient retention capacity from the biochar (Joseph et al., 2018) and also the liming effect of biochar which improves nutrient use efficiency and enhances the plant-available P in soils (Chintala et al., 2014; Glaser & Lehr, 2019). Hossain et al., (2011) reported that available phosphorus in biochar decreased increasing pyrolysis temperature in the range 400°C - 700°C, and Tian et al., (2019) observed a decrease in extractable P at pyrolysis temperatures ranging from 200°C to

700°C. A study of FS biochar showed the opposite trend was true with an increase in available P from 26.1 g/kg at 350°C to 33.3 g/kg at 600°C (Gold et al., 2018).

Table 2.12 *Total (P total) and extractable phosphorus (Extractable P) content of selected sewage sludge biochars, n/a denotes no data was available.*

Pyrolysis Temperature (°C)	P total (g/kg)	Extractable P (g/kg)	Reference
200	n/a	0.3644	Tian et al., (2019)
300	n/a	0.2358	
500	n/a	0.1813	
700	n/a	0.1267	
500[1]	5.4±0.37[1]	n/a	Zielińska et al., (2015)
600[1]	5.92±0.40[1]		
700[1]	6.31 ±0.42[1]		
500[2]	5.88+0.39[1]		
600[2]	6.48±0.42[1]		
700[2]	6.86±0.44[1]		
500[3]	5.47±0.37[1]		
600[3]	5.31±0.37[1]		
700[3]	5.6±0.38[1]		
500[4]	9.6±0.58[1]		
600[4]	9.22±0.56[1]		
700[4]	9.51±0.58[1]		
300[5]	42.6	n/a	Lu et al., (2013)
400[5]	58.5		
500[5]	59.5		
600[5]	57.6		
300[6]	29.5		
400[6]	29.2		
500[6]	34.1		
600[6]	35.5		
300[7]	32.7		
400[7]	38.1		
500[7]	40		
600[7]	41		
300 -500	0.11±0.00 [8]	n/a	Gwenzi et al., (2016)
500	n/a	0.2%	Barry et al., (2019)
300	41.1 g/kg	n/a	Sousa and Figueiredo, (2016)
450	15.4 g/kg	1.31 g/kg DTPA	T. Liu et al., (2014)
500	1.7[1]	n/a	Xu et al., (2014)

**In* Zielińska et al., (2015) *the sewage sludge samples were characterized by moisture content before pyrolysis, the superscript numbers indicate the moisture content of the sewage sludge samples: [1]4.9 %, [2]4.3 % , [3]4.6 % and [4]4.4%. In Lu et al. (2014) sewage feedstocks were sourced from three different WWTPs, the superscript number 5-7 indicate which WWTP the sewage was sourced from: [5] Xilang WWTP, [6] Liede WWTP), and [7] Datansha WWTP.*
[8] *the contribution (%) of elements in biochar*

Table 2.13 *Total (Total P) and extractable phosphorus (Available P) content of selected faecal sludge biochars, n/a denotes no data was available*

Pyrolysis Temperature (°C)	Total P g/kg	Available P	Reference
450	42.7 (g/kg)	n/a	Woldetsadik et al., (2018)
500-700 500-700	1.2 ± 0.2 g/kg 2.2 ± 0.6	61.0 ± 6.4 % 53.7 ± 12.1	Krueger et al., (2020)
350 (10 min) 350 (20 min) 350 (40 min) 450 (10 min) 450 (20 min) 450 (40 min) 600 (10 min) 600 (20 min) 600 (40 min	3.2 (± 0.2) 3.3 (± 0.3) 3.1 (± 0.0) 3.6 (± 0.2) 3.8(± 0.1) 3.5(± 0.1) 3.9(± 0.2) 4.0(± 0.2) 4.2(± 0.3)	26.1 25.3(± 1.4) 28.1 32.6 30.5 (± 0.7) 34.8 33.3 33.4(± 1.4) 36.0	Gold et al., (2018)
300 400 500 600 700	5.4 ± 1.2 wt.% 6.3 ± 3.1 7.9 ± 1.7 8.1 ± 1.6 7.8 ± 2.2	n/a	X. Liu et al., (2014)

2.4.9 Macronutrient concentrations Ca, Mg, K

Sewage and faecal sludge biochars contain large amounts of macro-nutrients such as calcium, potassium, and magnesium, with pyrolysis increasing the concentrations of these elements in biochar relative to the sludge. Increases in Ca, K, and Mg have also been identified with increases in pyrolysis temperature. This is caused by to the gradual loss of C, H and O (Al-Wabel et al., 2013) whereas elements Ca, K and Mg, cannot be lost through volatilization, since the oxides of these metals are not volatile (Novak et al., 2009). Evidence of large amounts of Ca, Mg and K in sewage sludge biochar (Hossain et al., 2011; T. Liu et al., 2014) and faecal sludge biochar has been reported previously (Krueger et al., 2020; Woldetsadik et al., 2018). Evidence of increasing Ca, Mg, and K concentrations with increasing pyrolysis temperature in sewage sludge derived biochar has been reported by (Lu et al., 2013; Zielińska et al., 2015) and in faecal sludge biochar (X. Liu et al., 2014).

The treatment process of sewage sludge can impact the concentration of certain elements, for example, Lu et al., (2013) found that one type of sewage sludge biochar had a relative high proportion of calcium which they postulated was due to the addition of CaO during the sludge conditioning process.

Table 2.14 *Macronutrient (Ca, Mg, K) concentrations in selected sewage sludge biochars. (Values in g/kg unless otherwise stated), n/a denotes no data was available.*

Pyrolysis temperature (°C)	K	Mg	Ca	Reference
500[1]	0.92 ±0.08 (%)	0.94 ±0.09 (%)	8.27 ±0.51 (%)	Zielińska et al., (2015)
600[1]	1.01 ±0.08 (%)	1.08 ±0.09 (%)	9.18 ±0.56 (%)	
700[1]	1.09 ±0.08 (%)	1.13 ±0.10 (%)	9.71 ±0.59 (%)	
500[2]	1.4 ±0.11 (%)	1.47 ±0.12 (%)	6.75 ±0.43 (%)	
600[2]	1.55 ±0.12 (%)	1.65 ±0.14 (%)	6.02 ±0.38 (%)	
700[2]	1.64 ±0.12 (%)	1.78 ±0.14 (%)	7.42 ±0.46 (%)	
500[3]	1.25 ±0.10 (%)	1.13 ±0.10 (%)	12 ±0.70 (%)	
600[3]	1.34 ±0.11 (%)	1.25 ±0.10 (%)	11.4 ±0.61 (%)	
700[3]	1.34 ±0.11	1.27 ±0.10 (%)	12 ±0.70 (%)	
500[4]	1.06 ±0.08 (%)	3.29 ±0.23 (%)	10.2 ±0.61 (%)	
600[4]	1.12 ±0.09 (%)	2.57 ±0.19 (%)	10. 8±0.64 (%)	
700[4]	1.12 ±0.10 (%)	2.44 ±0.18 (%)	11.9 ±0.70 (%)	
300[5]	2.1	8.2	8.1	Lu et al (2013)
400[5]	2.4	8.4	8.4	
500[5]	2.4	8.2	8.8	
600[5]	2.8	9.3	6.7	
300[6]	1.6	11	11.6	
400[6]	2	13.4	11.9	
500[6]	2.2	12.5	12.2	

600[6]	2.6	14.5	14.6	
300[7]	1.8	5.4	1.8	
400[7]	2.1	5.5	2	
500[7]	2.2	5.9	2.1	
600[7]	2.3	3	2.3	
300	n/a	0.35 ±0.01(%)	3.47 ±0.15(%)	Hossain et al., (2011)
400	n/a	0.43 ±0.01(%)	4.17 ±0.02(%)	
500	n/a	0.46 ±0.01(%)	4.62 ±0.12(%)	
600	n/a	0.54 ±0.01(%)	5.35 ±0.10(%)	
300-500	3.0±0.4	35.9±3.9	19.9±0.7	Gwenzi et al, (2016).
300	0.16	1.8	9.7(cmol kg^{-1})	Sousa & Figueiredo. (2016).
450	13.8	n/a	n/a	Liu., et al. (2014).
500	5.25	6.45[2]	65.7 (mg kg^{-1})	Xu, et al (2014).

**In* Zielińska et al., (2015) *the sewage sludge samples were characterized by moisture content before pyrolysis, the superscript numbers indicate the moisture content of the sewage sludge samples: [1]4.9 %, [2]4.3 % , [3]4.6 % and [4]4.4%. In Lu et al. (2014) sewage feedstocks were sourced from three different WWTPs, the superscript number 5-7 indicate which WWTP the sewage was sourced from: [5] Xilang WWTP, [6] Liede WWTP), and [7] Datansha WWTP.*

Table 2.15 *Macronutrient concentrations (Ca, Mg, K) in selected faecal sludge biochars. (Values in g/kg unless otherwise stated), n/a denotes no data was available.*

Pyrolysis temperature (°C)	K	Mg	Ca	Reference
450	28.9	n/a	32.8	Woldetsadik et al., (2018)
500-700	8.1±0.8	7.8±0.7	56.4±3.9	Krueger et al., (2020)
500-700	11.7±1.9	9.6±1.7	89.4±11.5	
300	1.9±0.9[1]	n/a	n/a	X. Liu et al., (2014)
400	2.1±0.9[1]	n/a	n/a	
500	2.8±0.3[1]	n/a	n/a	
600	2.7±0.9[1]	n/a	n/a	
700	2.6±0.6[1]	n/a	n/a	

[1] = wt%

2.4.10 Micronutrients

Sewage and faecal sludges contain relatively large amounts of micro-nutrients that can contribute to enhanced soil fertility. Therefore, sludge biochars also generally have relatively high concentrations of these micronutrients. Like macro-nutrients, pyrolysis also increases concentrations of these elements within the biochar.

Silicon is not considered an essential plant nutrient, but it is believed to be a valuable element for many plants (Epstein, 1994), in silicophilic plants Si is a major nutrient element. There are very few studies that have actually investigated the Si concentration in biochar and its role in soil and increased plant growth (Rizwan et al., 2018) even though Si is primarily a major inorganic constituent of biochar; and can alleviate abiotic and biotic stresses of plants (Y. Wang et al., 2019).

X-ray crystal diffraction of sewage sludge shows that SiO_2 is a major contributor to sewage sludge biochars with SiO_2 ranging from 35.8 to 58.1% of all crystallographic structures (Zielińska et al., 2015). Zielińska et al., (2015) concluded that the presence of SiO_2 in the sludges is related to the sand removed from sewage as a result of mechanical pre-treatment. However, both sewage and faecal sludge have high mineral components not dependent on the treatment processes. This high mineral content is still evident as sewage sludge biochars also record high silicon, iron, sodium and manganese concentrations (Table 2.16). In general, there is not a great deal of literature investigating these micronutrients as a valuable plant resource, in fact they are often referred to as *other nutrients* in the literature. There is potential for further research on this topic, especially perhaps the role that silicon in SS and FS biochars can play in alleviating plant stress.

Table 2.16 *Micronutrient concentrations in selected sewage and faecal sludge biochars, values in g/kg unless otherwise stated. n/a denotes no data was available.*

Pyrolysis temperature (°C)	Na	Mn	Fe	Si	Al	Reference
500[1]	n/a	n/a	11.5 ±0.68	7.81 ±0.49	3.33 ±0.24	Zielińska et al., (2015)
600[1]			12.5 ±0.73	8.73 ±0.54	3.7 ±0.27	
700[1]			13.2 ±0.76	9.11 ±0.56	3.86 ±0.27	
500[2]			9.53 ±0.57	6.11 ±0.41	2.31 ±0.18	
600[2]			10 ±0.60	6.84 ±0.44	2.58 ±0.19	
700[2]			10.7 ±0.64	7.47 ±0.47	2.74 ±0.21	
500[3]			2.41 ±0.17	9.11 ±0.56	3.21 ±0.23	
600[3]			2.51 ±0.19	9.4 ±0.57	3.39 ±0.24	
700[3]			2.57 ±0.19	9.72 ±0.59	3.44 ±0.24	
500[4]			2.26 ±0.16	4.8 ±0.33	2.78 ±0.21	
600[4]			2.37 ±0.17	5.09 ±0.34	3.09 ±0.22	
700[4]			2.6 ±0.19	5.48 ±0.37	3.23 ±0.23	
300[5]	2.2	n/a	n/a	n/a	52.2	Lu et al (2013)
400[5]	2.3				47.8	
500[5]	2.3				32.5	
600[5]	2.7				55.2	
300[6]	1.7				38.1	

400[6] 500[6] 600[6] 300[7] 400[7] 500[7] 600[7]	1.9 2.1 2.5 1.7 1.9 2 2.1	n/a	n/a	n/a	53.7 42.2 50.8 59.7 48.5 75.7 38.5	
300 400 500 600	n/a	n/a	7.8 ±0.09 (%) 8.85±0.08(%) 10.15±0.28(%) 11 ±0.00 (%)	n/a	n/a	Hossain, et al. (2011)
300	n/a	1.0 mg kg^{-1}	450 mg kg^{-1}	n/a	n/a	Sousa & Figueiredo (2016)
450	n/a	n/a	n/a	15.4	n/a	Liu., et al. (2014).
500	n/a	0.45	22.1	n/a	19.3 mg kg^{-1}	Xu, et al. (2014).
Faecal sludge BC						
450	5.73 g/kg	n/a	24.4 g/kg	n/a	n/a	Woldetsadik et al., (2018)

**In* Zielińska et al., (2015) *the sewage sludge samples were characterized by moisture content before pyrolysis, the superscript numbers indicate the moisture content of the sewage sludge samples: [1]4.9 %, [2]4.3 %, [3]4.6 % and [4]4.4%. In Lu et al. (2014) sewage feedstocks were sourced from three different WWTPs, the superscript number 5-7 indicate which WWTP the sewage was sourced from: [5] Xilang WWTP, [6] Liede WWTP), and [7] Datansha WWTP.*

2.5 SUMMARIZING DISCUSSION

The principal aim of this review was to provide a synopsis of the current knowledge of biochar produced by the slow pyrolysis of both sewage and faecal sludges. The chemical and physical properties of these biochars with regards to their potential as soil amendments were explained.

In developed nations such as those in the EU, sewage sludge landfilling and direct use in agriculture is strictly controlled by EU legislation. In developing countries untreated faecal sludge from onsite sanitation facilities is discarded directly into water bodies or nearby agricultural fields. This has led to eutrophication of surface water bodies, and contamination of groundwater and soils (Gwenzi & Munondo, 2008), causing risks to water resources and public health. While the reasons may differ, the same outcome is desired by both developed and developing nations: a new way of reusing sewage and faecal sludge. The slow pyrolysis of both FS and SS to produce biochar can play a pivotal role in a circular economy through the recovery and re-use of waste. Waste-derived biochar provides an opportunity to utilize an integrated systems-based approach in the water-energy-food nexus through its potential to improve soil health, increase crop yield, and improve water retention. The properties of FS and SS biochar must be clearly understood to evaluate its potential use as a soil amendment.

The review compared and contrasted a total of 17 research studies investigating sewage sludge and faecal sludge pyrolysis. The biochar properties from these studies reported in in Tables 2.4 - 2.7, and 2.9 - 2.15, were compared and discussed according to the biochars end use as a soil enhancer. The properties considered included elemental composition, surface area, pH, ash, CEC and heavy metal and nutrient concentration. These are all important parameters for evaluating biochar as a soil enhancer. There are many similarities between FS and SS biochars, both FS and SS biochars have high pH values and ash content with both these properties increasing with pyrolysis temperatures. These are important properties for a soil amendment and would be beneficial for use in acidic soil due to the liming effect. CEC values of both SS and FS biochars are generally low, again, due to the ash content reducing the surface area. However, due to the lack of CEC values in the literature for sewage and faecal sludge biochars, it is difficult to draw any conclusions about the affect pyrolysis temperature has on CEC values.

Both SS and FS derived biochars have high mineral content. Sewage and faecal sludges and their corresponding biochars contain relatively large amounts of micro-nutrients and macro-nutrients with pyrolysis increasing concentrations of these elements within the biochar. Sewage sludge and faecal sludge chars have high total phosphorus concentrations due to the phosphorus present in the original feedstock. Increasing pyrolysis temperatures generally increases the phosphorus content within the sludge biochars. Phosphorus is an irreplaceable plant limiting nutrient (Steen, 1998) and a finite resource. Recapturing phosphorus from waste in the form of sludge biochars could be an integral part of a circular economy and improve global phosphorus security. It is important to note that the phosphorus available to plants within biochar is less than the total phosphorus in biochar. Pyrolysis of sludge does increase available phosphorus in biochar, however at higher pyrolysis temperatures available phosphorus content is much lower. Other macronutrients such as calcium, potassium, and magnesium are found in relatively high levels in sewage and faecal sludge biochars with increases in Ca, K, and Mg corresponding to increases in pyrolysis temperatures.

Nitrogen is another plant limiting nutrient found within biochars. Available nitrogen in the forms NH_4-N and NO_3-N are found within sludge biochars, with ammonium N concentrations generally higher than nitrate concentration in these biochars. Ammonium nitrogen concentrations decrease with increasing pyrolysis temperature whereas NO_3-N concentrations increase with higher pyrolysis temperatures.

Micronutrients within biochars are a valuable plant resource, however there is limited literature available evaluating micronutrient concentrations and the effect these elements can have in soil and on crop yield.

Due to the high mineral content of faecal and sewage sludges, the resulting carbon concentrations in the biochars are relatively low compared to other feedstocks. In terms of biochar as a soil amendment, organic carbon within biochar has been shown to increase soil organic carbon (Gross et al., 2021). Therefore, the low carbon concentrations in these biochars indicate its greater potential in soils with low nutrient concentrations more so than soils with low organic carbon content.

Heavy metal concentration is highly variable both in sewage and faecal sludge and thus, heavy metal content in biochar is also variable. The general trend is an increase in heavy metal concentration within biochar with increasing pyrolysis temperature. Although biochars contain high concentrations of HMs, the heavy metals entrained within the biochar are in immobile and stable forms and not in a form biologically available to plants. This indicates that even biochars with high heavy metal concentrations could still have potential as soil amendments.

2.6 CONCLUSION

This review highlighted the many similarities between faecal and sewage sludge biochars, with the only differences caused by the transport and treatment of the raw product. Heavy metals are generally found at lower levels in faecal sludge than sewage sludge however there is still a large variation in faecal sludge concentrations depending on factors such as season and location. FS sludge can also be contaminated by sand and grit caused by poorly lined containment structures contributing to higher ash contents. Most HMs found in sewage come from point sources such as households and businesses and diffuse sources such as rainwater runoff from roofs, galvanized materials, traffic, and agricultural areas. Differences in heavy metal contents of faecal sludge and sewage sludge may not be critical as metals entrained within the biochar are generally in immobile and stable forms. However, heavy metal concentrations must still be taken into consideration as a potential limiting factor in application of sludge biochars to soil.

Another potential difference between FS biochar and SS biochar is the stabilization technologies employed with sewage sludge. Addition of alkaline materials such as lime can increase calcium content in sewage sludge biochars relative to faecal sludge biochars.

The low CEC and surface area of sludge biochars reviewed here indicate its potential as a soil amendment in soils with low water retention and low CEC values is limited. However, similar properties of both FS and SS biochars including high pH, high ash content and phosphorus and nitrogen concentration indicates its potential to improve soil health and crop yield in acidic, low nutrient soils.

Future research should concentrate on short-term and long-term field studies of sludge biochar application to acidic soils and the potential effect of micro-nutrients within biochar on crop yields.

3 MATERIAL AND METHODS

3.1 CHAPTER 4

3.1.1 Biochar sample preparation

The faecal feedstocks for the preparation of the biochars used in this study were sourced from three different faecal sludge and septage processors in India; Narsapur in Andhra Pradesh, Warangal in Telangana and Wai, Maharashtra. FS collected from septic tanks is delivered to each processing plant where it is stored in holding tanks for the homogenization of the sludge. The properties of individual loads can differ significantly between containments (Strande et al., 2014a). Tide Technocrats Private Limited have several community scale faecal sludges and septage processors which sanitize faecal waste and dewaters the sludge (5-10% moisture content) using solar energy. Solar drying was managed on-site and expedited by spreading the sludge in a 10 mm layer. The sludge was pyrolyzed into biochar using a flame temperature operating range of 550-750°C. The biochar was stored in an airtight box and quenched in a water bath. Three 5 kg biochar samples were collected from each processor in September 2018.

3.1.2 Acid washing

Acid washing biochar to remove ash content and increase surface area (Klasson et al., 2009) was achieved with 0.1 M HCl at a ratio of approximately 50:1 (v/w). Samples were shaken in a Uniwist 400 at 180 rpm for 2 hours before being filtered and washed with deionised water until a pH of 7 was reached. Samples were oven-dried at 80˚C overnight. The original biochar samples from Warangal, Narsapar and Wai were named WGL_BC, NSP_BC and WAI_BC respectively. Acid washed Warangal biochar was named WGL_AW.

3.1.3 Characterization of Biochars

3.1.3.1 Chemical analysis

Elemental C, N, S and H abundances were determined at Environmental Geosciences, University of Vienna, Austria using an elemental analyzer (Vario MACRO, Elementar). Oxygen was calculated from the subtraction of total percentage carbon, hydrogen, nitrogen, and sulphur and ash content from 100 (Castan et al., 2019).

3.1.3.2 Proximate Analyses

Moisture and ash content of the three biochars were determined in triplicate by methods adapted from literature (ASTM D 1762-84, 2011; Enders et al., 2012).

Crucibles and covers were cleaned by heating at 750°C for 6 hours and then cooling to 105°C, this volatilized residual material on the crucibles. The crucibles were transferred to desiccators and cooled to ambient temperature. The mass of crucibles and crucible covers were recorded to 0.1 mg and masses determined for all samples. Approximately 1.0 g of biochar was added into each crucible. For the moisture determination the crucibles and covers were heated at 105 °C for 12 - 18 hours and then transferred to desiccators whilst hot. The covers were removed briefly in order to safely remove the crucibles and covers from the oven. After cooling to ambient temperature, the mass of crucibles, covers and sample were recorded to 0.1 mg for all samples.

For ash determination the covered crucibles with 105°C dry biochar was placed in the furnace. The covers were adjusted so that they were askew to allow air flow into the crucibles, while reducing the possibility of physical losses. The samples were heated from ambient to 750°C at a rate of 2°C per minute. The furnace was programmed to hold the temperature at 750°C for 6 hours then programmed to switch off, where it took several hours to cool down to ~130°C. This step of the method was adapted to utilise the equipment available as it wasn't possible to program the furnace to cool down, but it could be turned off and allowed to cool down naturally. Several trials were conducted to determine the most appropriate heating rate and ensure that the correct temperatures were reached, and dwell time held for 6 hours. The heating rate was also adjusted to allow the furnace to cool down during the daytime when the equipment was accessible and crucible lids could be adjusted to sit flush when the temperature of 105°C was reached. The crucibles were then removed from the furnace and the covers adjusted to sit flush before placing in desiccators and left to cool to ambient temperature. The mass of each crucible and crucible cover with sample was recorded to 0.1 mg. Chars were ground to <850μm in a pestle and mortar to enhance representativeness of the sample and sieved to >149μm as this lessens physical losses upon rapid heating (Enders & Lehmann, 2015).

Volatile matter can also be determined by proximate analysis however this was deemed not possible with the equipment due to health and safety concerns. Volatile matter is determined by placing samples in furnace preheated to 950°C and removed after 10 minutes at this temperature. Unfortunately, there was no heat proof tray available on which to place the crucibles on and so no method of quickly placing or removing the crucibles from the furnace. The procedure must be done quickly and without a tray the covered crucibles and lids would need to be removed individually and this would unfortunately reduce repeatability. The high-temperature gloves would have made removing the crucibles with the lids still firmly on impossible and hence biochar would also have been exposed to oxygen during the procedure. Therefore, volatile matter content was not determined in this study.

3.1.3.3 pH and Electrical Conductivity

The pH of biochar samples was measured by suspending 5.0 g (ground to <2 mm) biochar in deionised water in a 1:10 ratio (B. Singh et al., 2017). After 1 hour of shaking, suspensions were allowed to stand for 30 minutes before pH measurements were taken using a Voltcraft soil pH meter calibrated using pH 7 and pH 10 buffers. Electrical conductivity (EC) was measured on the same samples using a calibrated Whatman CDM 400 EC meter. The analyses of pH and EC were performed in triplicate.

3.1.3.4 FT-IR analysis

Fourier Transform Infra-red (FTIR) spectra were used to determine the organic functional groups present on the surface of the biochar. The biochar samples were gently ground using a pestle and mortar and analyzed using a Perkin Elmer Spectrum 2 FTIR spectrophotometer applying the Attenuated Total Reflectance (ATR) method with a diamond crystal. The resulting spectra were an average of 16 scans obtained in the range from 400 to 4000 cm^{-1} with a spectral resolution of 2 cm^{-1} for biochars and 4 cm^{-1} for acid washed and ashed biochars.

3.1.3.5 Surface area

The BET (Brunauer, Emmett, and Teller) method is frequently used to determine the total surface area and pore size of materials. The BET analysis was conducted using the NOVA 2200e surface area and pore size analyzer (Quantachrome Instruments). The BET specific surface area of the three biochar samples were determined using two methods: N2 as adsorptive gas at 77 K and CO2 at 273 K.

Prior to the measurements, 200 mg – 300 mg of biochar (<2 mm) were heated to 130°C under vacuum for a minimum of 4 hours. The samples were outgassed at 105 °C for a minimum of 4 hours following the equipment's protocol. Samples were analyzed in triplicates.

For N_2 isotherms and CO_2 isotherms the BET equation was used to determine the specific surface areas from six points in the pressure region $P/P_0 = 0.01–0.30$ (Brunauer et al., 1938). For N_2 the pore size-distributions in the pressure region $P/P_0 = 0.01–0.98$ were ascertained using the built-in Density Functional Theory (DFT) model assuming slit-like pores. DFT considers micropore filling process, the development of the adsorbed film thickness, and importantly capillary condensation and evaporation, thus it can model hysteresis in the adsorption/desorption mesopore region of the isotherm.

For CO_2 isotherms the pore size-distribution, the cumulative pore volume (μPV) and the cumulative surface area (μSSA) in the pressure region $P/P_0 = 0.001–0.030$ were determined using the built-in Grand Canonical Monte Carlo (GCMC) simulation, again, assuming pores were slit-shaped.

The benefit of using of DFT and Monte Carlo simulation methods is that they provide a combined micro-mesopore analysis.

3.1.3.6 Measurement of zeta potential

Zeta potential measurements were undertaken according to methods reported in the literature (Samsuri et al., 2013; J. H. Yuan, Xu, & Zhang, 2011a). The zeta potential values were determined by weighing 0.045 g of 63µm sieved biochar into a 250 ml conical flask and adding 180 mL of 0.1M NaCl solution to each flask. The suspension pH was adjusted within a range 5.0 – 9.0 with HCl and then dispersed ultrasonically in a bath sonicator at a frequency of 40 kHz and a power of 300 W for 30 minutes at 30 ± 1 °C. The samples were then left to stand for 72 hours before being measured with a Malvern Zeta Sizer Nano.

3.1.3.7 X-ray diffraction (XRD)

The X-ray diffraction (XRD) analysis of the chars was conducted on a Bruker D8 Discover XRD operated at 40 kV and 40 mA. The data was gathered over a 2θ range of 20–70° using the Cu-Kα radiation at a scan rate of $2° \; min^{-1}$.

3.1.3.8 SEM/EDX

SEM–EDX analysis offers detailed imaging data about the morphology and surface texture of individual particles, with characterization of the elemental composition the analyzed volume. Scanning electron microscope (SEM) analysis was performed using a Hitachi TM3000 SEM fitted with a Bruker X-ray energy dispersive spectrometry (EDS). The two modes of operation in SEM analysis utilized here were backscattered electron imaging (BSE) and energy dispersive x-ray EDX. Ash particles were ground in a pestle and mortar to <125µm, acid washed particles of <2 mm were used in the form provided and original biochar particles used were in the size range 150 µm– 850 µm. Prior to analysis samples were spread onto double-sided carbon tape and mounted on a SEM stub.

3.1.3.9 Cation Exchange Capacity

Biochar samples were sent to the University of Santiago de Compostela for CEC analysis. The method used is reported below:

Cation exchange capacity measurements were conducted according to the summation method of the exchangeable base cations of Ca, Mg, Na, K, and Al. $ClNH_4$ 1M (25 ml) was added to the biochar sample (5 g) and shaken manually before being left to stand overnight (16 hours). The following day, 75 ml of $ClNH_4$ 1M was added and then filtered using quantitative, low ash filter paper. (Peech et al., 1947). Ca, Mg and Al were measured by PerkinElmer PinAAcle 500 Atomic Absorption Spectrometer and Na, K, were measured by Atomic Absorption Spectophotometer with Emission Flame.

3.2 CHAPTER 5

3.2.1 Soils

The soil used for this study was collected from farmland at Catheyld Isaf Farm (51°42'38.0"N; 3°54'40.9"W) near Swansea, Wales. The soil selected had similar pH values to Indian red soil which is found in many regions of India including Andhra Pradesh, and Telangana, and is acidic in nature with a pH 5.4 and a sandy to clay and loamy structure (Das & Mukherjee, 2014). The soil collected in South Wales has a loamy sand type texture and is acidic in nature with a pH measured at 5.0 ± 0.06. This acidic soil was chosen due to the highly alkaline nature of the biochars reported in **Chapter 4**. The rationale behind it is that plant growth would show significant increase upon alkaline biochar addition to acidic soil due to the liming effect. Previous work has shown that biochar addition to neutral or alkaline soils did not significantly impact growth or tomato yield (Polzella et al., 2019) or only plant growth increased but not fruit yield (Vaccari et al., 2015). A composite sample was collected down to 0.2 m of the topsoil layer and airdried indoors by spreading the soil in an even layer over a tarpaulin. The soil was raked every day to break up the larger clumps of soil and ensure consistent drying. The soil was sieved to pass through a 5 mm sieve before use. At the end of the trial 5:1 deionised water to soil solutions were prepared and the pH of soil measured with a Voltcraft soil pH meter and soil electrical conductivity was measured with a Whatman CDM 400 electrical conductivity meter.

Figure 3.1 *Soil collection at Catheyld Isaf farm, South Wales.*

Table 3.1 *Properties of the soil used in the glasshouse experiment.*

	Units	Mean
pH	-	5.0 ± 0.06
Electrical Conductivity	μScm^{-1}	73.6 ± 5.1
Texture Class[1]	-	Loamy sand
Nitrogen	%	0.8 ± 0.01
Carbon	%	15.4 ± 0.04
Available NH_4^+	$mgkg^{-1}$	13.8 ± 1.4
Available NO_3^-	$mgkg^{-1}$	27.4 ± 0.8
Available PO_4^{3-}	$mgkg^{-1}$	16.9 ± 0.1
Cation Exchange Capacity	$cmol/kg^{-1}$	8.71 ± 0.38

[1] Measured by Lancorp Laboratories

(See supplementary information for CEC and available nutrients methods)

3.2.2 Biochar

The faecal feedstocks for the preparation of the biochars used in this study were sourced from three different faecal sludge and septage processors, in Narsapur, Warangal, and Wai, all located in India. Faecal sludge collected from septic tanks is delivered to each processing plant where it is stored in holding tanks for the homogenization of the sludge. Tide Technocrats Private Limited have several community scale faecal sludge and septage processors which sanitize faecal waste and dewaters the sludge (5-10% moisture content) using solar energy. Solar drying is managed on-site and expedited by spreading the sludge in a 10 mm layer. The sludge is pyrolyzed into biochar using a flame temperature operating range of 550-750°C. The biochar was produced in September 2018 and stored in an airtight box and quenched in a water bath. Previous work showed that there were some differences in biochar properties in terms of pH, pore volume, electrical conductivity, carbon content and ash content (**Chapter 4**) (H. L. Nicholas, Mabbett, et al., 2022a). Therefore, the glasshouse trial included three replicates of each biochar to determine the effect on plant height and fruit yield of each biochar.

The basic characteristics of biochars WGL_BC (Warangal biochar), NSP_BC (Narsapur biochar), and WAI_BC (Wai biochar) are given in Table 3.1. Detailed properties of the biochar properties were reported previously (**Chapter 4**).

Table 3.2 *Proximate analyses, elemental analyses, pH, EC and surface area measurements of biochars (Chapter 4). (EC = Electrical Conductivity, C= Carbon, N= Nitrogen, S= Sulfur, Oxygen, SBET = Surface area measured by BET, TPV = Total pore volume, SSA = Specific Surface area, CEC=Cation Exchange Capacity)*

Parameter	Unit	WAI BC	NSP BC	WGL BC
pH	[ ]	11.81 ± 0.01	11.82 ± 0.01	12.25 ± 0.01
EC	[$mScm^{-1}$]	2.70 ± 0.09	1.79 ± 0.17	9.00 ± 0.02
Moisture	[%]	3.08 ± 0.01	2.15 ± 0.31	0.98 ± 0.05
Ash	[%]	62.3 ± 0.32	67.0 ± 2.68	88.3 ± 0.21
C	[%]	21.11	23.79	8.06
N	[%]	1.32	1.13	0.37
H	[%]	1.55	0.73	1.15
S	[%]	0.03	0.27	0.03
O*	[%]	13.7	7.1	2.1

H/C	[ ]	0.9	0.4	1.7
C/N	[ ]	18.7	24.6	25.4
O/C	[ ]	0.5	0.2	0.2
S_{BET} N_2	[m^2g^{-1}]	3.52 ± 0.78	3.69 ± 0.36	12.07 ± 4.12
N_2 TPV	[cm^3g^{-1}]	0.011	0.011	0.019
S_{BET} CO_2	[m^2g^{-1}]	46.72 ± 7.0	74.20 ± 4.0	26.11 ± 2.6
CO_2 µSSA	[m^2g^{-1}]	63.49 ± 8.3	99.62 ± 4.5	36.76 ± 3.0
CO_2 µPV	[cm^3g^{-1}]	0.017	0.027	0.010
CEC	[$cmolkg^{-1}$]	90.0 ± 6.5	41.9 ± 2.2	129.3 ± 2.3

3.2.3 Plant growth experiment

The micro tom cultivar (*Solanum lycopersicum.* L) was used to examine the impacts of faecal sludge biochar on plant height, fruit yield, water runoff, above and below ground biomass and leaf length. The tomato plant trials were carried out between June and August 2020 during covid lockdown. As there was no access to the university, the greenhouse trial took place in the garden of a rural residential property in CraigCefnParc, South Wales. The metal frame, walk – in, transparent greenhouse consisted of 4 tiers with 8 shelves with dimensions of 143 L x 73W x 195H cm. An environmental logger (Elitech RC-51H USB) was used to record temperature and humidity every 2 hours for the duration of the trial (Appendix 2). Temperature ranged from a minimum of 7°C to a maximum of 49°C and humidity from 17% to 100%. The average temperature for the duration of the trial was 19.3°C ± 6.2 and average humidity 80.6% ± 16.7.

Cylindrical plastic pots 9 cm in diameter and 8.7 cm in height were used for the pot trials. The experimental design was a completely randomized design with four treatments at nine replications. The four treatments were: (i) soil (control); (ii) soil with fertilizer (Fert); (iii) soil with biochar (BC); and (iv) soil with biochar and fertilizer (BC+ Fert). All treatments containing biochar, including the biochar and fertilizer treatments were divided into subgroups with three of each biochar from the three different processing plants in Warangal (WGL), Wai (WAI) and Narsapur (NSP). The fertilizer used was a commercial seaweed enriched fertilizer called Gro-Sure (NPK 6.0 3.0 10.0).

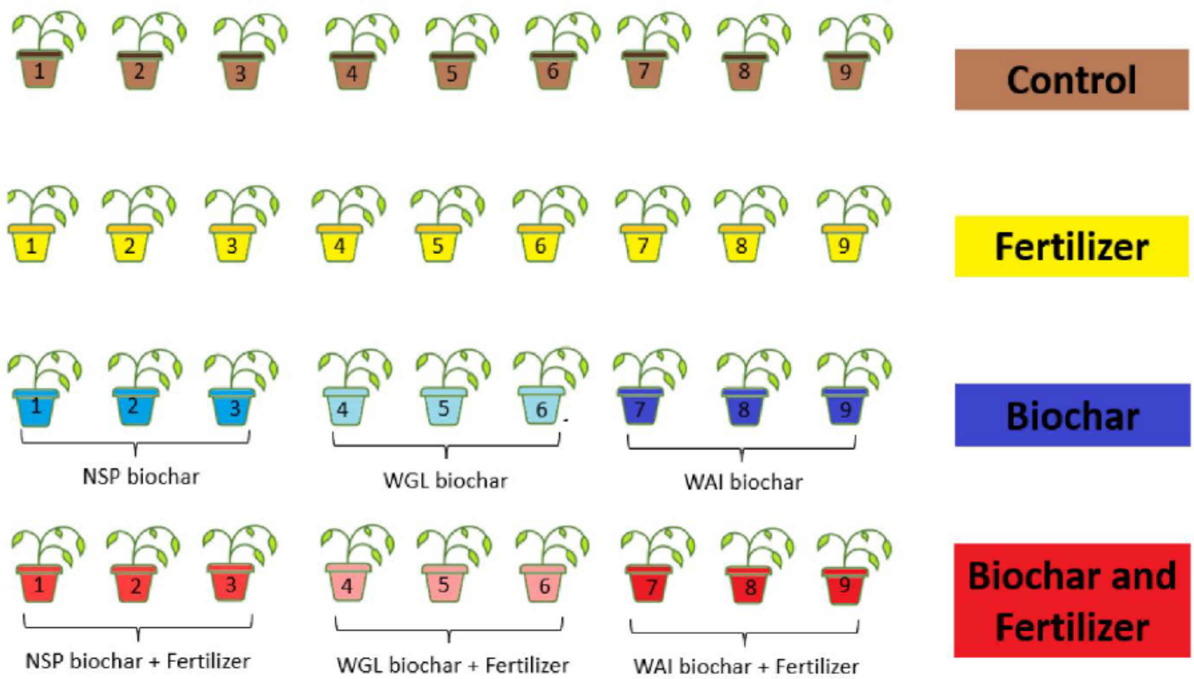


Figure 3.2 *Graphical representation of treatments and subgroups used in glasshouse experiment in Chapter 5.*

Table 3.3 *Number of pots per treatment and subgroups in each treatment*

Treatment	Number of pots per treatment	Subgroups	Number of pots per subgroup
Control (Control)	9	-	-
Fertilizer (Fert)	9	-	-
Biochar (BC)	9	NSP_BC	3
		WGL_BC	3
		WAI_BC	3
Biochar + Fertilizer (BC + Fert)	9	NSP + Fert	3
		WGL+ Fert	3
		WAI+ Fert	3

In each pot 137.74 g of air-dried soil was packed and biochar applied at 4.2% (w/w). A commercial, liquid tomato fertilizer was applied, equivalent to 90 kg of nitrogen:

50 kg of phosphorus and 50 kg of potassium ha^{-1}. Fertilization commenced 4 weeks after the seeds were planted and continued once a week for the duration of experiment. Seeds of tomato were sown in seedling trays using a commercial compost to encourage germination before being transplanted into the treatment pots. After two weeks the germinated seedlings from the seedling trays were transferred to the pots containing soil and biochar. The pots used in this study had drainage holes at the bottom so plastic sealable bags were used as pot liners to allow the filling of pots with air-dried soil. For the first 10 days the pots were watered, with equal volume of water, without drainage and moisture levels were monitored using a soil moisture sensor (Manufacturer: HYCKee). After 10 days the soil was wet enough to allow holes to be punctured within the liners and avoid loss of dry soil through the holes in the bottom of the pot. Other studies have utilized filter papers at the bottom of plants pots to prevent dry soil escaping but also allowing drainage, however due to Covid 19 there was no access to Swansea university laboratories to be able to purchase filter papers.

After 10 days sealable polythene bags were placed around each pot and the plants were watered with drainage to allow run-off water volume to be measured. All pots were irrigated with the same volume of water every other day and occasionally every day depending on weather conditions. Water runoff commenced on day 22 after initial seed planting and plant height measurements on day 31 when the plants had grown to a height that allowed accurate measurement. Plant heights were measured using a tape measure from soil to tip of the plant. During the trial each plant received the same volume of water and the runoff collected in a polythene bag placed around the pot. After an hour the volume of water runoff was measured by decanting the water from the polythene bags into a measuring cylinder. The length of the largest leaf in each plant was measured throughout the experiment starting from Day 24 after planting. At harvest all fruits were counted and weighed and the wet above ground and below ground biomass for each plant was measured. The roots were carefully removed from the soil and washed with water before being placed on paper towels to remove excess water before weighing.

The parameters measured during this study were chosen largely due to what was achievable in April – August 2020 during Covid-19 lockdown and without access to Swansea University laboratories. Plant growth and leaf length could be easily measured, as could the number of tomatoes, the fresh yield of tomatoes and fresh above and below ground biomass. Measurements of dried above and below ground biomass could not be conducted due to the lack of specialist equipment (an oven that could be set 65°C for 24 hours). Therefore, only fresh above and below ground biomass is reported.

3.2.4 Statistical analysis

The relationship between the biochar soil treatments and the specific plant responses and soil properties were examined using generalized linear models in R (R Core Team 2021). Plant growth responses which were, plant height, leaf length, and above and below ground biomass were examined against the four different treatments (control, fertilizer, biochar and combined biochar and fertilizer) using a GLM (Generalized linear model) and a post-hoc pairwise test was applied to examine the significance across the different treatments using the emmeans package (Lenth et al., 2022), which was adjusted accordingly for the different model distributions. For all plant responses the GLM was modelled to a gamma distribution due to the positive skewness displayed, except for plant height which was modelled to a gaussian distribution. A second set of GLMs were applied to the same plant growth responses using biochar presence (regardless of fertilizer treatment) to examine whether the presence of biochar was more influential than the combination of treatments. This analysis was then repeated but using fertilizer only to examine if the presence of fertilizer was the overriding factor affecting plant growth. AIC scores for each of the models in each case were compared to ascertain the most parsimonious model. The same set of analyses were repeated for soil properties including water runoff, ph. and electrical conductivity (EC) also using a gamma distribution due to the positive skewness in the dataset’s distributions. For fruit production (number of fruits and yield) the datasets also showed positive skewness, which was appropriate to a gamma distribution, however before the same set of analyses was conducted, the datasets were transformed to remove zeros to avoid model error from the small number of individuals that did not produce any fruit. For all plant and soil responses an additional analysis was conducted to examine if biochar type significantly altered the response variable. The data was sub-stetted into biochar presence and GLM models were applied to examine all response variables against the three different types of biochar, (Warangal, Narsapur and Wai), except for EC, as biochar was not significant in altering soil EC. The results are listed in Appendix 2.

3.3 CHAPTER 6

3.3.1 Experiment design

The continuous lighting experiment in **Chapter 6** took place in a controlled temperature and light room. at Swansea University when access to the university was once again permitted after the initial Covid-19 restrictions. The same soil, biochar and micro-tom tomato seeds were used as in **Chapter 5**. There was initially a 4th treatment of fertilizer used, similar to the glasshouse experiment, however, all tomato plants in fertilizer treatment group died soon after transplanting from the seedling trays. Plants exhibited dried leaf margins, wilting, and eventual death of the plants; all signs of over fertilization due to the 4% w/w fertilizer addition. The biochar and fertilizer treatment group included a fertilizer rate of only 2% w/w hence plants in the treatment group survived. Time constraints meant that the experiment could not be re-started. Only surviving plants were included in the analysis of **Chapter 6**.

Temperature and humidity were measured using an Elitech RC-51H USB Temperature and Humidity Data Logger. Data can be found in Appendix 3.

3.3.2 Plant growth experiment

A pot trial using tomato (*Solanum lycopersicum*. L) cultivar Micro-Tom as a crop species was performed to evaluate the impact of faecal sludge biochar on plant growth parameters, fruit yield and soil properties. The pot trials were carried out in a controlled temperature and light room. Temperature was maintained at a constant 21.2°C (±0.2) and a constant 24-hour photoperiod was maintained. After 91 days day/night heating temperatures were set to 15°C /21°C and the constant 24-hour photoperiod was altered to a 12 -hour photoperiod. The experiment concluded after 155 days.

Cylindrical plastic pots 9 cm in diameter, and 8.7 cm in height were used. The experimental design was a completely randomized design with three treatments. There were nine replications and a total of 27 pots. The three treatments were: (i) soil (Control); (ii) soil with biochar (BC); (iii) soil with biochar and fertilizer (BC + Fert). All treatments containing biochar were divided into 3 subgroups containing three pots containing biochar from the three different processing plants in Warangal (WGL), Wai (WAI) and Narsapur (NSP). In the biochar treatment there were three subgroups (NSP, WAI, WGL), with 3 pots of each biochar making 9 in total. Similarly for the biochar and fertilizer treatment (BC+ Fert) there were 3 pots containing three sub-groups of biochar and fertilizer NSPF, WAIF, WGLF adding up to 9 pots in total for the combined biochar and fertilizer treatment (Fig. 5. 1)

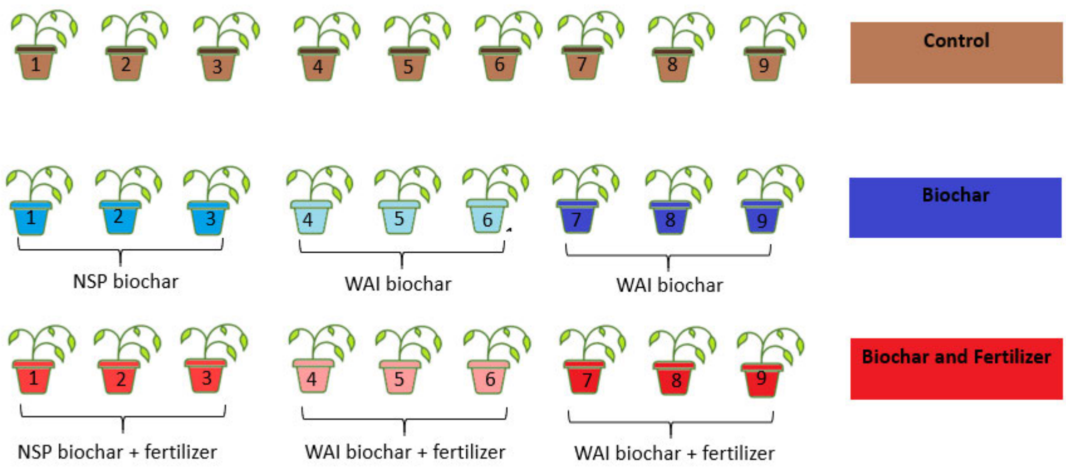


Figure 3.3 *Graphical representation of plant growth experimental layout*

Micro-tom seeds were sown in seedling trays using a commercial compost to encourage germination before being transplanted into the treatment pots. Twenty-two days after sowing, when the first true leaves had appeared, the seedlings were carefully removed from commercial compost mix without handling the stems. The compost was removed from the roots with deionised water. Seedlings were then individually planted in pots containing 136 g of air-dried soil, soil with biochar (4% w/w), and soil with fertilizer (2% w/w) and biochar (2% w/w). The fertilizer used was a commercial fertilizer *Miracle-Gro* 119914 Performance Organics Granular Plant Food, Fruit & Veg Plant Food NPK: 8-5-5.

All pots were well-watered with equal volumes of deionised water before adding the tomato seedlings. Plant heights were measured using a tape measure from soil to tip of the plant. For the water runoff measurements each plant received the same volume of water and the runoff collected in a polythene bag placed around the pot. After an hour the volume of water runoff was measured by decanting the water from the polythene bags into a measuring cylinder. Water runoff measurements commenced on day 25 after initial seed planting and were performed regularly for the duration of the trial. Plant height measurements commenced on day 34, once the plants had grown to a height that allowed accurate measurement. Tomatoes were harvested after 155 days (from seed to harvest). At harvest all fruits were counted and weighed, and the roots were carefully removed from the soil and washed with water before being placed on paper towel to remove excess water before weighing. The shoots and roots were divided into above ground and below ground biomass. The fresh weights were recorded, and the dry weights recorded after being oven-dried at 65 °C for 24 hours.

3.3.3 Statistical analysis

The effect of each treatment (control, biochar, combined biochar and fertilizer) on leaf number, flower number, above ground and below ground biomass, fruit yield, water runoff volume, soil pH and soil electrical conductivity were studied statistically by using the non-parametric Kruskal Wallis test to determine if there were any significant differences followed by pairwise comparison of treatments conducted using Dunn Tests. The effect of each treatment on plant height, was investigated using ANOVA to determine if there were any significant differences and then posthoc Tukey's range tests were conducted to determine differences between each pair of treatments. All statistical analyses were performed using R 3.6.3. Unless otherwise stated, the differences were significant at $p < 0.05$ level. The means and standard deviations of the types of biochars were compared to each other.

3.4 CHAPTER 7

3.4.1 Survey

Data for this study were collected through an online survey of 349 members of the public residing in Swansea, Wales. Data collection took place between October and November 2020 via sharing in online community Facebook groups in Swansea.

An online survey rather than face to face interviews was conducted due to difficulties faced during the COVID-19 pandemic. It used *Google Forms*, a cloud-based data management tool for designing and developing web-based questionnaires. Online surveys provide time saving and cost saving benefits, less paper wastage, no interviewer bias, and allow the respondents to complete the survey in their own time (Stoknes et al., 2021). However, they may present problems such as limiting access, low response rates and challenges in assuring anonymity (Dillman et al., 2014; Sax et al., 2003).

Another disadvantage is that, unlike face-to-face interviews, it is not possible to clarify questions or statements and some participants may not fully understand the questions (MacKerron et al., 2009). Mailout surveys have previously also presented challenges in obtaining adequate response rates from the younger population, who may not use the mail system readily (Dillman et al., 2014; Zuidgeest et al., 2011). However, the survey presented in this article recorded a low percentage of younger respondents despite being online. Overall, it was the best technique we could use at the time.

The standardized questionnaire – copy included in Supplementary Materials - consisted of 12 questions including information about the respondent (gender, location, age) and their consumption of organic food and efforts to reduce their carbon footprint. Participants received details of the study purpose and confidentiality information. Informed written consent was obtained before starting the survey.

Biochar is a charcoal-type substance produced by heating organic waste such as wood, crop waste, cow manure and sewage sludge. The main use of biochar is as a fertilizer.

Box 1. Definition of biochar as given in the questionnaire.

Respondent's attitudes towards consuming food grown in wood biochar (Box 1), faecal sludge biochar and biosolids were assessed using a 5-point verbal scale similar to the Likert scale. Each question or statement was followed by a choice from five ranked responses: very uncomfortable; uncomfortable; neutral; slightly comfortable; very comfortable. This type of scale was instantly understandable and decreased the risk of respondent confusion compared to the Likert scale (Hill et al., 2017). Two follow-up statements seeking more information on attitudes to FS biochar were also added to ascertain if a change in attitude could be elicited by providing more information on the safety of FS biochar and its carbon storage properties.

Fewer than one percent of participants reported their gender as something other than male or female. These responses were removed, and gender treated as a binary variable.

Fewer than 3% reported their organic food consumption as something other than the categories provided in the survey. Responses included: "I do not knowingly seek organic food, but my wife may purchase it and include items in our meals" and "Rarely odd occasions". These responses were grouped as "Other" and removed.

3.4.2 Statistical Analysis

Pearson's chi-square statistic was used to determine any statistically significant differences between expected and observed frequencies for key factors (age, gender, residential area, organic food consumption). A Wilcoxon signed rank sum test was also used to establish if the public perceptions of faecal sludge biochar were altered after receiving a follow-up statement providing more information on the safety of FS biochar. A probability level below 0.05 was considered statistically significant and this value was thus used as the cut-off point for significance. Analyses were conducted in R, version 3.6.3.

4 AGRONOMIC PROPERTIES OF WASTE DERIVED BIOCHAR FROM COMMUNITY SCALE FAECAL SLUDGE TREATMENT PLANTS

Larissa Nicholas[1] Ian Mabbett[2] Henry Apsey[3] Iain Robertson[4]

Corresponding author: Larissa Nicholas
hlarissa.nicholas@gmail.com
ORCID ID: 0000-0002-2710-6070

[1]Department of Chemistry, Faculty of Science and Engineering, Swansea University, Swansea, SA2 8PP, Wales, UK, 804174@swansea.ac.uk
[2]Department of Chemistry, Faculty of Science and Engineering, Swansea University, Swansea, SA2 8PP, UK, i.mabbett@swansea.ac.uk
[3]Department of Chemistry, Faculty of Science and Engineering, Swansea University, Swansea, SA2 8PP, UK, 960072@swansea.ac.uk
[4]Department of Geography, Faculty of Science and Engineering, Swansea University, Swansea, SA2 8PP, UK, i.robertson@swansea.ac

Chapter Overview

The dumping of untreated faecal sludge from non-sewered onsite sanitation facilities causes environmental pollution and exacerbates poor public health outcomes across developing nations. Long-term mechanisms to treat faecal sludge generated from these facilities are needed to resolve the global sanitation crisis and realize the Sustainable Development Goal (SDG) 6 "ensure availability and sustainable management of water and sanitation for all" by 2030. Pyrolysis of faecal sludge removes pathogens and generates biochar which has potential as a soil enhancer. The properties of faecal sludge biochars from three full-scale treatment plants in India were determined with regards to the biochars end use as a soil amendment. Results showed that all three biochars had relatively low specific surface area, high alkaline pH values, high ash content, and negative surface charge. Fourier transform infrared spectra showed the same surface functional groups present in each biochar. X-ray diffraction analysis showed the mineral composition of each biochar differed slightly. Scanning electron microscopy analysis indicated a porous structure of each biochar with ash particles clearly evident. All three biochars showed consistent properties: a high ash content, low porosity, low carbon content and high alkalinity suggesting potential use as a soil amendment particularly with acidic soils.

4.1 INTRODUCTION

According to the World Health Organization we are unlikely to meet the target of Goal 6 of the UNs 17 SDGs "to *ensure availability and sustainable management of water and sanitation for all*" by 2030. A total of 4.2 billion people still use inadequate sanitation facilities that leave faecal sludge untreated, and 673 million people still don't have access to toilets and practise open defecation (UNICEF & WHO, 2020). The lack of access to adequate, safely managed sanitation facilities can lead to the spread of diarrhoeal diseases (Lalander et al., 2013), with poor drinking water, sanitation and hygiene (WASH) services related to childhood health burdens, including stunting ('Leave No One Behind', 2023). In developing countries like India, poor nutrition and poor socioeconomic status increases mortality and morbidity linked to excreta-related diseases (Singh et al., 2017). To date faecal sludge management (FSM) in developing countries has generally been inadequate and has exacerbated sanitation problems (Ato Armah et al., 2018).

Improving sanitation along with hygiene practices and access to safe water are essential for improving socioeconomic development and health globally (Haller et al., 2007; Mara et al., 2010). Long term and more manageable solutions that deal with the high transport costs and landfill disposal costs of faecal sludge are needed (Mamera et al., 2021).

Recently the thermochemical treatment of faecal sludge has gained momentum, with an emphasis on pyrolysis as a safe method of treating faecal sludge (Krueger et al., 2020). Pyrolysis is the heating of biomass to temperatures of 350°C - 1000°C in an oxygen-free environment (European Biochar Foundation, 2016) which eliminates harmful pathogenic organisms within the sludge. Carbon-rich biochar produced from pyrolysis is safe to handle and has been demonstrated to be an important soil amendment (Chan et al., 2007). The original feedstock source, pyrolysis temperature, hold time, and heating rate are the main factors determining the characteristics of biochars (B.Chen et al., 2008; Crombie et al., 2015a; Lehmann & Joseph, 2012a; Tomczyk et al., 2020; Weber & Quicker, 2018a).

The use of biochar as a soil amendment is rapidly gaining impetus due to its ability to improve soil health, increase soil fertility, and increase crop yields. Its carbon sequestration properties make biochar a valuable tool in mitigating climate change (Sohi et al., 2010). There are multiple benefits to adding biochar to soil. Surface functional groups on the surface of biochar can lead to an increase in the cation exchange capacity of the soil (CEC) (Glaser et al., 2001); the microporous structure of biochar can increase the water holding capacity of the soil (Gaskin et al., 2007), and alkaline biochars can increase pH levels in acidic soil (Novak et al., 2009).

Biochar addition to soil has also been shown to reduce the bioavailability of heavy metals in soils (Park et al., 2011; Uchimiya et al., 2011; X. Zhang et al., 2013) including that of wastewater sludge biochar (Hossain et al., 2010) and sewage sludge biochar (Méndez et al., 2012). Biochar addition also reduces plant uptake of pesticides (X.-Y. Yu et al., 2009) and reduces the leaching of applied pesticides which can impact underground water contamination (Ahmad et al., 2014). Changes in soil microbial properties upon biochar addition have also been reported (Lehmann et al., 2011), including alteration of soil microbial community structure (Farrell et al., 2013), and an increase in microbial abundance (Awad et al., 2018).

There is a considerable amount of research investigating characteristics of sewage sludge-derived biochar but less on faecal sludge biochar (Gold et al., 2018; H. Nicholas et al., 2023). Many studies exist on the properties of faecal sludge itself (Awere et al., 2020; Bassan et al., 2013; Fanyin-Martin et al., 2017; Lama et al., 2022; Schoebitz et al., 2014; Septien et al., 2020). Only a handful of articles examine properties of faecal sludge biochar and these studies have a diverse range of objectives including biochar as a soil amendment to increase lettuce yields (Woldetsadik et al., 2018), biochars solid fuel characteristics (Krueger et al., 2020), cadmium adsorption by biochar (Koetlisi & Muchaonyerwa, 2017), recovery of ammonium in urine by biochar (X. Bai et al., 2018) and energy balance analysis of slow pyrolysis of human manure (X. Liu et al., 2014).

Most of the research into faecal sludge-derived biochar has focused on characterization of small-scale laboratory-produced biochar (Bleuler et al., 2021; Gold et al., 2018; X. Liu et al., 2014; Woldetsadik et al., 2018) while data from full-scale operations are very limited (Krueger et al., 2020). Investigating the feasibility of resource recovery of operational up-scaled sludge treatment technologies and production of FS biochar with consistent properties is imperative to alleviate the sanitation crisis (Andriessen et al., 2019; Strande et al., 2014a).

Krueger *et al.*, (2020) investigated the physico-chemical properties of full-scale faecal sludge biochars from treatment plants in Warangal and Narsapur, India. They focused on solid fuel properties of biochar, particle size distribution and heavy metal concentration. Heavy metal concentrations were found to be within the limits for land application set out by the EU (EEC, 1986) and the International Biochar Initiative (IBI, 2015) apart from the Narsapur biochar which contained concentrations of lead over the IBI stated threshold.

The objective of this investigation was to assess the uniformity of biochar characteristics produced from three full-scale faecal sludge treatment plants in Wai, Warangal and Narsapur, India. This study focused more on physico-chemical properties that would contribute to biochars end-use as a soil amendment. The biochar properties determined were ash content, pH, carbon content, organic surface groups, surface charge, mineral content, pore volume, and specific surface area.

4.2 RESULTS AND DISCUSSION

4.2.1 *Proximate analyses EC, pH and elemental analyses*

All three biochars had high ash contents with WGL_BC the highest at 88.3% and NSP_BC and WAI_BC lower at 67.0% and 62.3% respectively (Table 3.1.). WGL_BC also had the lowest moisture content at 0.98% in comparison with 2.15% and 3.08% for NSP_BC and WAI_BC respectively. Measured pH values were high for all three biochars with WGL_BC the most alkaline (pH 12.25) due to the higher ash content (Table 3.1). Singh et al, (2010) suggested that the general alkaline character of biochar results from the carbonate content and the release of alkaline elements such as Na, K, Ca, and Mg during the pyrolysis process (B. Singh et al., 2010b).

WGL_BC also recorded the largest electrical conductivity (EC) value again indicative of its higher ash content (Rehrah et al., 2014). After acid washing to remove alkaline salts and carbonates, the pH of WGL_AW decreased to 6.8 and EC decreased to 0.38 m $S.cm^{-1}$.

The measured high ash content is consistent with the literature (Gold et al., 2018; Koetlisi & Muchaonyerwa, 2017; X. Liu et al., 2014). The initial feedstock of sewage sludge is high in ash and sewage sludges have been found to contain very high concentrations of Si (19–58%), Ca (5.1–7.4%), and P (3.4–4.9%) (Zielińska et al., 2015). Ash content of faecal sludge is also high and has been measured at 17.0 wt.%, significantly higher than measured ash content of sawdust at 0.8% (X. Liu et al., 2014). There could be several reasons why the WGL biochar had a significantly higher ash content. Digestion during storage in onsite sanitation technologies can play a part in the high ash content of FS biochar (Gold et al., 2018) as well as contamination of FS by sand and grit caused by poorly lined containment structures (Niwagaba et al., 2014a). A recent study investigating biochar from the same treatment facilities in India observed that sintered mineral depositions had to be removed from the reactor on a weekly basis (Krueger et al., 2020). The high ash content and low carbon content could also be due to the processing conditions. Tide Technocrats do use a limited supply of oxygen to allow for partial oxidation enabling autothermal operation. If too much oxygen was allowed into the system this would result in more of a gasification product, implying WGL biochar is a gasification product rather than pure biochar.

A high ash content can be of benefit when evaluating the applicability of biochar as a soil conditioner as the soil benefits from the macro and micronutrients present and high liming value of the biochar attributed to carbonates present (Smider & Singh, 2014).

The high ash content of these biochars contributed to the very alkaline pH values. Increases in pH due to increases in ash content in biochars derived from sewage sludge feedstocks have been previously reported (Hossain et al., 2011; X. Liu et al., 2014). Singh et al, 2010 suggested that the general alkaline character of biochar results from the increase in quantities of alkali salts (Na, K) and salts of alkaline elements (Ca, Mg) during the pyrolysis process (B. Singh et al., 2010b).
Altering soil pH is one of several mechanisms by which biochar can improve soils and increase agricultural productivity. Acidic soils are responsible for the severe limitation of crop agriculture worldwide. Up to 50% of soils globally which are suited to arable agriculture are acidic (von Uexküll & Mutert, 1995). The high pH of the studied biochars would induce a liming effect in soils and this liming effect is one of the main processes influencing the enhanced plant growth seen on biochar addition to soils (Jeffery et al., 2011).

Table 4.1 *Proximate analyses, elemental analyses, pH, EC and surface area measurements of faecal sludge biochars. (EC = Electrical Conductivity, C= Carbon, N= Nitrogen, S= Sulfur, Oxygen, SBET = Surface area measured by BET, TPV = Total pore volume, SSA = Specific Surface area, CEC=Cation Exchange Capacity, WAI BC = biochar from Wai treatment plant, NSP BC = biochar from Narsapur treatment, WGL BC = biochar from Warangal treatment plant, WGL AW= acid washed biochar from Warangal treatment plant)*

Parameter	Unit	WAI BC	NSP BC	WGL BC	WGL AW
pH	[ ]	11.81 ± 0.01	11.82 ± 0.01	12.25 ± 0.01	6.28 ± 0.019
EC	[$mS.cm^{-1}$]	2.70 ± 0.09	1.79 ± 0.17	9.00 ± 0.02	0.38 ± 0.02
Moisture	[%]	3.08 ± 0.01	2.15 ± 0.31	0.98 ± 0.05	-
Ash[1]	[%]	62.3 ± 0.32	67.0 ± 2.68	88.3 ± 0.21	-
C	[%]	21.11	23.79	8.06	-
N	[%]	1.32	1.13	0.37	-
H	[%]	1.55	0.73	1.15	-
S	[%]	0.03	0.27	0.03	-
O[2]	[%]	13.69	7.08	2.09	-
H/C[3]	[ ]	0.9	0.4	1.7	-
C/N[3]	[ ]	18.7	24.6	25.4	-
O/C[3]	[ ]	0.5	0.2	0.2	-
S_{BET} N_2	[$m^2.g^{-1}$]	3.52 ± 0.78	3.69 ± 0.36	12.07 ± 4.12	18.06 ± 1.76
N_2 TPV	[$cm^3.g^{-1}$]	0.011	0.011	0.019	0.017
S_{BET} CO_2	[$m^2.g^{-1}$]	46.72 ± 7.0	74.20 ± 4.0	26.11 ± 2.6	33.29 ±4.55
CO_2 µSSA	[$m^2.g^{-1}$]	63.49 ± 8.3	99.62 ± 4.5	36.76 ± 3.0	45.18 ± 5.76
CO_2 µPV	[$cm^3.g^{-1}$]	0.017	0.027	0.010	0.013
CEC	[$cmol.kg^{-1}$]	90.0 ± 6.5	41.9 ± 2.2	129.3 ± 2.3	-

[1] measured on a dry basis.
[2] Oxygen was calculated from the subtraction of total percentage carbon, hydrogen, nitrogen, and sulphur and ash content from 100.
[3] The molar element ratios H/C, C/N, and O/C were calculated from the elemental composition (CHNS and O) and ash content of the biochars.

The elemental composition (Table 4.1.) shows relatively low percentage of carbon within the samples, 21-23% for NSP_BC and WAI_BC and a very low 8% for WGL_BC consistent with the measured ash content.

Pyrolysis generally concentrates carbon in the biochar with an increase in C content relative to the feedstock frequently reported. However, most studies on sewage sludge (SS) –derived biochar show a decrease in the percentage of C in the final product relative to the feedstock (Agrafioti et al., 2013; Khan et al., 2013). FS- and SS–derived biochars generally have low total C concentrations (11 % - 40 %) in comparison with cellulose derived biochars. This is due to the high ash content in the original feedstock of faecal and sewage sludge.

4.2.2 FTIR

FTIR spectra indicated that all three sludge biochars have a complex chemical bond structure with both organic matter and mineral compounds evident within the biochar. FTIR spectra of all three biochars were very similar indicating the presence of the same organic functional groups present on the surface (Fig 4.1).

High ash content in sludge-derived biochars leads to a high mineral content with bands arising on the spectrum at similar wavenumbers to organic functional groups. For example, a broad peak in the 1000-1200 cm^{-1} region can arise due to several functional groups such as inorganic and organic silicon, phosphorus compounds, as well as C-O stretching and sulphate groups (Coates, 2004).

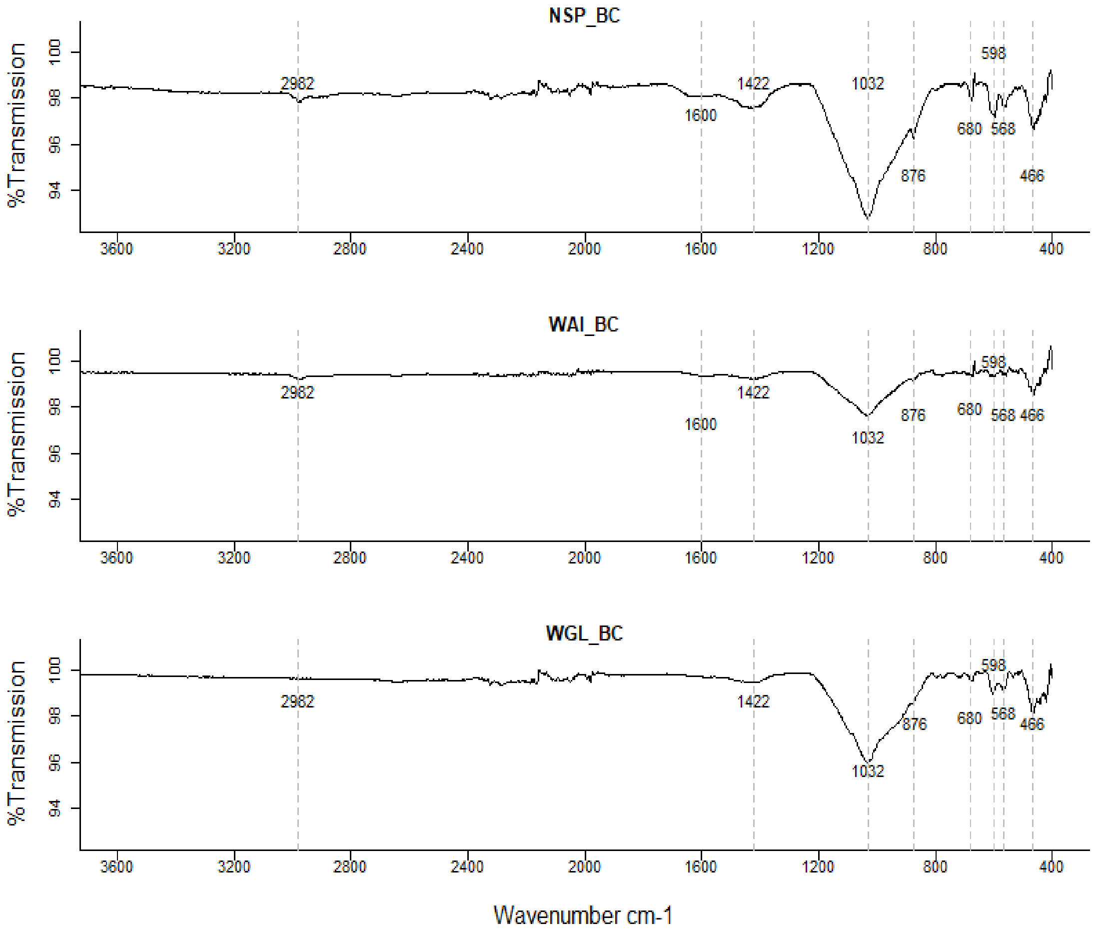


Figure 4.1 *Fourier-transform infrared (FTIR) spectra of the three biochars NSP, WGL and WAI with dotted lines representing the main absorption (cm-1) peaks.*

To determine the exact nature of groups within the biochar, FTIR spectra was obtained for biochar, ashed biochar (biochar heated to 750°C for 6 hours) and deashed biochar, (biochar washed with 0.1M HCl).

Low intensity peaks evident in the 3800 cm^{-1} - 3600 cm^{-1} region relate to OH group vibrations within mineral matter (Hossain et al., 2011) which indicates the presence of clay type compounds within the biochar (Supplementary Table 1). Two peaks at 2980 cm^{-1} and 2890 cm^{-1} indicate asymmetric and symmetric aliphatic ν(CH) from terminal $–CH_3$ groups respectively (Socrates, 2001). However, these CH bands disappear at high temperatures due to demethylation and dehydration (J. Zhang et al., 2015) therefore in biochar pyrolyzed at 550 - 700°C the peaks are negligible.

Small peaks in the 2700-2100 cm^{-1} region could be due to P-OH groups in phosphorus acids and esters which produce one or two broad bands (Stuart, 2004).

A peak at 1424 cm^{-1} corresponds to asymmetric stretches of carbonate groups, which correlates with the small peak at 874 cm^{-1} due to the out-of-plane bending for CO_3^{2-} (Zhao et al., 2013). This could indicate the presence of calcite (calcium carbonate) in the sample. The presence of carbonate was verified as the FTIR spectrum of the acid washed biochar showed no clear peaks at 1424 cm^{-1} or 874 cm^{-1} confirming that acid washing removed carbonates from the sample (Supplementary Figure 2).

Another interesting difference between the ashed and deashed biochar is a broad trough between 3400 cm^{-1} and 2500 cm^{-1}. This implies the presence of O-H in carboxylic acids however there is only a very weak intensity peak at ~1700 cm^{-1} which could correspond to C=O in carboxylic acids. Other possible groups responsible for peaks within the 3400 cm^{-1} and 2500 cm^{-1} region include ν(OH) from sorbed water and hydrogen bonded OH (Keiluweit et al., 2010).

The low intensity peak in biochar between 1540 and 1650 cm^{-1} could be indicative of C=O stretching vibrations for amides (Calderón et al., 2006), aromatic C=C stretching and carboxylate anion vibrations (Deacon & Phillips, 1980). The peak in the deashed biochar at 1580 cm^{-1} to 1600 cm^{-1} is indicative of a carboxylate ion, the conjugate base of a carboxylic acid (Deacon & Phillips, 1980; Ellerbrock & Gerke, 2021) (Supplementary Figure 2). This peak was not evident in the ashed biochar (Supplementary Figure 1). It's been suggested that a reduction in inorganics by acid demineralization allows previously hidden carbon to emerge so increasing the amount of acidic functional groups (Lou et al., 2011).

In the ashed biochar (Supplementary Figure 1) there are very visible peaks ~1450 cm^{-1} indicative of a carbonate stretch (CO_3^{2-}) whereas the peaks in the acid- washed samples (Supplementary Figure 2) are much less visible indicating some carbonate salts within the ash content have been successfully removed by acid demineralization. The very broad band in the range 1200-970 cm^{-1} is indicative of several functional groups. Inorganic and organic silicon and phosphorus compounds, as well as carbohydrates and sulfates can contribute to this broad peak (Wen et al., 2007). Sewage chars are known to contain high phosphorus levels suggesting that the peaks observed in 1200-950 cm^{-1} band arise from P containing functional groups such as asymmetric and symmetric stretching of PO_2 and $P(OH)_2$ in phosphate (Jiang et al., 2004). Si-O asymmetric stretching could be present between 1000-1100 cm^{-1} (Falaras, 1999) as well as symmetric C-O stretching of ethers.

A peak at 462-464 cm^{-1} evident in both biochar and acid washed biochar is indicative of bending vibration of Si-O-Si (459-463 cm^{-1}) (Qian & Chen, 2013). In the ashed biochar this peak seems to shift to a lower wavenumber 456 cm^{-1}. It is possible the signals at 462-464 cm^{-1} relate to bending vibration of Si-O-Si (459-463 cm^{-1}) and the signal at lower wavelength in the ashed biochar at 452 cm^{-1} relates to Si-O rocking (Shahrokh Abadi et al., 2015). A weak intensity signal at 1984 cm^{-1} is evident in the ashed biochar but not in the deashed samples. This signal could indicate metal – carbonyl bonds, typically terminal M-CO bonds occur at 2125 - 1850 cm^{-1}. A quartz doublet at 796 cm^{-1} and 780 cm^{-1} is evident in the ashed biochar sample (Farmer, 1974).

There are more signals recorded in the 900-400 cm^{-1} region for the ashed biochar than the deashed biochar which relate to clay minerals associated with biochar. Bands below 600 cm–1 can be caused by stretching inorganic compounds such as KCl and $CaCl_2$ (Hossain et al., 2011).

The oxygen containing functional groups (OCFGs) present on biochars surface such as C=O groups determine its cation exchange capacity (Spokas, 2010). It is this property that enables biochars to adsorb cationic nutrients such as NH_4^+, Ca^{2+}, and K^+ within the soil and increases soils nutrient retention capability. The lack of C=O groups present in WGL_BC would affect its ability to retain nutrients within soil and thus makes it a less ideal candidate for soil amendment purposes.

4.2.3 Surface area

The shape of the isotherms recorded for all biochars indicate a pseudo-type II isotherm associated with delayed capillary condensation due to the limited amount of pore curvature and non-rigid framework of the aggregate (Sing & Williams, 2004). Isotherms of each biochar indicate a degree of both mesoporosity and microporosity.

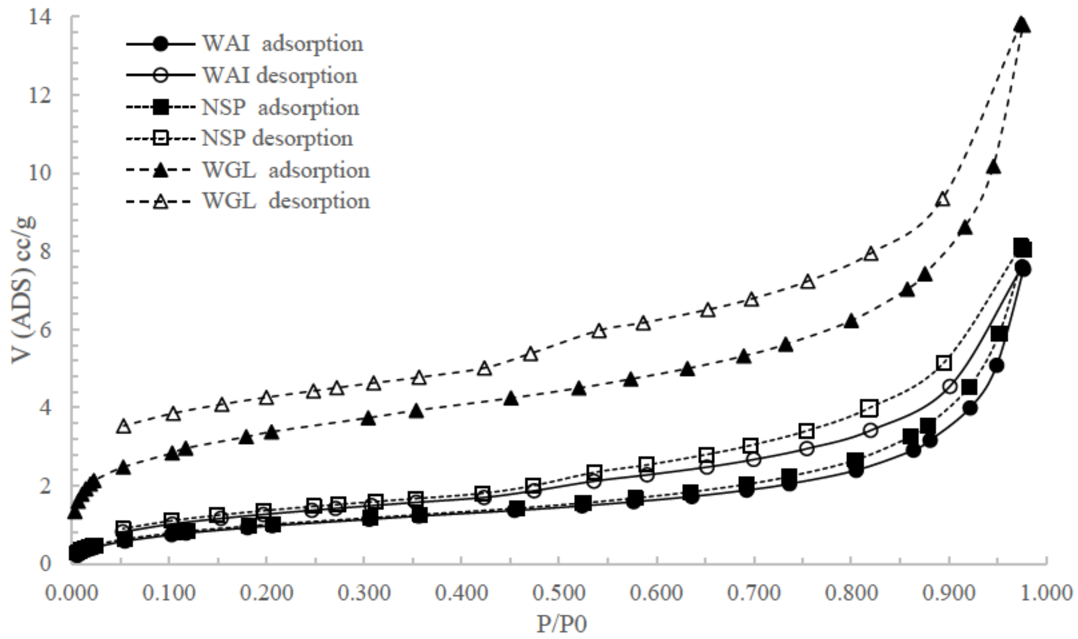


Figure 4.2 *N_2 adsorption and desorption isotherms of WAI, WGL and NSP biochars (P/P0= Relative pressure, V (ADS) cc/g = Volume of adsorption)*

Hysteresis is present in all isotherms and can be classified as H3/H4 in accordance with the International Union of Pure and Applied Chemistry (Thommes et al., 2015). Hysteresis is caused by capillary condensation and is typical of mesoporous materials. H3 type is typical for loose aggregates of plate-like particles and in porous materials typical of pore networks containing macropores not entirely filled with condensate. H4 type loops suggest presence of slit-shaped pores including pores in the micropore region and plate-like particles with spaces between the parallel plates (Mokaya & Jones, 1995) and are common with activated carbons. H4 hysteresis loops are commonly observed with more complex materials consisting of both micropores and mesopores.

Adsorption and desorption N_2 isotherms for all biochars (Fig 4.2) showed low surface areas of between 3.52 – 12.07 m^2g^{-1} (Table 4.1*)* consistent with results reported in the literature for sewage sludge biochars which have low surface areas due to high ash content (Agrafioti et al., 2013; Bagreev et al., 2001; Schimmelpfennig & Glaser, 2012). It has been postulated that high ash contents reduce surface area by filling or blocking access to the biochar micropores (Song and Guo, 2012).

The low nitrogen uptake of all three biochars can be characteristic of materials with small ultra-micropores that are close to the kinetic diameters of nitrogen, since molecules cannot overcome the activation energy for passing through the pores at cryogenic temperatures (Kim et al., 2011). To investigate this potential microporosity further CO_2 adsorption isotherms at 273 K were recorded for the three biochar samples (Fig 4.3).

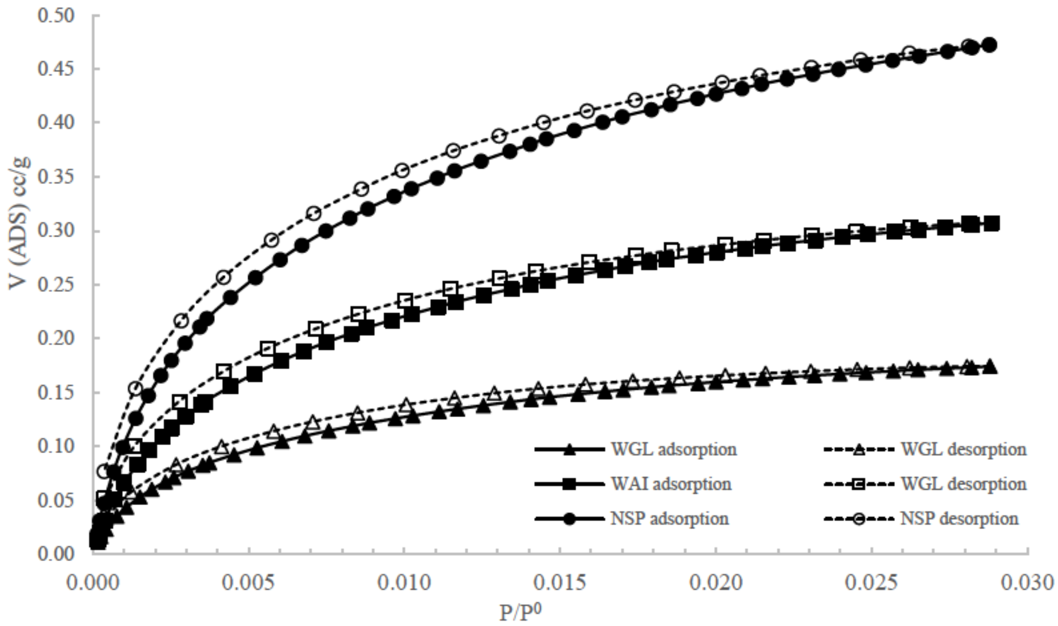


Figure 4.3 *CO_2 adsorption and desorption isotherms for WAI, WGL and NSP biochars (P/P0= Relative pressure, V (ADS) cc/g = Volume of adsorption cc/g)*

The CO_2-based BET SSA, µSSA and µPV values were significantly larger than the N_2-derived BET SSA and TPV values signifying that kinetic limitations with N_2 physisorption were present for all biochars and there is some degree of microporosity present. NSP biochar showed the largest surface area measured with CO_2 and the lowest with N_2 indicating a more microporous structure whereas WGL biochar had the highest N_2 SSA and lowest CO_2 µSSA signifying a slightly less microporous and more mesoporous structure.

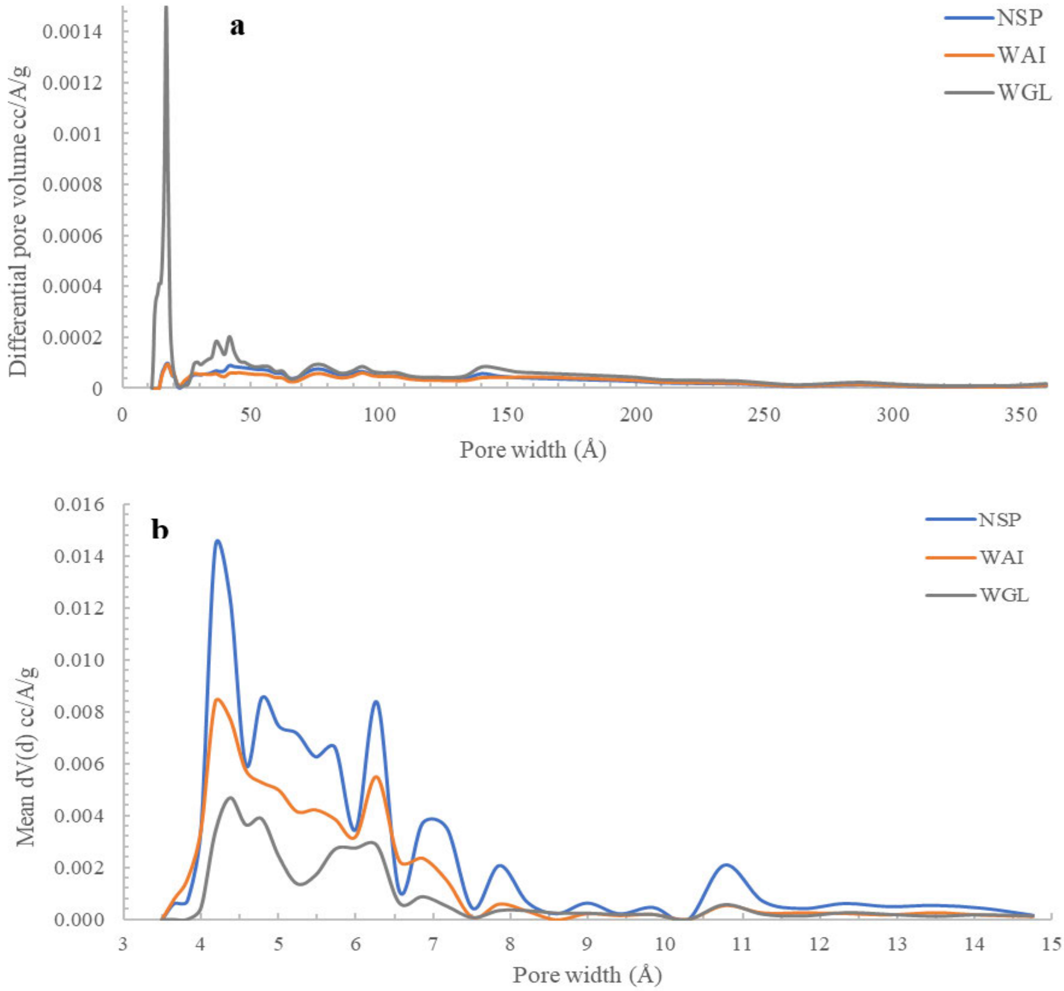


Figure 4.4 *Pore volume weighted pore size-distribution derived from a) N_2 (mesopore region 2-50nm) and b) CO_2 (micropore region<2nm) for NSP, WAI and WGL biochars.*

The greatest pore size distribution at pore diameters 4–15Å was recorded for NSP biochar also indicating it had more of a microporous structure than WGL biochar which recorded relatively sparse pore size distributions in this region (Fig 4.4b). In the mesoporous region, (16-150 Å), WGL biochar pore size distributions were much greater than both NSP and WGL biochar confirming WGL biochar has a more mesoporous structure (Fig 4.4a).

The acid washed WGL biochar (WGL_AW) had a higher surface area in both the mesopore region and micropore region confirming that high ash content reduces the surface area by blocking both micro and mesopores (Table 4.1.). The surface area and pore volume for WGL_AW, however, was still relatively low compared to biochars produced from other feedstocks (Novak et al., 2009). The values obtained demonstrate the complex pore network within the biochar, even though the surface area values are generally low compared to other biochars there is still a degree of both microporosity and mesoporosity within the biochars. Low surface area biochars may be unsuitable for use as soil amendments as the water holding capacity is relatively low and the low porosities are not conducive to promoting soil microbial growth (Ishii & Kadoya, 1994; Thies & Rillig, 2009), which play an important role in nutrient cycling (Lambers et al., 2008). The surface area could be increased by increasing the pyrolysis temperature (W. Song & Guo, 2012b; Tomczyk et al., 2020). The fast pyrolysis of municipal sludge biochar at temperatures 500 - 900 °C showed that increasing temperatures resulted in a greater microporous network within the biochar (T. Chen et al., 2014).

4.2.4 Zeta Potential

Zeta (electrokinetic) potential signifies the net charge between the surface plane and slip plane of a colloidal particle (Hiemenz & Rajagopalan, 1997). Zeta potential values yield information about the external surface charges of biochar particles in solution and indicates the sorption and nutrient holding characteristics of the biochar in soil. Negatively charged surfaces are unlikely to sorb negatively charged ions such as phosphate but are more likely to sorb positive cations such as heavy metal ions and ammonium ions.

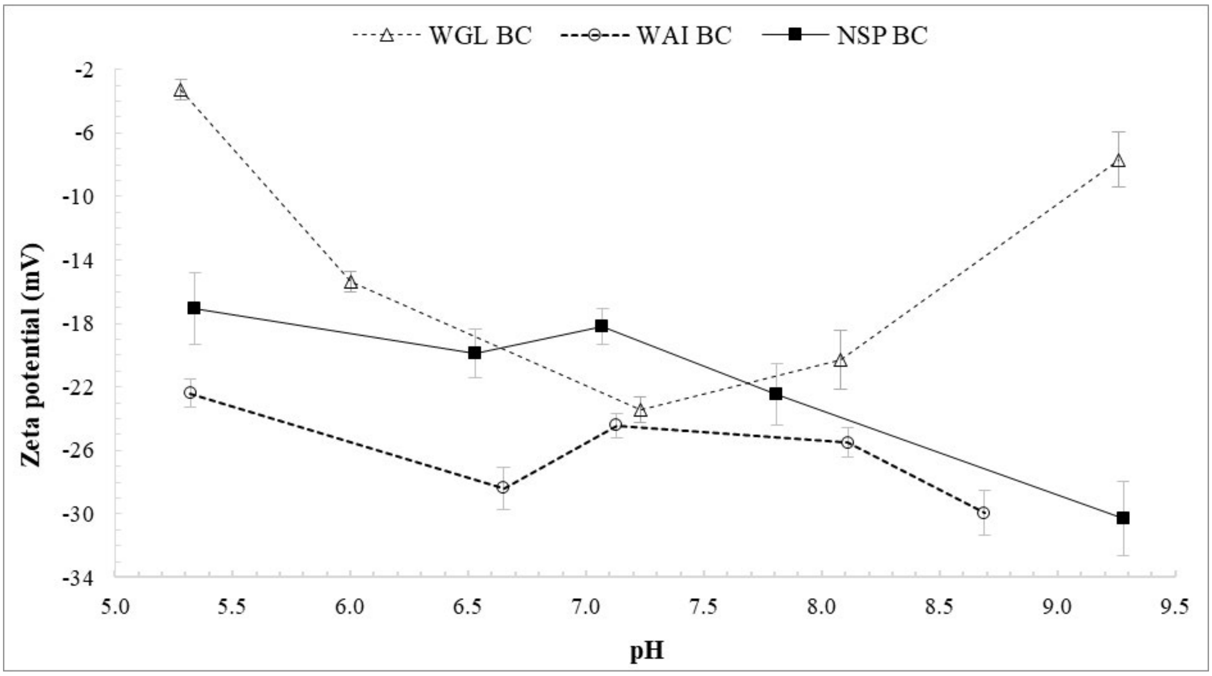


Figure 4.5 *Zeta potentials of WGL_BC, WAI_BC and NSP_BC at pH values from 5-9.5*

The zeta potential values for all three biochar samples were negative in the pH range 5.0-9.5, revealing that the negative charges are carried on the surface of the biochar particles. (Fig 4.5) FTIR spectra revealed the existence of oxygen- containing functional groups (–COO^- and–OH) on the biochars surface which can contribute considerably to surface charge of the biochars (Fig 4.1). The negative zeta potentials of all three biochars in the pH range 5.0 – 9.5 support this interpretation.

At acidic pH, the zeta potentials of the biochar samples became less negative, indicating that the association of –COO^- and –O^- with H^+ reduced the negative charge of the biochars. With increasing pH, the zeta potential of WAI_BC and NSP_BC biochars become more negative due to increasing deprotonation of the biochar surface functional groups (J. H. Yuan, Xu, & Zhang, 2011a).

4.2.5 X-ray Diffraction (XRD)

X-ray diffraction (XRD) analysis of the biochars revealed that mineral components in crystal form were present in all three biochars (Fig 4.6). Quartz was identified as the predominant crystalline phase with the highest peak at 2θ around 26.6° (d = 3.33 Å) in NSP and WGL biochars. WAI biochar exhibited a more intense peak relating to $CaSO_4$ (Anhydrite). Quartz, sylvite, calcite, calcium sulphate, albite were the most common phases identified. These minerals are formed during pyrolysis due to a reaction between CO_2 and alkaline-earth metals and alkaline oxyhydroxides.

Previous research has shown sewage sludge biochar to have a turbostratic structure where the carbon fraction is dominated by disordered graphitic crystallites (Srinivasan et al., 2015; Uchimiya et al., 2011). This is in discordance with the XRD results for NSP _BC and WGL_BC showing a distinct lack of C (002) diffraction peaks (2θ = 15-30°) and C (101) diffraction peaks (2θ = 40-50°) due to amorphous carbon structures and graphite structures respectively. However, WAI_BC showed a possible tail end of a diffraction peak (2θ = 15-30°) indicating an amorphous carbon structure (Figure 4.6). This peak is clearer for WAI_BC due to the lower -intensity quartz peaks present. The biochars studied here do have a very high ash content and the lack of these peaks for WGL_BC and NSP_BC is as a result of interference of high-intensity quartz peaks (Feng et al., 2015).

The difference in mineral composition between the three biochars could be due to possible contamination of FS by sand and grit caused by poorly lined containment structures (Niwagaba et al., 2014a). The containment structures at each location would have to be investigated to reach a definitive conclusion. The high content of nutrients within the biochars Ca, Si, and K, and high alkalizing capacity of calcite ($CaCO_3$) indicate their potential use as a soil amendment particularly within low nutrient and acidic soils.

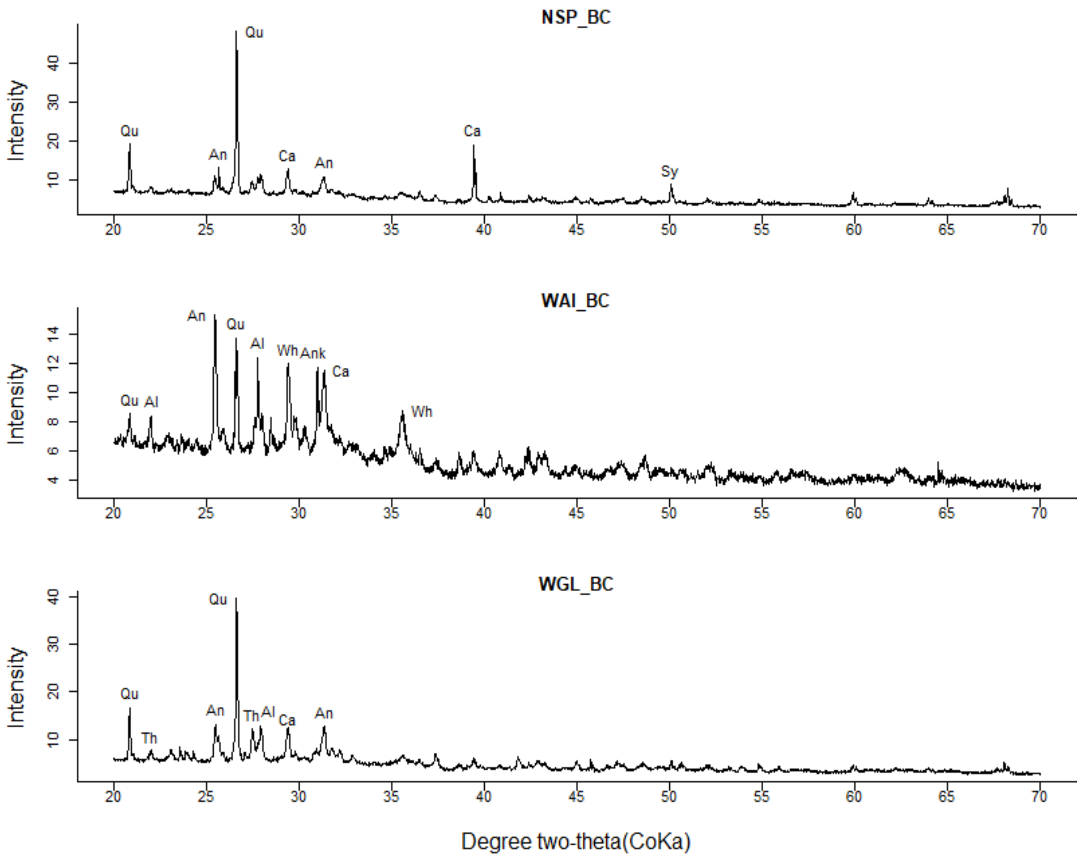


Figure 4.6 *XRD patterns of NSP, WAI and WGL biochar (Qu= Quartz, Al=Albite, Ca=Calcite, An = Anhydrite, Sy = Sylvite, Wh = Whewellite, Ank=Ankerite, Th= Thermonatrite)*

4.2.6 Scanning Electron Microscopy (SEM) with Energy Dispersive X-Ray Analysis (EDX)

SEM analysis shows all three biochars have high ash content with EDX confirming the presence of mineral elements (Figure 4.7). The SEM images clearly showed a high presence of clay mineral particles/ash (white/grey) with a smaller amount of biochar particles present (black). The surface coverage with clay particles on the biochar was confirmed by the EDX analysis. EDX spectra of the ash surface showed high peaks for silicon, calcium and small amounts for aluminium, potassium, magnesium, phosphorus, and sodium, typical of the composition of clay minerals. Sewage sludge is known to contain very high concentrations of these elements (Zielińska et al., 2015). The pore structure of biochars strongly resemble the cellular structure of the original feedstock (Fuertes et al., 2010; Yao et al., 2011). In the case of faecal sludge, cellular macroporous structures arise from undigested fibrous vegetable matter. The biochars themselves exhibit a complex porous structure evident in all biochars (Figure 4.7). The morphology of the biochar is honeycomb-like with cylindrical and slit like holes clearly observable. Visually WGL biochar had a higher ash content which is concurrent with the ash percentage from proximate analyses. EDX results on the biochar particles themselves revealed high volumes of carbon and oxygen (Fig 4.8).

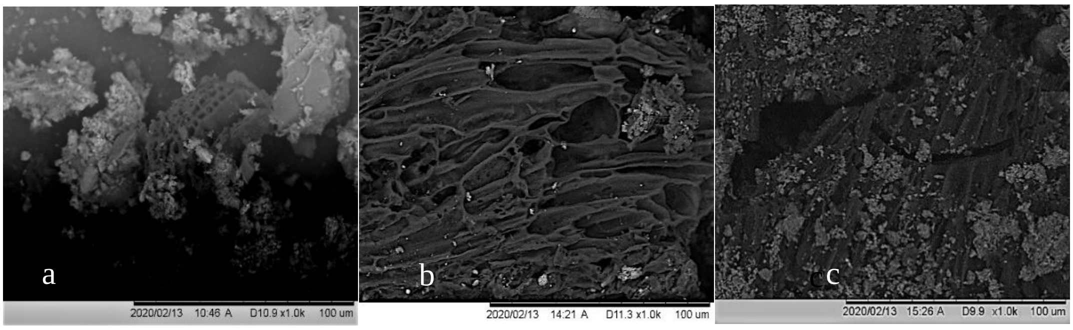
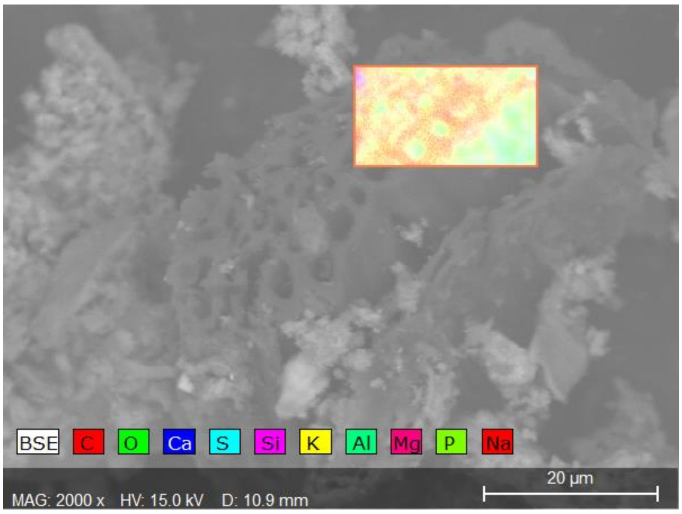


Figure 4.7 *SEM micrograph of (a) Original WGL biochar, (b) Original NSP biochar, (c) Original WAI biochar*



Element	Wt. %
C	70.55
O	21.00
Ca	3.24
S	1.62
Si	1.29
K	0.73
Al	0.63
Mg	0.50
P	0.27
Na	0.17

Figure 4.8 *SEM-EDX map for all elements distribution across the area highlighted in image and associated energy dispersive X-ray (EDX) quantification of biochar*

Acid washing the biochars did not seem to have any noticeable effect on mineral content. Ash is still observable under the scanning electron microscope (Supplementary Figure 6) and EDX quantification data did not show a significant decrease in clay mineral elements (Si, Ca, Al etc.). One reason for this is that only hydrofluoric acid can effectively dissolve quartz and other silicates. Calcium is also still present in the deashed biochar; thus, it is possible that the very high ash content of the biochars requires a much more rigorous acid-washing regime as calcium bound within the biochar structure is not fully dissolved by acid washing with HCl.

EDX quantification of the ashed samples all show high mineral element concentrations as expected for ash with high amounts of silicon (20.5%) concurrent with XRD and FTIR analysis. Spheres present in all samples could be amorphous alumino-silicate spheres of the type found in fly ash (Supplementary Fiure.7).

4.2.7 Cation exchange Capacity

Cation exchange capacity (CEC) enables biochars to adsorb cationic nutrients such as NH_4^+, Ca^{2+}, and K^+. It is thought this characteristic of biochar results predominantly from formation of carboxylic functional groups during oxidation (Cheng et al., 2006). There was a large variation in CEC values with WGL biochar (WGL BC) the highest CEC at 129.3 cmolkg^{-1} and NSP biochar the lowest CEC at 41.9 cmolkg^{-1} (Table 3.1). Fresh biochars from lignocellulosic biomass generally have lower CEC, with manure-based biochars exhibiting higher CEC values (Tag et al., 2016). In the literature CEC values for biochar are highly variable, commonly ranging from 6 cmol$_{(+)}$ kg^{-1} (Munera-Echeverri et al., 2018) to 36.3 cmol$_{(+)}$ kg^{-1} (W. Song & Guo, 2012b) to as high as 304 cmol$_{(+)}$ kg^{-1}.

Yuan et al. (2011) proposed that high ash content biomass creates high CEC biochars and that K, Na, Ca, Mg, and P in the feedstock would promote formation of O-containing acidic functional groups such as carboxylic, and phenolic groups on biochar surface during pyrolysis and thus, result in higher CEC (Gaskin et al., 2008). However, FTIR analysis showed a lack of acidic functional groups such as phenolic groups in these biochars. The determination of CEC in biochars is made difficult due to the presence of alkaline ashes in biochar. It is possible that the high ash content of these biochars could contribute to methodological problems in determining CEC (Graber et al., 2017). There is a large range of CEC values reported in the literature and measurements are often poorly reproducible (Munera-Echeverri et al., 2018). The high ash content and lack of O-containing functional groups indicate that the high CEC values reported here are due to an overestimation of CEC. FTIR shows carbonates and silicates present in these biochars which would result in the release of base cations and interference with the sum of exchangeable base cations (Munera-Echeverri et al., 2018).

4.3 STUDY LIMITATIONS

Resource constraints, compounded by external factors such as the global COVID-19 pandemic, hindered my ability to perform comprehensive analyses of heavy metal content and available nutrient content in this study. Determining the heavy metal content would aid in assessing the potential environmental risks associated with the application of faecal sludge biochar as a soil amendment. High levels of heavy metals can have adverse effects on soil quality, plant growth, and groundwater contamination. Also, regulatory bodies often have limits on the permissible levels of heavy metals in soil amendments or fertilizers.

Evaluating the nutrient content would have been beneficial in investigating the biochar's potential as slow-release fertilizer.

All three biochars had alkaline pH values ranging from 11.81 to 12.25 which is consistent with other biochars, as during pyrolysis inorganic elements Ca, K and Mg, are not lost through volatilization, and increase relative to the feedstock (Novak et al., 2009). These high pH values indicate the potential of these biochars as amendments to acidic soil, however a more quantifiable method could have been performed which is the assessment of calcium carbonate equivalents (CCE) (Ippolito et al., 2015).

4.4 CONCLUSION

This study characterized faecal sludge biochar produced by community-scale treatment plants at three sites in India. The physical and chemical properties of the biochars were evaluated with regards to the potential end-use as a soil amendment or fertilizer. It was observed that the high ash content of all three biochars contributed to very high pH values with a potential liming effect in acidic soils. The high ash content contributed to the biochar's low specific surface areas by blocking or filling the micropores which would affect soils water retention capacity. Warangal biochar had significantly higher ash content than Narsapur biochar and Wai biochar which could be related to pyrolysis process conditions, digestion during storage or contamination of FS in containment structures. The high nutrient content (Si, Ca, K and Mg) of all three biochars demonstrates the potential as a soil amendment particularly in low nutrient soils. This study underlines the need to take into account the volume and composition of ash when evaluating the potential of FS biochars as soil amendments. Future work should focus on evaluating FS biochars in crop-growing trials concentrating on acidic and nutrient depleted soils.

Declarations

Availability of data and material

The datasets generated during and/or analysed during the current study are available in the Mendeley Data repository,

DOI: 10.17632/2xsdbdb38k.1https://data.mendeley.com/datasets/2xsdbdb38k/1

Competing interests

The authors declare that they have no known relevant financial or non-financial interests to disclose.

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Authors' contributions

HLN: Conceptualization, Methodology, Investigation, Writing – original draft. IM: Conceptualization, Methodology, Writing – review and editing. HA: Investigation. IR: Writing – review & editing. MC: Methodology. TD: Investigation. GS: Investigation

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5 THE EFFECT OF FAECAL SLUDGE BIOCHAR ON THE GROWTH AND FRUIT YIELD OF TOMATO (*SOLANUM LYCOPERSICUM L.*) CULTIVAR MICRO-TOM

Larissa Nicholas[1] Aisling Devine[2] Ian Mabbett[3] Iain Robertson[4]

[1] Department of Chemistry, Faculty of Science and Engineering, Swansea University, Swansea, SA2 8PP, Wales, UK, 804174@swansea.ac.uk

[2]Department of Biosciences, Faculty of Science and Engineering, Swansea University, Swansea, SA2 8PP, Wales, UK, 960072@swansea.ac.uk

[3] Department of Chemistry, Faculty of Science and Engineering, Swansea University, Swansea, SA2 8PP, Wales, UK, i.mabbett@swansea.ac.uk

Geography Department, Faculty of Science and Engineering, Swansea University, Swansea, SA2 8PP, Wales, UK, i.robertson@swansea.ac.uk

Chapter Overview

Thermochemical treatment of untreated faecal sludge (FS) from onsite sanitation facilities in developing nations produces biochar as an end-product. Biochar is carbon-rich, safe to handle, free from the pathogens contained in the original sludge and has enormous potential as a soil amendment.

The faecal sludge biochars presented here were produced in full-scale treatment plants in India via solar drying of collected faecal sludge before pyrolysis at 550°C - 750°C. Currently there is very little information on the effect of large-scale commercially produced FS biochar on plant growth and yield.

The effect of faecal sludge biochars on soil properties, growth, yield, and water runoff in Micro-Tom, a dwarf cultivar of tomato (*Solanum lycopersicum L.*), were investigated in an outdoor glasshouse environment. Four different treatments were used, an acidic, sandy, poor-quality control soil, biochar, fertilizer, and a combined fertilizer and biochar treatment. Biochar was applied at ~10 t ha^{-1} (4.2% w/w).

All parameters including plant height, leaf length, the number of Micro-Tom cultivar tomatoes and yield were greatest when biochar was applied in combination with the fertilizer. The application of biochar and fertilizer produced a tomato yield 2,980% greater than tomato yield grown in soil alone. Application of biochar on its own improved the yield of tomato cv. Micro-Tom by producing a yield 1,060% (approximately 12x) greater compared to that of control soil conditions. The results show the potential of faecal sludge biochar to increase soil fertility and improve crop yield in developing countries with acidic soil and inadequate water and nutrient supplies.

5.1 INTRODUCTION

It is estimated that 2 billion people in the world still do not have access to even a basic level of sanitation facility (UNICEF & WHO, 2020). In developing countries, the dumping of untreated faecal sludge from onsite sanitation facilities straight into the environment causes water pollution due to the high nutrient content and is a danger to public health due to the high pathogen content. An estimated 1.9 million deaths worldwide could be prevented with adequate water, sanitation, and hygiene (WASH) services (UNICEF & WHO, 2020). There is a pressing need for durable, economical, and sustainable processes that can treat faecal sludge at scale. Recent research has investigated the thermochemical treatment of faecal sludge by pyrolysis. Pyrolysis of faecal sludge at temperatures of 350°C – 1000 °C in an oxygen-free environment generates biochar, a carbon-rich solid material characterized by a high degree of aromaticity and usually high porosity (Rombel et al., 2022). The original feedstock source and pyrolysis temperature are the two principal factors determining the physico - chemical properties of biochars (Chen et al., 2008; Tomczyk et al., 2020; Weber & Quicker, 2018a). Other parameters influencing biochar properties include residence time, heating rate, and feedstock particle size (Agrafioti et al., 2013). Retention times have been shown to have no difference on ash content, or pH and that feedstock is the primary driver in terms of inorganic mineral content, pH and ash content of biochar (Wang et al., 2020).

Biochar is a promising resource for improving soil health, increasing carbon storage in soils and increasing crop yields. Biochar addition to soil enhances the chemical, physical and biological properties of soils. Biochar addition alters soils physical properties by enhancing soil structure, increasing porosity (and water retention), and reducing bulk density (Baiamonte et al., 2015). Chemically, soils treated with biochar have shown an increase in cation exchange capacity by 20 % (Laird et al., 2010b), lower soil acidity by 31.9% (Oguntunde et al., 2004), increased nutrient levels (Glaser et al., 2001), as well as a reduction in toxic metals such as arsenic, cadmium and zinc (Park et al., 2011). In terms of the effect of biochar on biological properties; soil biological community composition has been shown to increase upon biochar addition (Grossman et al., 2010), as well as an increase in soil microbial biomass by 125% (Liang et al., 2006). Biochar application to soil can also provide long-term carbon sequestration, reduce yearly greenhouse emissions, and ultimately mitigate climate change (Woolf et al., 2010).

Biochar can be applied to improve poor acidic soils, the majority of which are found in the tropics and subtropics (Yang et al., 2015) in developing nations, which are more at risk of climate change and food insecurity (Mekuria & Noble, 2013; Salinger et al., 2005). Many developing nations such as countries located in Sub-Saharan Africa suffer from soil degradation (Gwenzi et al., 2015a), including low soil pH, low fertility and low water holding capacity (Nyamapfene, 1991).

The greatest rise in food demand is also projected to occur in the world's poorest nations, where climate change will likely decimate crop yields by 15-20% (World Bank, 2015b). In developing nations subsistence farming and small-scale agricultural settings are widespread so improving soil health is critical to increase crop yield and alleviate food insecurity in these regions. The application of inorganic fertilizer to improve soil fertility has increased over the years in developing nations. However, there are still potential constraints to large-scale application such as supply problems and inappropriate fertilizer blends for local soil properties (Ricker-Gilbert, 2020). These constraints are higher in countries with limited or non-existent input subsidy programs and overall, approximately only a third of sub-Saharan African farmers use inorganic fertilizers (Sheahan & Barrett, 2017). Biochar has the potential to be used as either an alternative, where fertilizer is not readily available or to be used in combination with fertilizer to improve nutrient uptake and increase crop yield (Ye et al., 2020). The application of biochar with inorganic fertilizer has shown to improve crop yield and profitability in Ghana (MacCarthy et al., 2020). Additionally, only a small fraction of acidic soil is used for arable crops globally but approximately 50% of the earth's potential arable lands are acidic (von Uexküll & Mutert, 1995). Faecal sludge biochar with its liming capability has the potential to improve these soils and increase crop productivity.

Aside from poor infertile soils, climate change induced droughts will exacerbate food insecurity by decreasing farming output and negatively impacting the livelihoods of smallholder farmers in developing nations (FAO, 2008) It is estimated that half of the world's population could be residing in regions experiencing water scarcity in just 2 years' time, and by 2030 approximately 700 million people could be displaced due to intense water scarcity. Rapid economic and population growth are the reason behind the rising demand for water, declining water resources, and increasing water pollution (WWAP, 2018).

Biochar has the potential to alleviate drought conditions and improve crop yield due to its water holding capacity (WHC) (Novak et al., 2012). The porous structure of biochar results in greater WHC of soil (Herath et al., 2013) and increases water availability (Blanco-Canqui, 2017; Omondi et al., 2016; Uzoma et al., 2011). Biochar application has been shown to reduce wilting in tomato seedlings under drought conditions (Mulcahy et al., 2013). Adsorption behaviour of biochar is also strongly aligned with cation exchange capacity and this along with WHC is critical to improving water and nutrient retention in the sandy soils of smallholding farms in developing regions such as Sub-Saharan Africa (Gwenzi et al., 2015a).

Biochar production from faecal sludge creates an opportunity to recover nutrients from waste alongside increasing soil fertility, crop yields and food security in the poorest regions on the planet. There is a considerable amount of research investigating characteristics of sewage sludge derived biochar but less on faecal sludge biochar (Gold et al., 2018). Faecal sludge biochar has been shown to increase yield and tissue nutrient concentrations in lettuce (Woldetsadik et al., 2018), and increase pH and CEC of soil (X. Bai et al., 2018). Research has largely focused on small-scale laboratory produced biochar however it is becoming increasingly important to investigate biochar characteristics and agronomic properties of operational up-scaled sludge treatment technologies (Andriessen et al., 2019). The real-world large-scale production of FS biochar can result in biochars with varying characteristics which influence the effectiveness of these biochars in improving soil properties and increasing crop yield. The properties of faecal sludge itself can vary over season and location (Alvarenga et al., 2016), and heavy meal concentrations within biochars can be affected by the disposing of polluting waste in community toilets (Barani et al., 2018). In large-scale treatment facilities sintering of the material can occur in the reactor, leading to the removal of these sintered mineral depositions from the reactor on a weekly basis (Krueger et al., 2020). Therefore, biochar towards the end of the week may contain more sintered material which would affect its properties. The ash content of biochar influences the biochar pH and plays an important role in it use as soil amendment due to the liming effect. Ash content of FS biochars can vary over time and location due to contamination of faecal sludge by sand and grit caused by poorly lined containment structures (Niwagaba et al., 2014a), and sand adhering to the faecal sludge from the surface of drying beds (Cunningham et al., 2016). Investigating the effectiveness of faecal sludge biochars from large-scale treatment plants as soil amendments is crucial to inform the use of these biochars in the future and go towards solving the sanitation crisis in developing countries.

Tomatoes were chosen for this study as they are one of the most popular and most widely grown vegetables in the world (Sainju et al., 2003) and in developing countries tomato production is a major source of income for smallholder farmers (Gil et al., 2019; Mango et al., 2015; Njenga et al., 2015). Tomatoes are an important crop as they are beneficial for human health due to containing phytochemicals and nutrients such as lycopene, beta-carotene, iron, potassium, vitamin C and folate (Bhowmik et al., 2012; Toor et al., 2005). Drought stress can significantly affect tomato plants resulting in significantly lower yields (Harmanto et al., 2005; Wahb-Allah et al., 2011) as well as significantly affecting nutrient content (Sivakumar & Srividhya, 2016). Drought stress can also cause a reduction in leaf growth and fruit size, mineral deficiency and flower rot (Lamin-Samu et al., 2021). Tomato plants are susceptible to reduced irrigation during reproductive development, particularly during flowering and fruit growth stages (Solankey et al., 2015).

The tomato cv. Micro-Tom was chosen as it is an ideal candidate cultivar as tomato's model system. This is due to its small size, rapid life cycle (70–90 days from seed to fruit ripening) and its suitability for large-scale cultivation (Campos et al., 2010; Meissner et al., 1997).

The aim of this study was to assess the agronomic potential of three large-scale produced faecal sludge biochars on the yield of the tomato cultivar Micro-Tom (*Solanum lycopersicum* L.) in acidic, nutrient poor soils. The effect on plant height leaf length, tomato yield, above and below ground biomass, water runoff and soil properties of application of biochar, fertilizer and combined fertilizer and biochar treatments were investigated.

5.2 RESULTS

5.2.1 Plant growth responses

5.2.1.1 Plant height and leaf length

There a was marked difference between plant height for individuals that were treated with biochar and those that were not (Fig. 5.1b).

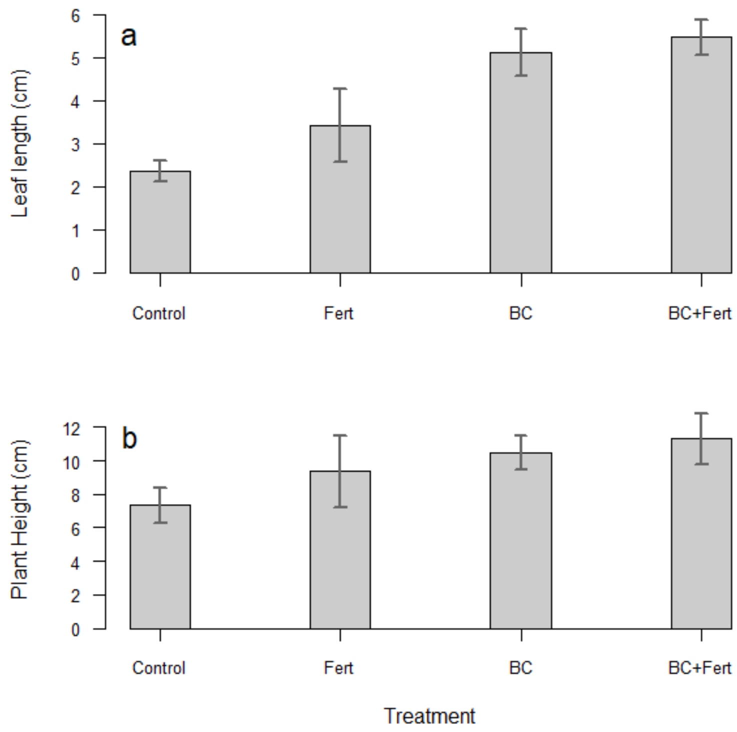

Figure 5.1 *Plant growth responses using different soil treatments, Control (control), Fert (fertilizer), BC (biochar), BC+Fert (biochar and fertilizer.: (a) mean leaf length per plant recorded at the end of the experiment; (b) mean plant height per plant recorded at the end of the experiment. Error bars denote standard deviation from the mean of each treatment.*

Plants under the biochar and fertilizer combination grew the tallest and plants that were subjected to biochar only were the second tallest. The model that included all biochar and fertilizer treatment terms demonstrated that all treatments were significant from each other apart from the biochar and biochar + fertilizer treatments and the comparison between biochar only and fertilizer only (Table.5.1). The best model explaining plant height variation was the one in which all treatment terms were included, as it had the lowest AIC value of 136.2828 (Table 5.2). Whilst the model that included biochar presence only as a term was also significant it had a higher AIC value of 141.8475 (Table 5.2), showing that the most parsimonious model was the one that examined the combination of fertilizer and biochar. The model containing fertilizer presence only term, had the highest AIC value and was shown to be non-significant.

Interestingly when we explored the accumulation of height over time for all individuals across all treatment (Fig.5.2), all treatments displayed similar patterns of growth, showing classic asymptote patterns of growth. It is just those individuals that were not subject to either biochar or a combination of biochar and fertilizer were markedly smaller.

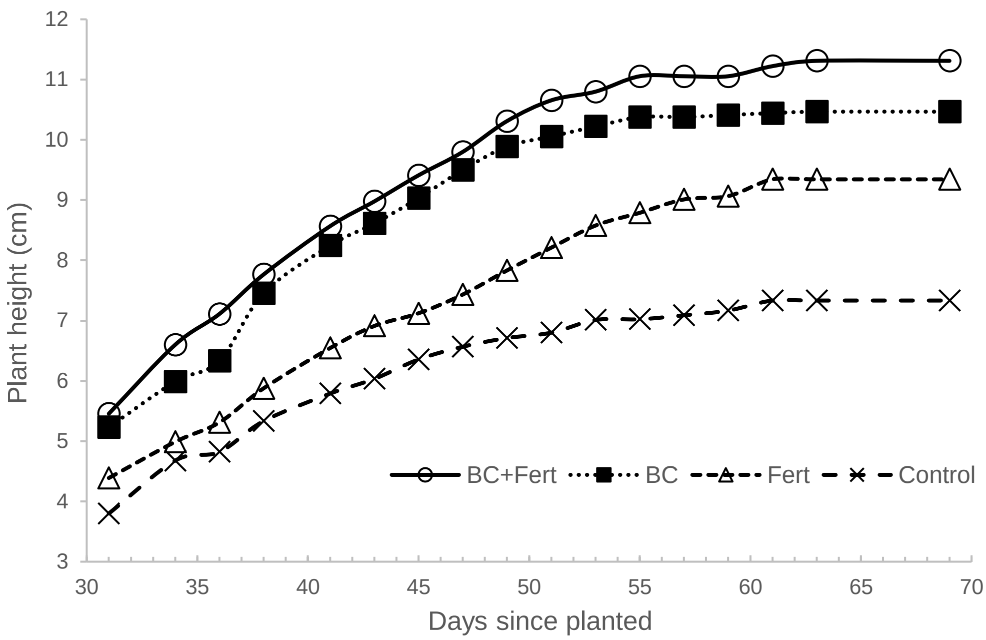

Figure 5.2 *Plant height measured during the experiment for each treatment Control (control), Fert (fertilizer), BC (biochar), BC+Fert (biochar and fertilizer).*

Leaf length also showed very similar patterns to that of plant height, where there was a marked difference in plants that were either grown in biochar or biochar + fertilizer (Fig.5.1). The most parsimonious model explaining leaf length was the model that included all treatment terms, having the lowest AIC value of 74.4528 (Table 5.2). Moreover, all treatments were significantly different from each other, except for biochar and biochar + fertilizer (Table 5.1). Again, similar to plant height, though the biochar presence model was significant it had a higher AIC value (90.45016) than that of the model that included all treatment combination terms. The model that included fertilizer presence only, was shown not to be significant and had a much higher AIC value (130.4761) compared to the other two models. Overall, the presence of fertilizer seemed less effective than just the presence of biochar alone in both plant height and leaf length. Additionally, biochar type was examined to see if this impacted plant height and leaf length. The generalised linear models showed no significant difference in growth across the different biochar types (Supplementary Table 2), showing that the origins/properties of the biochar did not alter plant growth responses.

Table 5.1 *The effects of biochar and fertilizer treatments on different plant growth responses using a linear model including pairwise comparison for plant height and gamma generalised linear model including pairwise comparison for leaf length and for both above and below ground biomass.*

Plant growth response	**Treatment pairwise comparison**		**Estimate**	**Std.error**	**t value**	***P*-value**
Plant height	Biochar	Biochar and fertilizer	-0.844	0.699	-1.208	0.6263
	Biochar	Control	3.133	0.699	4.83	0.0005
	Biochar	Fertilizer	1.122	0.699	1.6.6	0.3899
	Biochar and fertilizer	Control	3.978	0.699	5.691	<.0001
	Biochar and fertilizer	Fertilizer	1.967	0.699	2.814	0.0394
	Control	Fertilizer	-2.011	0.699	2.877	0.034
Leaf length	Biochar	Biochar and fertilizer	0.0126	0.0135	0.934	0.787
	Biochar	Control	-0.2288	0.0236	-9.708	<.0001
	Biochar	Fertilizer	-0.0974	0.0178	-5.48	<.0001
	Biochar and fertilizer	Control	-0.2415	0.0233	-10.357	<.0001
	Biochar and fertilizer	Fertilizer	-0.11	0.0174	-6.312	<.0001
	Control	Fertilizer	0.1315	0.026	5.054	0.0001
Above ground biomass	Biochar	Biochar and fertilizer	0.2234	0.0545	4.101	0.0015
	Biochar	Control	-1.2401	0.2414	-5.137	0.0001
	Biochar	Fertilizer	-0.0564	0.0775	-0.728	0.885
	Biochar and fertilizer	Control	-1.4635	0.2368	-6.179	<.0001
	Biochar and fertilizer	Fertilizer	-0.2798	0.0618	-4.527	0.0005
	Control	Fertilizer	1.1837	0.2432	4.868	0.0002
Below ground biomass	Biochar	Biochar and fertilizer	0.111	0.0922	1.203	0.6294
	Biochar	Control	-1.465	0.3568	-4.107	0.0015
	Biochar	Fertilizer	-0.298	0.1462	-2.04	0.1957
	Biochar and fertilizer	Control	-1.576	0.3533	-4.461	0.0006
	Biochar and fertilizer	Fertilizer	-0.409	0.1374	-2.977	0.0272
	Control	Fertilizer	1.167	0.3711	3.145	0.0181

Table 5.2 *Akaike's information criterion outputs for three different sets of models for the different plant growth responses, one with treatment as a factor with four different levels (biochar, biochar + fertilizer, fertilizer, and control) and the other two were fitted as a binary presence/absence factor, one for biochar presence and absence and the second with fertilizer presence and absence only.*

	AIC model outputs		
Plant growth response	**All treatments**	**Biochar presence**	**Fertilizer presence**
Plant height	136.2828*	141.8475	154.9203
Leaf length	74.45228*	90.45016	130.4761
Above ground biomass	108.4831*	138.5443	143.7842
Below ground biomass	87.85519*	96.97702	113.2051

5.2.1.2 Above and below ground biomass

Plants had greater above ground biomass when they were grown under the treatment of biochar + fertilizer (Fig 5.3). Plants grown in the fertilizer only treatment and biochar only treatment showed similar biomass production. Whilst plants grown in the control condition had markedly lower biomass than all other treatments. The most parsimonious model was the model that included all terms, having the lowest AIC of 108.4831 (Table 5.2). Additionally, all combinations of the treatments were significant from each other, except fertilizer only and biochar only treatments (Table. 5.1), which is evident in Figure 5.3 from the overlapping ranges. The model that contained biochar as a presence only term was significant but had a much higher AIC value of (138.5443) than that of the model including all treatment terms. The fertilizer only term model was not significant and had a much greater AIC value than the most parsimonious model. Additionally, biochar type was separately analysed for all plants receiving biochar application and it was shown that biochar type had no significance upon above ground biomass (Supplementary Figure 12).

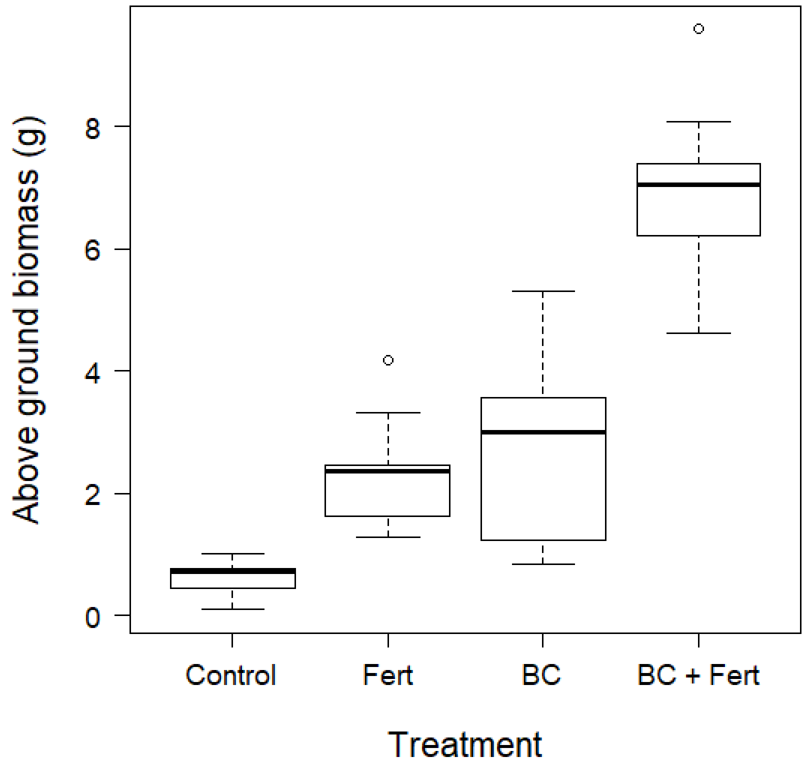

Figure 5.3 *Above ground biomass (g) measured at harvest for each treatment, Control (Control), Fert (fertilizer), BC (biochar), BC+Fert (biochar and fertilizer). Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum. Open circle symbols indicate outlier.*

Belowground biomass also differed across treatments, where plants grown in biochar or biochar + fertilizer treatments had markedly greater below ground biomass than those plants that were grown only in fertilizer or in the control treatments (Fig.5.4). The most parsimonious model was that which included all treatments terms, having the lowest AIC value of 87.85519 (Table 5.2). All combinations of treatments were significantly different from each other apart from biochar and biochar + fertilizer, and biochar and fertilizer only (Table 5.1). Similar to all other plant growth responses, the biochar only presence model was significant but had a higher AIC value in comparison to the model which included all treatment terms. The fertilizer only presence model was not significantly different and had a much higher AIC than the other two models in comparison. Interestingly, for belowground biomass, when biochar type was examined separately there was a significant difference between biochar types (Supplementary Table 2 and Supplementary Figure 13.), with plants grown in the NSP biochar type having significantly lower below ground biomass in comparison to the

WAI and WGL biochar types. This significant difference may indicate that biochar type may not impact above ground plant growth but may be important in altering belowground growth and processes.

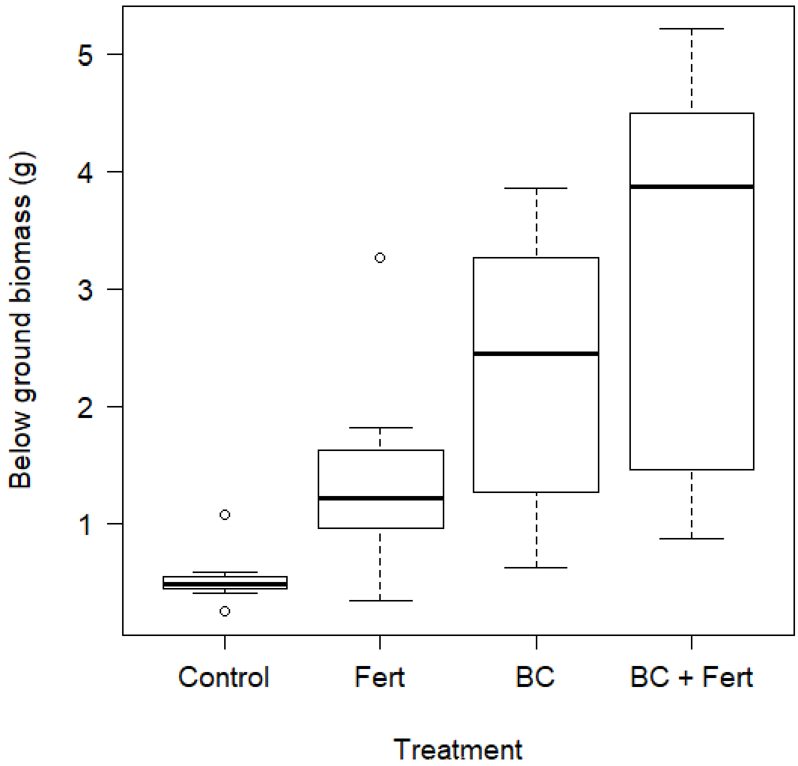

Figure 5.4 *Below ground biomass (g) measured at harvest for each treatment, Control (control), Fert (fertilizer), BC (biochar), BC+Fert (biochar and fertilizer). Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum. Open circle symbols indicate outlier.*

5.2.2 Fruit production

The number of fruits produced per plant was markedly higher for plants grown in the biochar and the biochar + fertilizer treatments, with the biochar + fertilizer treatment producing the most amount of fruit (Fig.5.5).

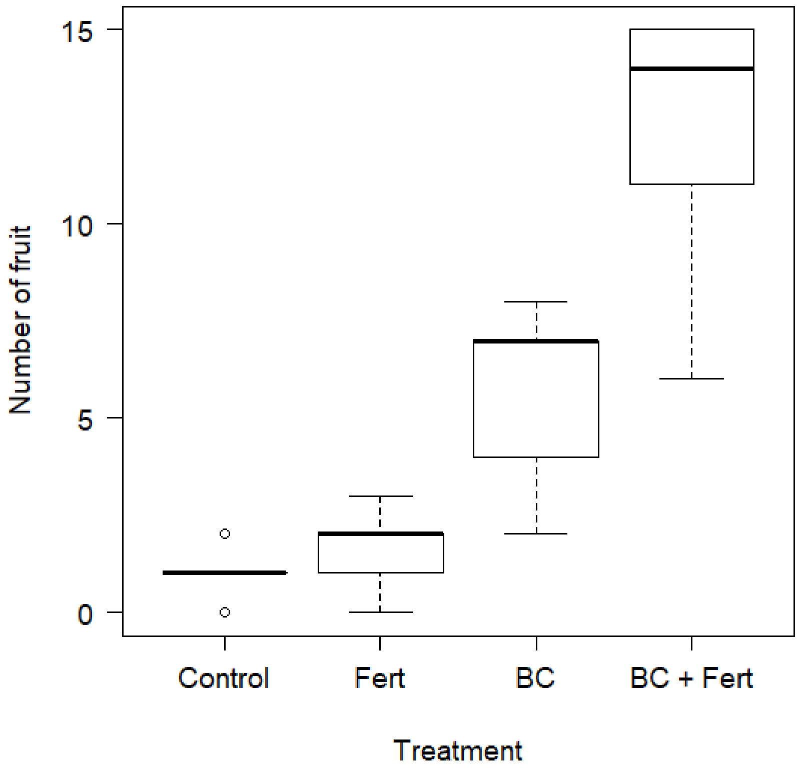

Figure 5.5 *Number of tomatoes measured at harvest for each treatment, Control (control), Fert (fertilizer), BC (biochar), BC+Fert (biochar and fertilizer). Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum. Open circle symbols indicate outliers.*

The model that included all combination treatment terms was the most parsimonious model, having the lowest AIC value of 142.6897 (Table 5.4) and all treatments were significantly different form each other except the control and fertilizer only treatments, which both produced much fewer fruit (Table 5.3). Both the biochar presence term model and fertilizer presence term model were significant, however both models had much high AIC values than the model that included all treatment terms (Table 5.4).

Fruit yield also showed similar patterns, with the biochar +fertilizer treatment having markedly higher yields (Fig.5.6).

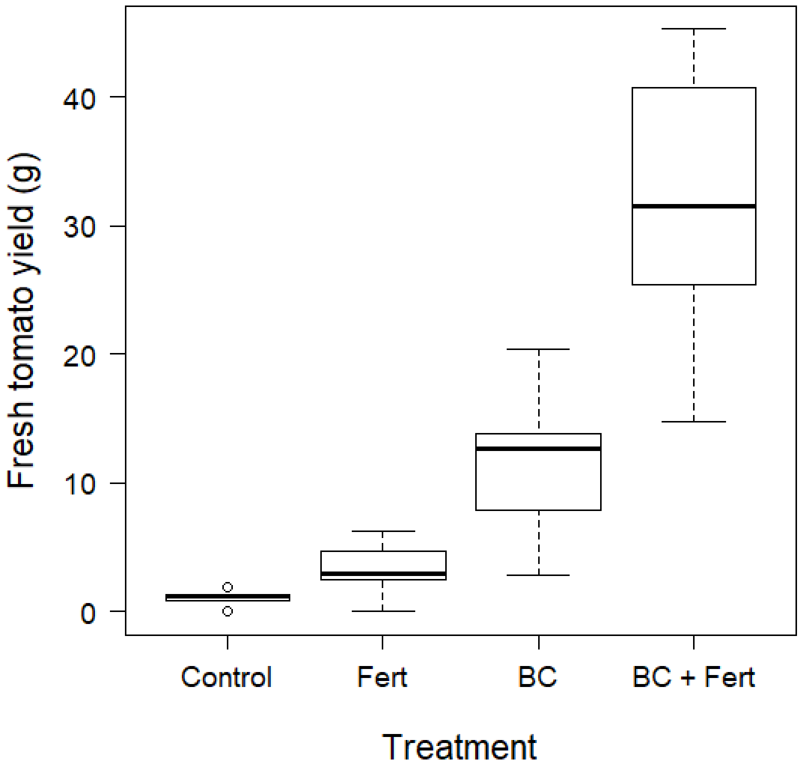

Figure 5.6 *Tomato yield (g) measured at harvest for each treatment, Control (control), Fert (fertilizer), BC (biochar), BC+Fert (biochar and fertilizer). Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum. Open circle symbols indicate outliers.*

The most parsimonious model was the one which included all treatment terms with an AIC of 191.688 (Table 5.4), with all combinations being significantly different from each other, with plants grown under the control treatment showing very low fruit yield (Table 5.3). Both the biochar presence only term model and the fertilizer presence only term were significant, however both had much higher AIC values than the treatment model (213.0751 and 255.12 respectively). For both fruit production responses biochar type was separately analysed (Supplementary Table 3 and Supplementary Figures 14 and 15), and biochar type had no significant different on either the amount of fruit that was produced or the weight.

Table 5.3 *The effects of biochar and fertilizer treatments on fruit production responses using gamma generalised linear models including pairwise comparison for number of fruits and fruit yield.*

Fruit production	**Treatment pairwise comparison**		**Estimate**	**Std.error**	**t value**	***P*-value**
Number of fruits	Biochar	Biochar and fertilizer	0.072	0.0176	4.099	0.0014
	Biochar	Control	-0.355	0.0562	-6.309	<.0001
	Biochar	Fertilizer	-0.23	0.0434	-5.291	<.0001
	Biochar and fertilizer	Control	-0.427	0.0546	-7.818	<.0001
	Biochar and fertilizer	Fertilizer	-0.302	0.0413	-7.312	<.0001
	Control	Fertilizer	0.125	0.0675	1.851	0.269
Yield	Biochar	Biochar and fertilizer	0.0464	0.011	4.22	0.001
	Biochar	Control	-0.4161	0.0659	-6.312	<.0001
	Biochar	Fertilizer	-0.1568	0.0325	-4.819	0.0002
	Biochar and fertilizer	Control	-0.4625	0.0653	-7.087	<.0001
	Biochar and fertilizer	Fertilizer	-0.2032	0.0312	-6.519	<.0001
	Control	Fertilizer	0.2594	0.0721	3.597	0.0056

Table 5.4 *Akaike's information criterion outputs for three different sets of models for the different fruit production responses, one with treatment as a factor with four different levels (biochar, biochar + fertilizer, fertilizer and control) and the other two were fitted as a binary presence/absence factor, one for biochar presence and absence and the second with fertilizer presence and absence only.*

	AIC model outputs		
Fruit outputs	**All treatments**	**Biochar presence**	**Fertilizer presence**
Number of fruits	142.6897*	155.8337	200.9442
Yield	191.688*	213.0751	255.12

5.2.3 Soil properties

Water runoff was much higher in plants grown without biochar or biochar and fertilizer (Fig.5.7). The model containing all treatment combinations was the most parsimonious (AIC 457.4257) and showed that all combinations were significantly different from each other apart from the control and fertilizer only treatments (Table 5.5 and 5.6).

Both the biochar presence only term model and the fertilizer presence only term model were significant, however both had higher AIC values, especially for the fertilizer presence only model (473 and 503.8 respectively). Interestingly when biochar type was separately analysed there was no significant difference, showing that the origins and/or properties of the biochar did not alter the water holding capacity of the soil.

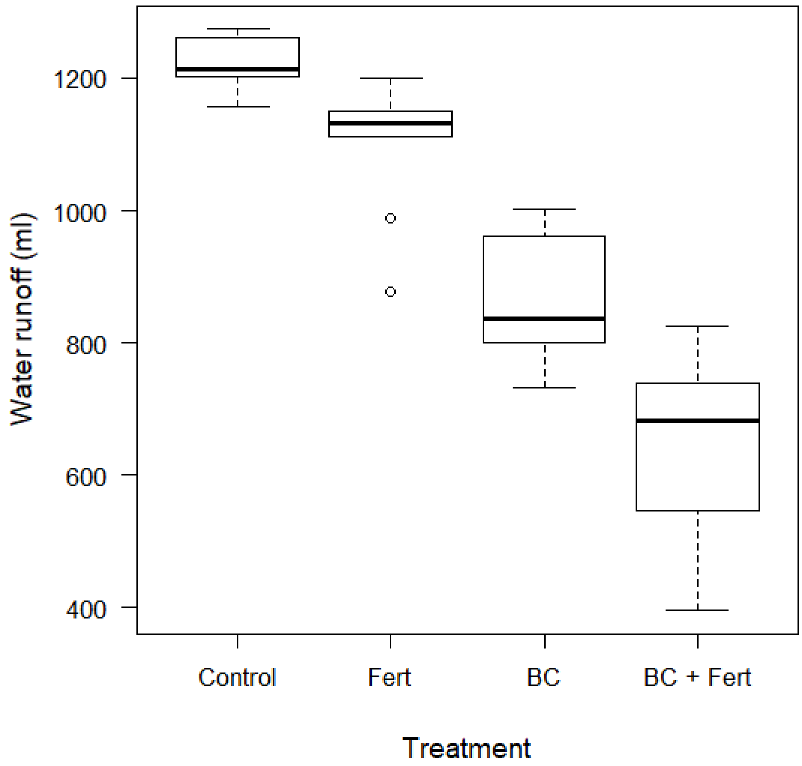

Figure 5.7 *Total water runoff for each treatment, Control (control), Fert (fertilizer), BC (biochar), BC+Fert (biochar and fertilizer). Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum. Open circle symbols indicate outlier.*

The soil pH displayed unusual results (Fig. 5.8), though both the biochar and biochar fertilizer treatments had a higher pH overall, they were not significantly different from soil in the control treatments (Table 5.5). The model containing all treatment combination terms was not the most parsimonious with an AIC value of 37.294 (Table 5.6). The model that explained the most variation in the data was that of the model containing biochar presence only term (AIC 35.74), showing that the presence of biochar was more important in explaining the changes in the pH. The model with the fertilizer presence only term was not significant and had the highest AIC value overall (41.24). There was a significant difference between biochar type when this was examined separately, with the WGL biochar type being significantly different to both the WAI and NSP biochar type, thus showing biochar type is an important factor influencing soil pH (Supplementary Figure 18).

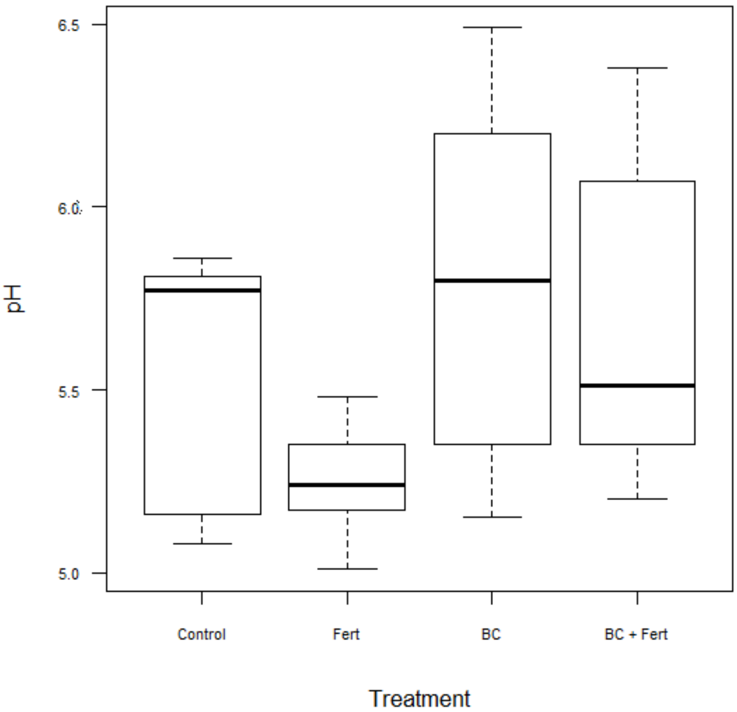

Figure 5.8 *Soil pH values measured at harvest for each treatment, Control (control), Fert (fertilizer), BC (biochar), BC+Fert (biochar and fertilizer). Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum.*

Electrical conductivity was higher in soils treated with just fertilizer alone, rather than the application of biochar (Fig. 5.9). The model with all combination treatment terms was the most parsimonious model (Table 5.6) and showed that the fertilizer treatment was significantly different from all other treatments apart from the biochar only treatment (Table 5.5), but this is likely due to two outliers (Fig. 5.6). There was no significant difference between the biochar treatment and biochar + fertilizer treatment. The model containing biochar presence only term was not significant and the least parsimonious, whilst the model containing fertilizer presence only term was significant but had a higher AIC value than the treatment term model.

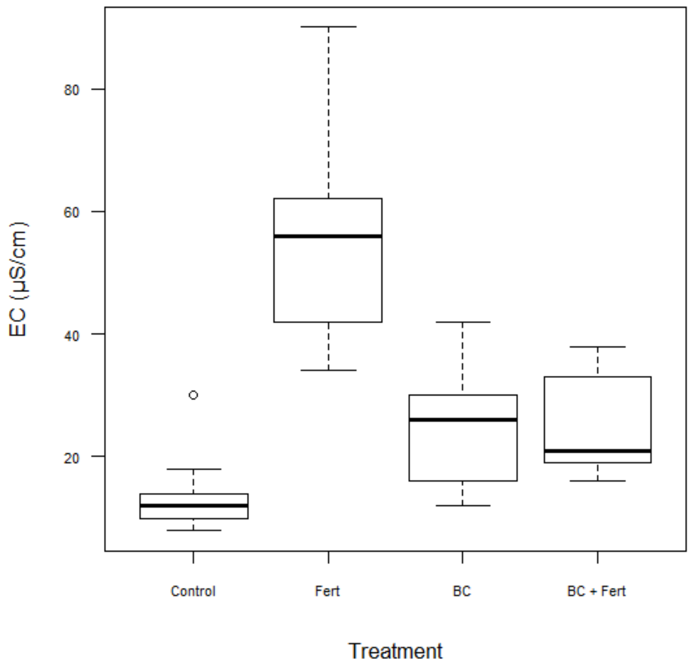

Figure 5.9 *Soil electrical conductivity (µS/cm) values measured at harvest for each treatment, Control (control), Fert (fertilizer), BC (biochar), BC+Fert (biochar and fertilizer). Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum. Open circle symbols indicate outliers.*

Table 5.5 *The effects of biochar and fertilizer treatments on soil properties using gamma generalised linear models including pairwise comparison for number of fruits and fruit yield.*

Soil properties	**Treatment pairwise comparison**		**Estimate**	**Std.error**	**t value**	***P*-value**
Water runoff	Biochar	Biochar and fertilizer	-0.000405	0.00009	-4.657	0.0003
	Biochar	Control	0.000346	0.00006	5.468	<.0001
	Biochar	Fertilizer	0.000255	0.00007	3.883	0.0026
	Biochar and fertilizer	Control	0.000751	0.00008	9.54	<.0001
	Biochar and fertilizer	Fertilizer	0.000660	0.00008	8.181	<.0001
	Control	Fertilizer	-0.000091	0.00005	-1.672	0.3548
pH	Biochar	Biochar and fertilizer	-0.00217	0.00559	-0.389	0.9797
	Biochar	Control	-0.00785	0.00568	-1.382	0.5195
	Biochar	Fertilizer	-0.01644	0.00582	-2.824	0.0385
	Biochar and fertilizer	Control	-0.00567	0.00571	-0.994	0.7541
	Biochar and fertilizer	Fertilizer	-0.2032	0.0312	-6.519	<.0001
	Control	Fertilizer	0.2594	0.0721	3.597	0.0056
EC	Biochar	Biochar and fertilizer	-0.00831	0.00865	-0.961	0.7722
	Biochar	Control	-0.04089	0.01293	-3.162	0.0174
	Biochar	Fertilizer	0.01332	0.00598	2.228	0.1381
	Biochar and fertilizer	Control	-0.03258	0.01373	-2.374	0.1035
	Biochar and fertilizer	Fertilizer	0.02163	0.00755	2.866	0.0354
	Control	Fertilizer	0.05421	0.01222	4.435	0.0006

Table 5.6 *Akaike's information criterion outputs for three different sets of models for the different fruit production responses, one with treatment as a factor with four different levels (biochar, biochar + fertilizer, fertilizer and control) and the other two were fitted as a binary presence/absence factor, one for biochar presence and absence and the second with fertilizer presence and absence only.*

	AIC model outputs		
Fruit outputs	**All treatments**	**Biochar presence**	**Fertilizer presence**
Water runoff	457.4257*	473.0119	503.7687
pH	37.294	35.74379*	41.23772
EC	277.1746*	303.3129	310.2736

5.3 DISCUSSION

The application of biochar overall improved plant growth and yield. For plant height and leaf length the application of biochar and biochar + fertilizer improved growth greatly but were not markedly different from each other, showing that the additional application of fertilizer with biochar did not result in more growth than just biochar alone. However, this was not the case for biomass and fruit production, which is a more commercially important factor. For biomass (both above and below) and fruit production (number and weight) the combination of biochar and fertilizer greatly increased yield in comparison to just biochar application alone. However interestingly for nearly all plant and fruit parameters apart from height and above ground biomass the application of biochar alone outperformed the application of fertilizer alone. Thus, showing that biochar could potentially be used as alternative to fertilizer in poor soils if needed, however the best conditions for higher tomato yields is the application of both fertilizer and biochar.

The changes in the soil properties in this study were more variable than that of the plant growth and yield parameters. Water run-off greatly decreased with the application of biochar when compared to the control or fertilizer only treatments, which is not surprising considering the water holding capacity properties of biochar. Interestingly water runoff was the lowest under the biochar + fertilizer and was significantly different to the biochar only treatment, this may be due to higher water requirements needed for those plants grown in this treatment as they produced higher yields, rather than differences in soil properties between biochar and biochar + fertilizer treatments. The changes in soil pH were less clear-cut than that of the water runoff. Biochar application did increase soil pH making it more alkaline but there was no clear pattern across the different treatment types. What appeared to be more important was just the presence of biochar regardless of the fertilizer combination. The electrical conductivity of the soil was also complex with no clear pattern across the different treatments, however soil that only had fertilizer application had much higher EC values. This result is likely related to the poor soil quality where plants were unable to access the fertilizer and therefore there was a higher accumulation of salts from the fertilizer only application.

Overall biochar type did not generally impact most parameters. Below ground biomass was the only plant parameter with significant differences between biochar types. NSP biochar recorded significantly less below ground biomass than all other biochar types (Supplementary Table 2). One possible explanation for this is that NSP biochar recorded the lowest CEC value out of all three biochars (Table 4.2). Certain properties of biochar that improve the chemical and physical characteristics of a soil such as pH or nutrient availability (CEC) have been shown to impact root growth (Lehmann et al., 2011). In the soil properties it was only pH that was significantly different between biochar types. WGL biochar recorded significantly greater soil pH values, compared to WAI biochar and NSP biochar (Supplementary Table 4). This is due to the high pH of WGL biochar itself (12.25) compared to the pH of WAI (11.81) and Narsapur (11.82) biochar (Table 4.2).

5.3.1 Implications for plant growth and crop yield

Previous research has shown that the application of biochar to soil improves plant growth in tomatoes (Akhtar et al., 2014; Tartaglia et al., 2020; Vaccari et al., 2015), including sewage sludge biochar (Hossain et al., 2015; Velli et al., 2021). Additional studies have also shown that faecal sludge biochar improves plant yields in other crops, such as lettuces (Woldetsadik et al., 2018). Our work supports this research, where it was clear the application of biochar increased plant height, leaf length and biomass. Interestingly our study also showed that the application of biochar greatly improved fruit yield both in total number of tomatoes and weight of tomatoes. This is in contrast to Polzella et al. (2019) and Vaccari et al., (2015), in which these studies reported no significant impact on tomato yields. However, both studies used alkaline or neutral soil whereas our study used acidic poor soils, demonstrating that the application of biochar to increase crop yields works best on poorer and acidic soils. Thus, showing that faecal sludge biochar, which is highly alkaline can be used to ameliorate acidic soil and increase crop yields, which has important implications for food security.

Jeffery et al., (2011) proposed that the increased plant growth observed in biochar amended soils is largely due to the liming effect of alkaline biochars. This mechanism could also explain the disparity between studies, with the pH of the soil, and pH of the biochar amendment both playing a significant role in plant growth and increased yield with biochar addition. A meta-analysis of field studies reported that soils with initial pH values ≤ 6.5 tended to show greater yield increases with biochar addition than those with initial pH values > 6.5 (Ye et al., 2020).

The increase in yield, plant height and above and below and above ground biomass with a combined biochar and fertilizer treatment is consistent with previous studies. A meta – analysis of previous research showed that biochar and inorganic fertilizer addition caused an increase in yield $\geq 15\%$ greater than fertilizer treatment without any biochar amendment (Ye et al., 2020). They postulated that the liming effect from alkaline biochar is a significant factor in the increases observed.

The biochar induced liming effect increases nutrient availability, thus in the combined biochar and fertilizer treatments the bioavailability of nutrients within the fertilizer is enhanced. Phosphorus adsorption and bioavailability are both affected by soil pH with the most available forms of phosphorus occurring at pH ranges between 5.5 and 7.0. (Nigussie et al., 2012). It is not just phosphorus availability impacted by the liming effect but also calcium availability and potassium availability (Atkinson et al., 2010).

The liming effect of biochar can also decrease soil exchangeable acidity and increase soil exchangeable base cations thereby increasing the CEC of the soil itself (Chintala et al., 2014; Yuan et al., 2011). The CEC of biochar itself is also crucial, biomass with a high ash content, such as faecal sludge, produces biochar with a high CEC (Yang et al., 2015), in fact, the CEC of manure-derived biochars are generally higher than that of woody biochars (Tag et al., 2016). Revell et al., (2012) reported that biochar application produced positive effects on CEC in a sandy loam soil and ammoniumsaturated FS biochar has increased pH and CEC in a neutral pH soil (Bai et al., 2018). An increase in CEC (cation exchange capacity) within soils after biochar addition has been linked to an increase in crop yield (Glaser et al., 2002). The high CEC of biochars and larger surface areas limit nutrient leaching in soils, (Lehmann and Joseph, 2012) and improves nutrient retention (Song and Guo, 2012). The soil in this study has a low CEC of 8.7 $cmolkg^{-1}$. Soils with CEC of less than 10 $cmolkg^{-1}$ have weak nutrient retention and supply capacities (Bai et al., 2018). The CEC of the biochars were relatively high (Table 3.1.), therefore, the significant increase in yield and above ground biomass observed with combined biochar and fertilizer addition is partly due to the high CEC of the biochar. This enhances the adsorption of applied fertilizers to biochars surface area, enabling nutrients within the fertilizer to be taken up more effectively by crops (Xu et al., 2013).

5.3.2 Implications for soil properties

Increased soil pH significantly impacts soil microbial biomass and microbial activity (Aciego Pietri and Brookes, 2008), with long-term studies showing that soil pH is a major factor in determining microbial composition, biomass and diversity (Zhalnina et al., 2015). The liming effect of biochar has also been shown to increase nitrifying bacterial abundance, microbial community structure and diversity within soils (Zhang et al., 2017).

The liming potential of faecal sludge biochar with high ash content may, however, be short-lived compared to other benefits such as CEC and water holding capacity which are longer lasting (Kätterer et al., 2019; Woolf et al., 2018). The processes behind increased water holding capacity are thought to relate to an increase in micropores for physically retaining water, or an increase in aggregation creating pore space for retaining water (Novak et al., 2009).

In this study the water runoff from the biochar treatment was significantly lower than the control and the fertilizer treatments (Fig.5.7), indicating that there is an increase in soil water holding capacity from biochar addition alone. Addition of biochar to greenroof soil has previously resulted in an increase in water retention (Beck et al., 2011) and reduced runoff volume has been measured in sandy clay loam soil plots amended with biochar (Sadeghi et al., 2016).

The combined biochar and fertilizer treatment however, recorded a significant decrease in water runoff compared to biochar treatment alone (Fig 5.7). This finding indicates that that it is not just the water holding capacity of biochar that results in reduced water runoff and that there are additional mechanisms occurring. Notably the addition of biochar + fertilizer produced plants with significantly greater above ground biomass than that of just biochar alone. The greater above ground biomass explains the reduced water runoff compared to biochar treatment as larger plants require more water.

The fertilizer treatment recorded a high EC value that was significantly different between all other treatments, the only other pairing that showed a significant difference was between the combined biochar and fertilizer treatment and the control. The liquid fertilizer contained soluble salts which explains the high EC of the fertilizer treatment. The combined biochar and fertilizer treatment however had a lower EC value. One explanation for this is the plants treated with both biochar and fertilizer were significantly taller and produced significantly greater yield of tomatoes compared to plants treated with fertilizer alone. Therefore, the lower EC values for combined biochar and fertilizer treatment can be attributed to these plants taking up more of the liquid fertilizer from the soil than the plants treated with fertilizer alone. Also, biochar can retain nutrients due to its surface charge (cation and anion exchange capacity) and its porous structure (X. Yu et al., 2018).

5.3.3 Implications for food security

The significant increases in yield with combined biochar and fertilizer treatment has implications for inorganic fertilizer use by smallholder farmers in developing nations. The use of inorganic fertilizer to increase soil fertility and crop yield is much lower in developing countries than developed countries (MacCarthy et al., 2020; Sanchez et al., 2009). The addition of biochar indicates a greater yield can be produced using similar quantities of fertilizer as used previously. It also implies that biochar addition and a reduction in fertilizer would produce the same yield as that produced with previous fertilizer requirements. Producing the same crop yield but with less fertilizer would benefit global phosphorus security. Phosphorus is an irreplaceable plant limiting nutrient (Steen, 1998) and as such is a crucial component in fertilizer with most global phosphorus resources used as fertilizers in agriculture. However, phosphorus is a finite resource, and our phosphorus reserves are already massively depleted with the remaining reserves becoming increasingly difficult to mine (Cordell et al., 2009). It is estimated that the depletion of all remaining natural phosphorus reserves will occur within the next 100 – 400 years (Cisse et al., 2004; Günther, 1997; Van Vuuren et al., 2010). Faecal sludge biochar can improve phosphorus security not just by reducing the fertilizer requirement but also by providing a renewable form of phosphorus. Almost 100% of phosphorus consumed in food is excreted (Jonsson et al., 2004) and total P concentrations of FS biochar have been reported at 3.2% - to 3.9% (Gold et al., 2018) and 5.4 - 8.1 wt.% (Liu et al., 2014). Pyrolysis of faecal sludge is one method to recapture phosphorus from the food system as part of a circular economy thereby increasing countries' phosphorus security and reducing the dependance on increasingly inaccessible phosphate fertilizer markets.

The reduced water runoff observed with biochar addition also has implications for future water security. Water scarcity already affects every continent with 1.8 billion people globally already impacted by drought and land degradation/desertification (WWAP, 2018). In the future competition for water resources will intensify, which will have a significant impact on agriculture as it is the most water-demanding economic sector (WWAP, 2018). The predicted increase in water scarcity is linked to climate change induced droughts which are predicted to increase in frequency and severity due to decreased precipitation and increased evaporation (IPCC, 2018). Water scarcity is also related to a rise in water pollution with the greatest increase in exposure to pollutants predicted to occur in developing countries due to greater economic and population growth and the lack of wastewater management systems (WWAP, 2018).

5.4 STUDY LIMITATIONS

Several limitations must be acknowledged in the conduct of this research:

1. Impact of External Factors:

The global COVID-19 pandemic had a profound impact on the collection of soil chemical data. The experimental phase of this study coincided with lockdown measures, resulting in restricted access to university laboratories and equipment. For instance, obtaining the dry yield of tomatoes proved challenging due to the unavailability of an oven set to the required temperature of 70 °C for a 12-hour duration. Additionally, issues were encountered with pH and electrical conductivity meters, and the absence of access to specialized university staff hindered efforts to address metering equipment malfunctions.

2. Limited Replications:

The study design included only three replications for each biochar treatment. This limited number of replicates may not be ideal for robust statistical analysis. However, increasing the number of replications was logistically challenging, given the constraints of conducting the research independently whilst away from university premises. Each measurement of plant parameters, particularly the time-consuming water runoff measurements, posed significant time constraints.

3. Lack of Environmental Control:

Conducting experiments within an outdoor greenhouse environment introduced limitations in terms of controlling light and temperature conditions.

While these limitations present challenges to the study's comprehensiveness and statistical power, they are important to consider when interpreting the results, in particular the differences between the three biochars from different treatment facilities (Wai, Warangal and Narsapur). Despite these constraints, the research provides valuable insights into the impact of faecal sludge biochar on growth and yield of tomatoes in acidic soil and underscores the need for future investigations that can address these limitations to build upon the findings presented here.

5.5 CONCLUSION

The results from this study show for the first time that commercial, large -scale faecal sludge biochar addition to an acidic soil can increase yield, fruit number, plant height and plant biomass in Micro-Tom tomatoes. The application of biochar alone outperformed the application of fertilizer alone. Thus, faecal sludge biochar has the potential to become an alternative to fertilizer in poor, acidic soils. Biochar treatment produced a fruit yield of tomato cv. Micro-Tom approximately 1,060% greater compared to that of control soil conditions. The combination of biochar and fertiliser significantly increased above ground biomass and fruit yield compared to just biochar application alone. The combined application of biochar and fertilizer produced a tomato yield 2,980% greater than that of control soil conditions.

The results of this study highlight the importance of both the soils physical and chemical properties and those of the biochar and shows that full-scale faecal sludge pyrolysis in developing nations is a credible technology for treating human waste. The benefits are numerous, the removal of disease-causing pathogens from sludge and the concurrent creation of biochar, which has been shown to enhance crop productivity. The potential of faecal sludge biochar to improve acidic, low CEC, water constrained soils and crop yield in developing nations more at risk of water scarcity and food insecurity is huge. It is crucial that the appropriate soil must be chosen in conjunction with faecal sludge biochar amendment to enable largescale use of faecal sludge biochars in the future.

It is possible that the liming effect from faecal sludge biochar could be short-lived so longer-term field studies using acidic soil are needed to assess the duration of the reported positive effects of faecal sludge biochar addition.

6 THE EFFECT OF BIOCHAR ON THE GROWTH AND FRUIT YIELD OF TOMATO (*SOLANUM LYCOPERSICUM L.*) CULTIVAR MICRO-TOM UNDER CONTINUOUS LIGHT

Chapter Overview

High-tech industrial greenhouses could play a vital role in achieving sustainable food production and food security as they offer the ability to control key environmental conditions such as lighting. Supplemental (LED) lighting increases plant growth and has been widely used to increase yield of greenhouse vegetables resulting in more energy-efficient crop production. Continuous light (up to 24 hours of supplemental light) also has the potential to increase crop yield in greenhouse production, however tomato plants exposed to continuous light develop inter-vascular chlorosis, a leaf injury which leads to a reduction in leaf chlorophyll content and necrosis. In this study the effect of faecal sludge biochar on Micro-Tom, a dwarf cultivar of tomato (*Solanum lycopersicum* L.) grown under continuous light and constant temperature conditions were investigated. A pot experiment was conducted to measure the growth, yield, and water runoff from Micro-Tom tomatoes using three different treatments, an acidic control soil, biochar (4% w/w), and a combined fertilizer (2% w/w) and biochar (2% w/w) treatment. Faecal sludge biochar at 4%w/w significantly increased plant height, tomato yield and above ground biomass compared to control, however biochar addition resulted in greater leaf injury compared to the biochar and fertilizer treatment. The combined biochar and fertilizer treatment produced a significant increase in number of leaves, and above ground biomass compared with the biochar treatment and showed less visual evidence of continuous light induced leaf injury and necrosis.

6.1 INTRODUCTION

In **Chapter 5** there were study limitations in terms of controlling light and temperature conditions due to conducting the experiment in an outdoor greenhouse environment which was necessitated by Covid-19 lockdown restrictions. With covid restrictions relaxed, access to controlled environment laboratories became available. Therefore, it became possible to repeat the tomato growth experiments conducted in **Chapter 5** in a controlled laboratory environment. However, the laboratory environmental controls malfunctioned, resulting in the tomato plants being exposed to continuous lighting and constant temperature for the first 3 months of the study. This significantly altered the scope of the study and the results reported in this chapter reflect the effect of continuous lighting on tomato plants under biochar and fertilizer treatment regimes.

High-tech greenhouses offer the ability to control key environmental conditions such as temperature, humidity, and lighting (La Notte et al., 2020). Globally greenhouse energy usage, especially in higher latitudes is rising due to wider and more intensive use of heating and supplemental lighting (Hemming et al., 2019). Supplemental lighting is used either for daylength control, to regulate plant developmental mechanisms such as flowering (Katzin et al., 2021) or as assimilation lighting to compensate for a lack of natural light intensity that impedes crop growth (La Notte et al., 2020). Supplemental lighting has been widely used to increase the growth and yield of greenhouse vegetables (Demers & Gosselin, 1991; Hurd & Thornley, 1974; Logendra et al., 1990; McAvoy & Janes, 1984).

Continuous light is photoperiods of up to 24 hours of supplemental light and has the potential to increase plant growth and fruit yield in greenhouse production (Shao et al., 2022; Velez-Ramirez et al., 2011). Tomato plants exposed to continuous light stress develop inter-vascular chlorosis (Hillman, 1956), a leaf injury indicated by yellowing spots and a mottled appearance of the leaf which eventually leads to a reduction in leaf chlorophyll content and necrosis (Arthur et al., 1930; Demers et al., 1998a; Hillman, 1956; Logendra et al., 1990). Despite being first discovered in the 1920s (Arthur et al., 1930), the mechanisms of chlorosis from exposure to continuous lighting is still not fully understood. Several theories exist including an accumulation of carbohydrates in the leaves (Demers et al., 1998a; Dorais et al., 1996; Velez-Ramirez et al., 2011), photooxidative damage to the leaf pigments (Murage & Masuda, 1997), phytochrome signaling (Velez-Ramirez et al., 2019), and unbalanced excitation in photosystem I (PSI) and photosystem II (PSII) (Velez-Ramirez et al., 2014a).

Continuous light is a form of stress and plants exposed to various types of abiotic stress such as drought stress, salt stress, high temperature stress, and heavy metal toxicity have been shown to benefit from biochar addition (Abbas et al., 2017; Akhtar et al., 2014; Artiola et al., 2012; Batool et al., 2015; Fahad et al., 2015; Kamran et al., 2020; Kul et al., 2021; J. Sun et al., 2016). To date there has been no research conducted to study the effect of biochar addition on tomato plants grown under continuous light stress.

Plants exposed to oxidative stress produce a reactive oxygen species (ROS) (Abbasi et al., 2015; Miller et al., 2010). Biochar has enhanced the defence system in plants under drought stress by modifying the ROS scavenging enzymes (Mansoor et al., 2021) and under salt stress the application of biochar, markedly reduced ROS in the plants (Farhangi-Abriz & Torabian, 2018). In plants the detoxification of stress-induced ROS is regulated by antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT) and peroxidase (POD) (Mittler et al., 2004). In bean seedlings under salt stress conditions, biochar addition has reduced SOD compared to non-biochar treatment (Farhangi-Abriz & Torabian, 2017) and Ibrahim et al., (2019) reported that biochar significantly reduced CAT activities in lettuce (*Lactuca sativa* L.) plants grown in metal-contaminated soils. Biochar treatment has also been shown to reduce cadmium phytotoxicity, enhance wheat growth and increase POD activity under drought stress (Abbas et al., 2018).

Understanding the biological mechanisms behind leaf injury caused by continuous light stress is of paramount importance. This significance arises from the fact that cultivating plants under a 24-hour photoperiod, with a relatively low photon flux density, is an effective approach for conserving resources and enhancing plant productivity within high-tech greenhouses and plant factories employing artificial lighting.

The results reported in this chapter are focused on the effect of faecal sludge biochar on Micro-Tom cultivar grown under continuous light conditions. The parameters measured include soil properties, plant height, water run-off, tomato yield, and above and below ground biomass.

6.2 RESULTS

6.2.1 Plant growth responses

6.2.1.1 Plant height and leaf number

The plant heights in all treatments were measured starting from Day 34 to Day 155. There were significant differences in medians between the control treatment and the biochar treatment and between the control and combined biochar and fertilizer treatments (Fig 6.1)

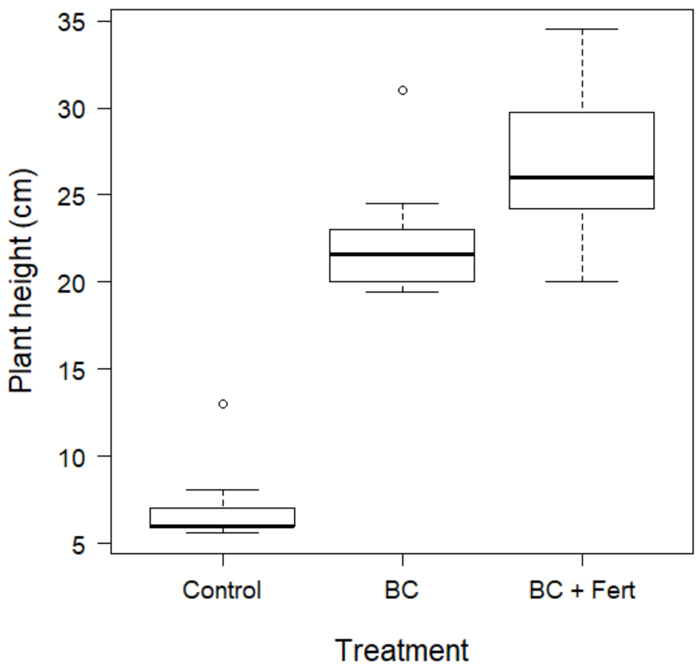

Figure 6.1 *Plant height (cm) measured at harvest for each treatment, Control (control), BC (biochar), BC+Fert (biochar and fertilizer). Box plots show minimum, first quartile, median (the horizontal solid line in the box), third quartile, and maximum. Open circle symbols indicate outliers.*

The biochar and fertilizer treatment showed the highest median plant height (26.0 cm), followed by the biochar treatment (21.6 cm), and the control (6.0 cm).

Statistical analysis shows that significant differences ($p<0.05$) between groups were found between the combined biochar and fertilizer treatment and the control and also between the biochar and the control treatment (Table 6.1).

Plant heights of the combined biochar and fertilizer treatment and the biochar treatment were not significantly different however combined biochar and fertilizer treatment did record greater plant heights. Plant heights of these two treatments displayed similar patterns of growth, showing classic asymptote patterns of growth. It was observed that 74 days after planting the plant height in the combined biochar and fertilizer treatment increased at a greater rate compared to biochar alone (Fig.6.2). The growth of the plants in the control group stopped around day 50.

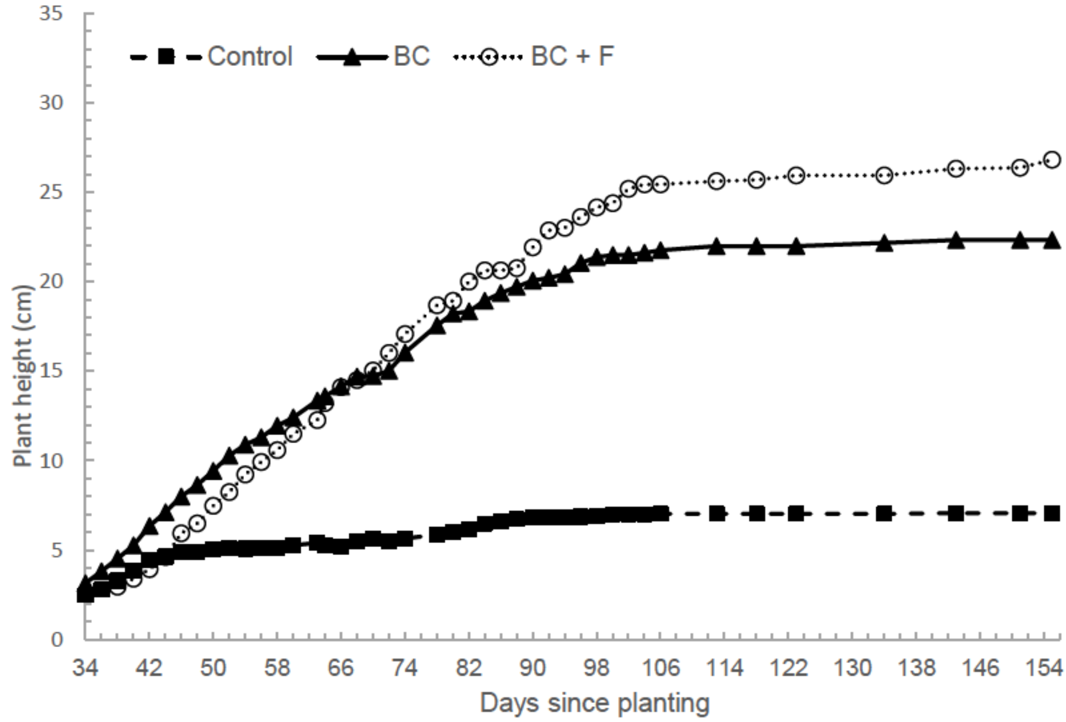

Figure 6.2 *Plant height measured approximately every two days from day 34 to day 155 for each treatment – Control (Control), biochar (BC), and combined biochar and fertilizer (BC + Fert).*

The analysis of the sub-treatments showed only marginal differences in plant heights between biochars types. The results (Supplementary Figure 21) revealed that WAI biochar and fertilizer (WAIF) recorded the optimum plant height performance compared to all other sub-treatments with a mean of 31.2 cm (± 4.5). There was very little difference in plant heights between WGL biochar (WGL) and WGL biochar and fertilizer (WGLF), and between NSP biochar (NSP) and NSP biochar and fertilizer (NSPF). However, there was a large difference between WAI biochar and fertilizer (WAIF) 31.2 cm ±4.5 and WAI biochar 21.2 cm ± 1.1 (Supplementary Figure 21).

There is a very marked significant increase in the median number of leaves with combined biochar and fertilizer addition (88.5) compared to biochar addition (17.0) and the control (11) (Fig.6.3). There was not a significant increase in leaf number in the biochar amended plants compared to the control treatment (Table 6.1).

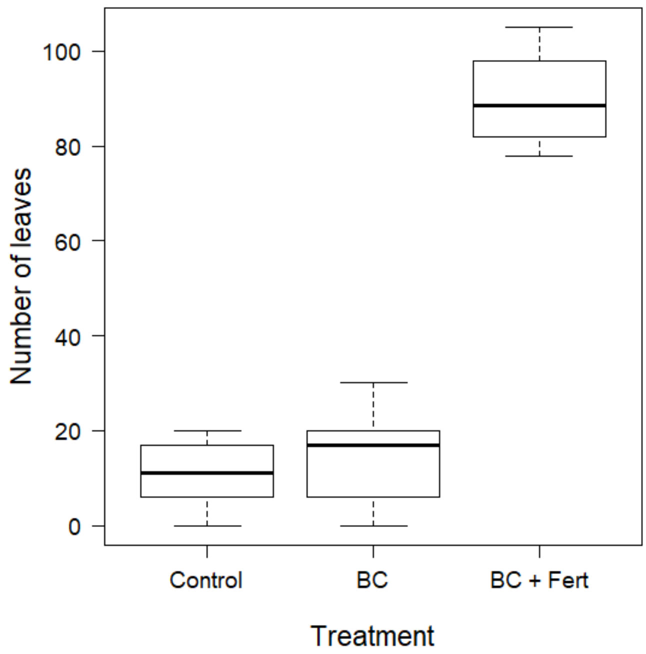

Figure 6.3 *Number of leaves for each treatment, Control (control), BC (biochar), BC+Fert (biochar and fertilizer). Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum.*

Table 6.1 *Significant difference indicated by p values between pairs of treatments for all plant growth parameters measured – plant height, number of leaves, fresh and dried above and below ground biomass. (Significant difference at p<0.05 indicated by *).*

Plant parameters	Pairwise treatment comparison p values		
	Biochar + Fertilizer *compared to* **Biochar**	**Control** *compared to* **Biochar**	**Biochar + Fertilizer** *compared to* **Control**
Plant height	0.13	0.006*	0.00005*
Number of leaves	0.003*	0.44	0.0003*
Fresh above ground biomass	0.022*	0.029*	0.00002*
Dried above ground biomass	0.065	0.01*	0.00002*
Fresh below ground biomass	0.005*	0.23	0.0001*
Dried below ground biomass	0.06	0.10	0.0009*

6.2.1.2 *Above ground biomass*

The median above ground biomass for the combined biochar + fertilizer (BC + Fert) treatment (15.76 g) was significantly greater than the biochar (BC) treatment (1.28 g) and the control (Cont) (0.14 g) (Table 6.1). The above ground biomass for the biochar treatment was also significantly greater than the control treatment ($p<0.05$).

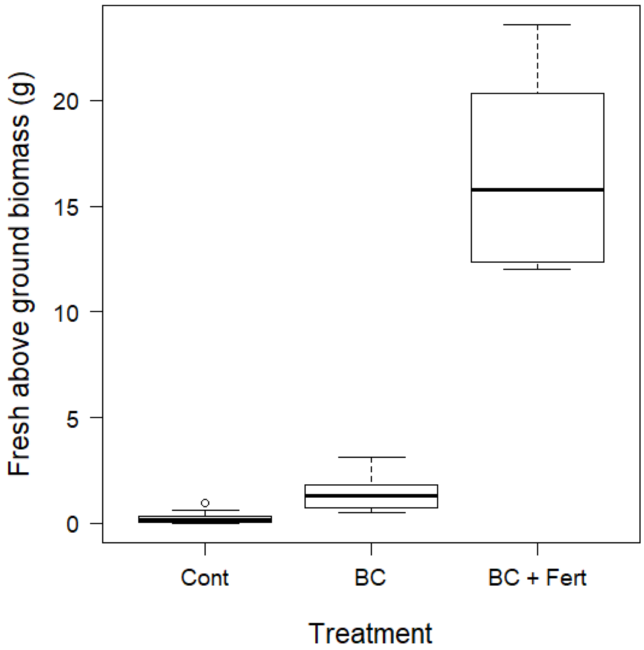

Figure 6.4 *Fresh above ground biomass (g) measured at harvest for each treatment, Cont (control), BC (biochar), BC+Fert (biochar and fertilizer). Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum. Open circle symbols indicate outliers.*

The difference in above ground biomass compared to tomato yield or plant height is far more marked between the combined biochar and fertilizer treatment and the biochar treatment (Fig.6.4).

A similar pattern emerged with dried above ground biomass (Supplementary Figure 26). There is a significant difference ($p<0.05$) between above ground biomass for the combined biochar and fertilizer (BC+Fert) treatment and the control (Cont) and the biochar (BC) treatments. The above ground biomass for biochar treated plants was only marginally higher than that of the control. This corresponds with the visual observation of significant leaf loss in the biochar treated plants.

In relation to the difference between sub-groups the combined Narsapur biochar and fertilizer sub-group (NSPF) generated the greatest above ground biomass (18.0 g ±7.9) followed by the Warangal biochar and fertilizer (WGLF) sub-group (16.5 g ± 4.6) then the Wai biochar and fertilizer (WAIF) sub-group (15.7 g ± 3.6) (Supplementary Figure 22).

6.2.1.3 Below ground biomass

Similar to above ground biomass, the combined biochar and fertilizer (BC + Fert) treatment significantly increased the median below ground biomass (0.55 g) compared to the biochar (BC) treatment (0.14 g) and the control (Cont) treatment (0.08 g) (Fig 6.5)

There was no significant difference between the biochar and the control treatment in below ground biomass indicating little difference in extent of root systems with the addition of biochar compared to the control group (Table 6.1).

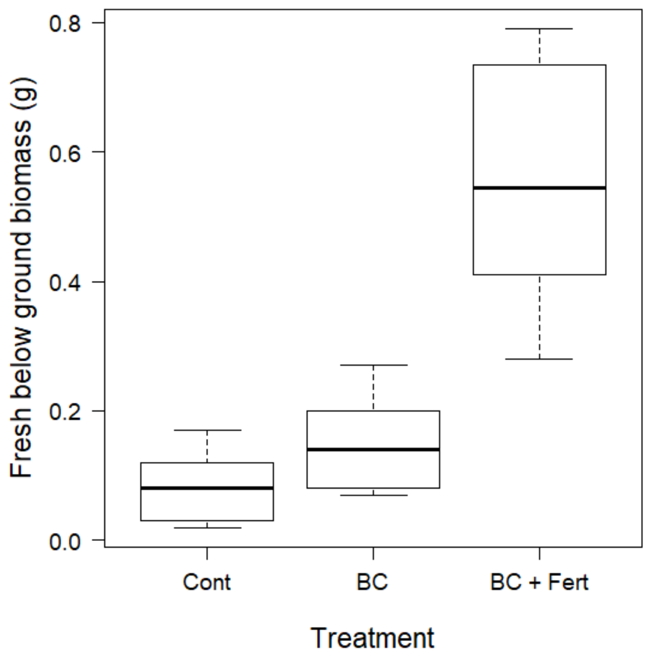

Figure 6.5 *Fresh below ground biomass (g) measured at harvest for each treatment, Cont (control), BC (biochar), BC+Fert (biochar and fertilizer). Box plots show minimum, first quartile, median (the solid horizontal line in the box), third quartile, and maximum. Open circle symbols indicate outliers.*

In the sub-groups the combined NSP biochar and fertilizer sub-group (NSPF) produced the greatest below ground biomass (0.7 g ±0.1) followed by the WAI biochar and fertilizer (WAIF) sub-group (0.6 g ±0.1) and then the WGL biochar and fertilizer (WGLF) subgroup (0.4 g ±0.1) (Supplementary Figure 23).

6.2.2 *Fruit production*

6.2.2.1 Number of flowers

Flowers were counted 75 days after planting (approximately halfway through the experiment). The combined biochar and fertilizer treatment (BC+Fert) produced significantly ($p<0.05$) more median flowers (59.5) than the control (<0.00) and the biochar treatments (17.0) and the biochar treatment produced significantly more flowers than the control treatment (Table 6.2 and Fig. 6.6). In the sub-groups Wai biochar and fertilizer (WAIF) produced a mean number of flowers of 60.3 ± (9.6) compared to Wai biochar (WAI) at 16.7 ± 0.6.

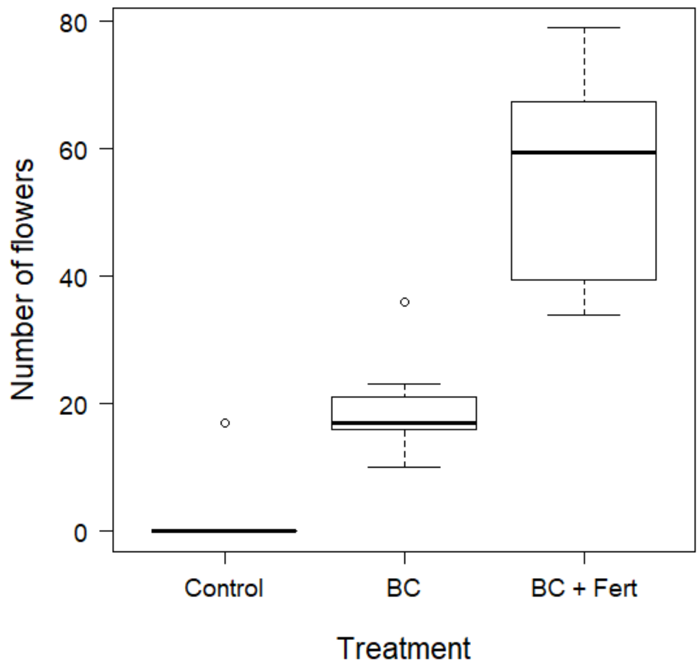

Figure 6.6 *Number of flowers counted at 75 days for each treatment, Control (control), BC (biochar), BC+Fert (biochar and fertilizer). Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum. Open circle symbols indicate outliers.*

6.2.2.2 Fresh fruit weight

There were significant differences in median fresh fruit weights between the control (<0.01 g) and the biochar treatments (6.76 g) and between the control and combined biochar and fertilizer treatment (14.07 g) (Table 6.2). Biochar and fertilizer treatments show a very large range of tomato yields ranging from 5.8 g - 30.8 g (Fig.6.7). There were significant differences in median dried yield between the biochar treatment (0.70 g) and the combined biochar and fertilizer treatment (1.80 g) (Table 6.2 and Supplementary Figure 28)

Table 6.2 *Significant difference indicated by p values between pairs of treatments for all fruit production parameters measured – plant height, number of leaves, fresh and dried above and below ground biomass. (Significant difference at p<0.05 indicated by *).*

Fruit production parameters	Pairwise treatment comparison p values		
	Biochar + Fertilizer *compared to* **Biochar**	**Control** *compared to* **Biochar**	**Biochar + Fertilizer** *compared to* **Control**
Number of flowers	0.026*	0.021*	0.00001*
Fresh fruit yield	0.063	0.009*	0.00002*
Dried fruit yield	0.021*	0.018	0.00001*

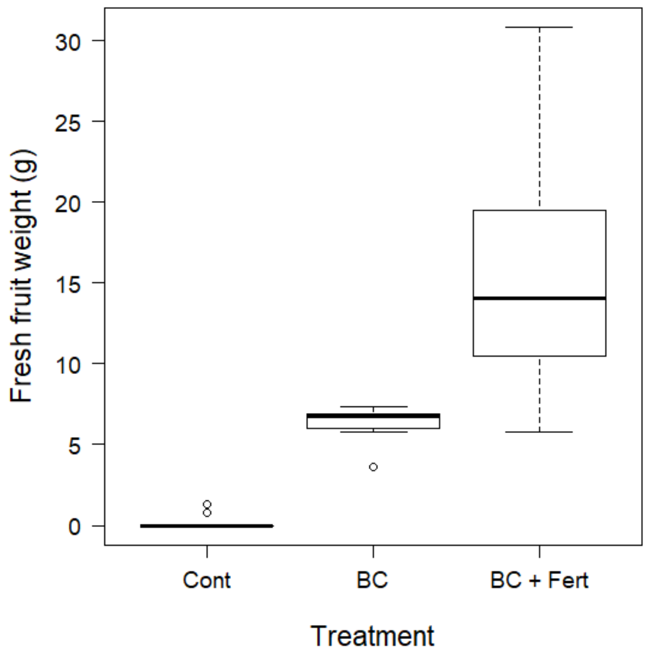

Figure 6.7 *Fresh fruit weight for each treatment, Cont (control), BC (biochar), BC+Fert (biochar and fertilizer). Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum. Open circle symbols indicate outliers.*

The greatest mean yields were harvested from the combined biochar and fertilizer treatments, in particular the NSP biochar and fertilizer sub-group (NSPF) produced a tomato yield of (24.7 g) followed by the sub-groups WAI biochar and fertilizer (WAIF) (13.7 g) and WGL biochar and fertilizer (WGLF) (11.4 g). The control treatment produced the lowest yield (0.23 g) (Fig 6.7). The application of biochar increased tomato yield, however the application of biochar and fertilizer showed the biggest increase in yields.

There is very little difference in means between the three biochars themselves WGL, NSP and WAI (Supplementary Figure 24). The biochar and fertilizer treatments revealed the biggest standard deviations. This is due to partly due to the NSP biochar and fertilizer (NSPF) treatment containing only two plants as one plant perished early in the study. One possible explanation for this is that the plant suffered injury during the transplanting process.

6.2.3 Soil properties

6.2.3.1 pH

There were significant differences in pH between every treatment (Table 6.3). The biochar (BC) treatment recorded the highest median pH value (6.10) followed by the combined biochar and fertilizer (BC + Fert) treatment (5.34) and finally the control (Cont) treatment recorded the lowest pH at 4.87 (Fig.6.8).

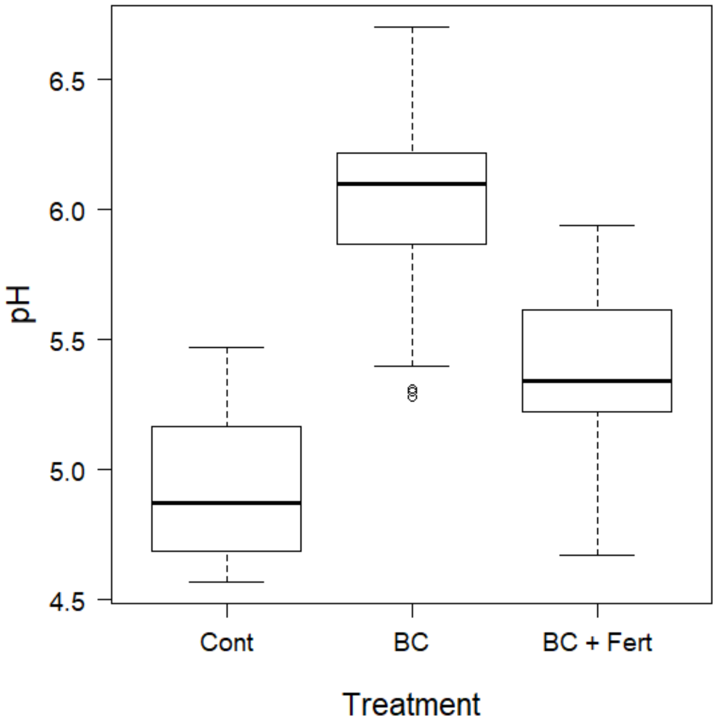

Figure 6.8 *Soil pH measured at harvest for each treatment, Cont (control), BC (biochar), BC+Fert (biochar and fertilizer). Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum. Open circle symbols indicate outliers.*

Soil amended with WGL biochar (WGL) showed the highest mean pH value at (6.3) followed by WAI biochar (6.0) and NSP biochar (5.7) indicating that biochar on its own at 4% has a more marked liming effect than the combined biochar (2% w/w) and fertilizer (2% w/w) treatment.

Table 6.3 *Significant difference indicated by p values between pairs of treatments for all soil properties measured – pH, electrical conductivity (EC) and water runoff. (Significant difference at p<0.05 indicated by *).*

Soil properties	Pairwise treatment comparison p values		
	Biochar + Fertilizer *compared to* **Biochar**	**Control** *compared to* **Biochar**	**Biochar + Fertilizer** *compared to* **Control**
pH	0.0002*	3.5×10^{-11}*	0.003*
EC	0.39	0.000001*	0.0002*
Water runoff	0.00002*	0.00001*	$<1 \times 10^{-12}$*

6.2.3.2 EC

Both the biochar (BC) treatment (66.5 $mScm^{-1}$) and the combined biochar and fertilizer (BC + Fert) treatment (63.15 $mScm^{-1}$) recorded significantly greater median electrical conductivity values than the control (Cont) treatment (0.20 $mScm^{-1}$) (Fig.6.9).

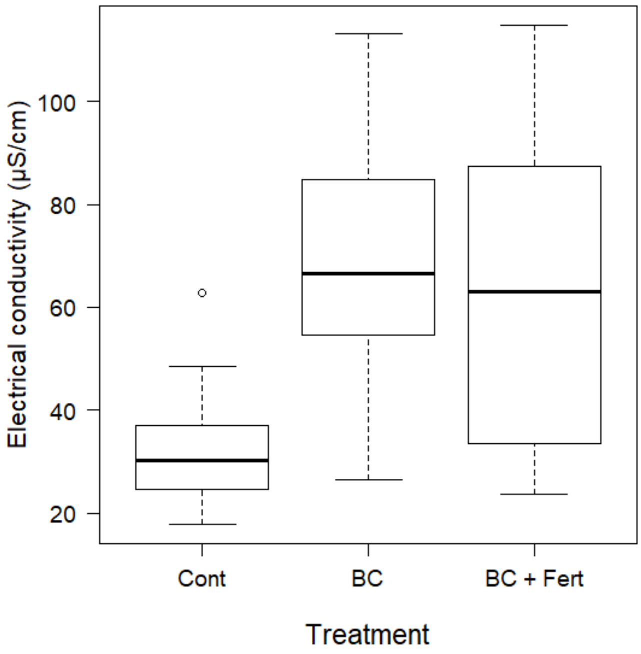

Figure 6.9 *Soil electrical conductivity measured at harvest for each treatment, Cont (control), BC (biochar), BC+Fert (biochar and fertilizer). Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum. Open circle symbols indicate outliers.*

However, soil electrical conductivity of biochar (BC) and combined biochar and fertilizer treatment (BC+Fert) showed a different trend to that of the soil pH measurements. Soil pH was significantly higher in the biochar treatment than the combined biochar and fertilizer treatment whereas there was no significant difference in soil electrical conductivity between these two treatments. The similar soil electrical conductivity values indicate that both treatments (biochar (4% w/w) and combined biochar (2% w/w) and fertilizer (2% w/w)) contribute similar amounts of soluble salts to the soil.

It was noted that there was high standard deviation for the soil electrical conductivity values in the biochar containing treatments   No reason could be found as to why there was such a large difference in electrical conductivity values between the replicates in these treatments.

6.2.3.3 Water runoff

Water runoff for all treatments was measured starting from Day 25 to Day 106 after seed planting. The results revealed the impact of biochar on measured water runoff as the biochar treatment (BC) showed a significantly lower median water runoff total (687 ml) compared to the control (Cont) treatment (1257 ml) (Fig 6.10). The combined biochar and fertilizer (BC + Fert) treatment conditions had the lowest water runoff (306 ml) out of all the treatments with a significant decrease in water runoff compared to both the control (Cont) and the biochar (BC) treatments (Table 6.3.)

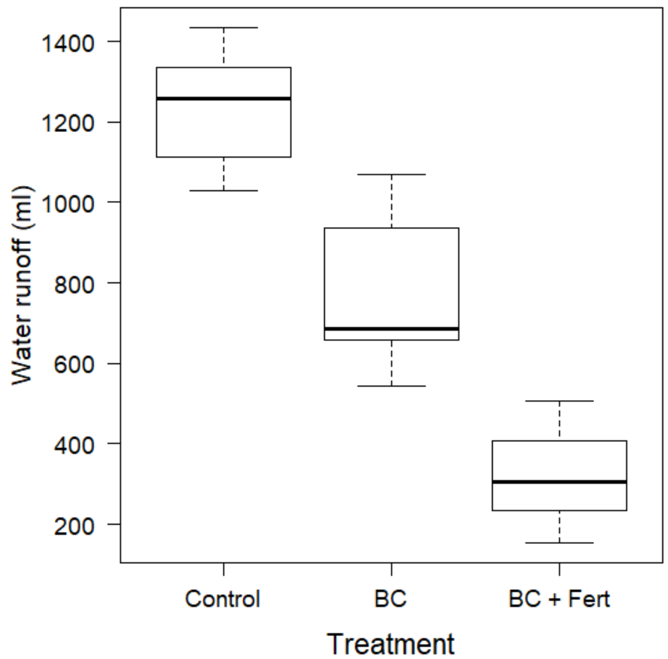

Figure 6.10 Total water runoff measured at harvest for each treatment, Control (control), BC (biochar), BC+Fert (biochar and fertilizer). Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum.

6.2.4 Visual evidence of CL-induced chlorosis

Photographic images of the Micro-Tom tomato plants were taken for the duration of the study (Fig 6.11 and Fig 6.12). This allowed visual monitoring of the approximate number of leaves, extent of leaf injury and growth.

Figure 6.11 *Visual comparison of above ground biomass between (left-to right) control treatment, the WGL biochar subgroup treatment and WGL biochar sub-group with fertilizer treatment 31 days after continuous light.*

Figure 6.12 *Top row - left to right, WAI biochar treatment subgroup, NSP biochar treatment subgroup and WGL biochar treatment subgroup. Bottom row WAI biochar and fertilizer treatment, NSP biochar and fertilizer treatment and WGL biochar and fertilizer treatment.*

6.3 DISCUSSION

The results show that the application of faecal sludge biochars to tomato plants grown in continuous light promoted plant growth and fruit yield compared to acidic, low nutrient soil. However, biochar addition alone caused severe continuous-light injury to the leaves. In contrast, biochar and fertilizer treatment showed much less CL-induced leaf injury along with increased plant growth, fruit yield and above and below ground biomass.

6.3.1 Implications for soil properties

Water runoff was significantly lower for the combined biochar and fertilizer treated plants compared to the control (Fig.5.15), a similar finding to results reported in Chapter 5 (H. L. Nicholas et al., 2023) and in other studies (Beck et al., 2011; Sadeghi et al., 2016). The water runoff for the combined biochar and fertilizer treated plants was significantly lower than the biochar amended plants despite having less biochar (2% w/w compared to 4% w/w). This could be due to the significant difference in fresh below and above ground biomass between the biochar and fertilizer treated plants and the biochar treated plants. The greater biomass of the biochar and fertilizer treated plants indicates these plants required a greater volume of water and therefore the water runoff volume was greatly reduced.

Soil electrical conductivity of biochar (BC) and combined biochar and fertilizer treatment (BC+Fert) showed a different trend to that of the soil pH measurements. Soil pH was significantly higher in the biochar treatment than the combined biochar and fertilizer treatment whereas there was no significant difference in soil electrical conductivity between these two treatments. The similar soil electrical conductivity values indicate that both treatments (biochar (4% w/w) and combined biochar (2% w/w) and fertilizer (2% w/w)) contribute similar amounts of soluble salts to the soil and that these highly soluble nutrients that contribute to electrical conductivity values were taken up by the tomato plants (Glaser et al., 2015).

It was noted that there was high standard deviation for the soil electrical conductivity values in the biochar containing treatments   No reason could be found as to why there was such a large difference in electrical conductivity values between the replicates in these treatments.

The biochar amended soil recorded the highest median pH value of 6.10 compared to the control soil with a mean pH of 4.87 (Fig.5.13). Biochar addition is thought to increase plant growth largely due to the liming effect (Jeffery et al., 2011). Thus, the significant increase of plant growth in biochar amended soils compared to control is in part due to the liming effect of the biochar. A meta-analysis showed that the highest yield increase upon biochar application was observed in very acidic soils (pH $\leq$5) (Bai et al., 2022). Biochar treatment elevated the pH to significantly higher levels than the combined biochar and fertilizer treatment (Fig.5.13). These high pH values should point to an increased growth compared to combined biochar and fertilizer treatment – but this is not the case. Interestingly the height of biochar treated Micro-Tom plants were greater than the combined biochar and fertilizer treated plants until approximately day 70. After day 70 the combined biochar and fertilizer treated plants showed an increased growth rate. The extent of continuous light induced leaf injury was visually noticeable in the biochar treatment group after 45 days, after 98 days, leaf necrosis was visually more marked than the combined biochar and fertilizer treatment group (Supplementary Figures 25 and 1). The injury and eventual death of the leaves in the biochar treatment group likely hindered the plants' photosynthetic ability resulting in a reduction in growth rate after 70 days, in fact the downregulation of photosynthesis due to continuous light has been observed in several studies (Demers et al., 1998b; Globig et al., 1997; Matsuda et al., 2014; Velez-Ramirez et al., 2014b). Thus, at the end of the experiment there was no significant difference in plant height between the biochar (BC) treatment and the combined biochar and fertilizer (BC + Fert) treatment despite recording significantly different soil pH values (Table 5.3).

6.3.2 Implications for plant growth and crop yield

There were no significant differences in plant height, between the combined biochar and fertilizer treatment and the biochar treatment. The previous study (**Chapter 5** – (Nicholas et al., 2023)) under natural light conditions produced Micro-tom tomato plants with mean height 7.3 cm in the control treatment and only 10.6 cm in the biochar treatment. In this study under continuous light conditions the control treatment plants grew to a mean height of approximately 7 cm (similar to the results in Chapter 5) however, the biochar amended Micro-Tom plants produced significantly greater plant growth (mean plant height 22.3 cm). Micro-Tom tomatoes are a dwarf variety and are only expected to grow to 10 – 13 cm. This suggests that continuous light had a significant impact on the biochar and biochar + fertilizer amended Micro-tom plants and caused these plants to almost double in height. This is in contrast to work by Demers et al. (1998b) that found that the total growth of tomato plants grown under continuous light were lower than plants exposed to a 14 h photoperiod. In the same study it was observed that, for the first 5 to 7 weeks of treatments, tomato plants grown under continuous light had better growth than plants receiving the 14 h photoperiod and the growth rate decreased during the second half of the experiment (Demers et al., 1998b). In this study the growth rate of plants in the combined biochar and fertilizer treatment group did not decrease until day 102 (Fig 6.2), a much longer timeframe than that observed by Demers et al. (1998b).

In terms of fruit production, biochar and combined biochar and fertilizer treatments significantly outperformed the control group, a finding concurrent with that of the previous outdoor greenhouse experiment (**Chapter 5**). Another finding similar to that reported in Chapter 5 is that the combined biochar and fertilizer treatment produced an increase in the number of flowers and a significant increase in dried tomato yield compared to biochar. It has been reported that fruit yield reductions caused by exposure to continuous light are linked with decreases in leaf photosynthetic rate, chlorophyll content and the activity of sucrose phosphate synthase (Matsuda et al., 2014). Therefore, the reduced yield seen in the tomato plants amended with biochar could be due to the greater CL-induced leaf injury observed in these plants compared to those in the combined biochar and fertilizer group.

The number of leaves and above ground biomass are both properties that can be affected by continuous light stress. The combined fertilizer and biochar treatment produced a significant increase in both the number of leaves and above ground biomass compared with biochar treatment (Fig. 6.3). Whereas biochar on its own did not significantly increase the number of leaves or above ground biomass compared to control (Fig. 6.3). This along with visual evidence, suggests that the biochar treatment compared to the combined biochar and fertilizer treatment resulted in significant CL-induced leaf injury and necrosis. Control treatment plants produced less leaves and lower plant growth due to the poor - quality soil rather than continuous light stress as evidenced by the significantly lower plant height and fruit yield (**Chapter 5**). The number of leaves produced by the control and the biochar treatments were not significantly different (Table. 6.1), despite biochar amended plants outperforming the control group in other parameters such as plant height (Table. 6.1).

6.3.3 Continuous - light leaf injury

The mechanism behind leaf injury and necrosis in certain plants exposed to continuous light stress is still not fully understood despite the phenomenon being first observed 100 years ago (Arthur et al., 1930; Demers et al., 1998a; Hillman, 1956; Logendra et al., 1990). Most research to date has concentrated on investigating the effect of spectral light distributions and temperature on alleviating CL-induced leaf chlorosis and epinasty. Pham et al. (2019) showed that red and blue light at ratios of 3:1 and 1:1 alleviated leaf chlorosis and epinasty in tomato plants, and daily temperature variations reduced leaf chlorosis in tomato plants grown under continuous light (Haque et al., 2017). Soil treatments, such as biochar addition have not been investigated as a method to reduce CL-induced leaf chlorosis in tomato plants despite biochar treatment benefitting plants under various other forms of stress (Abbas et al., 2017; Akhtar et al., 2014; Artiola et al., 2012; Batool et al., 2015; Fahad et al., 2015; Kamran et al., 2020; Kul et al., 2021; J. Sun et al., 2016).

The significantly lower number of leaves for biochar treated plants compared to the biochar and fertilizer amended plants indicates leaf injury and death is occurring due to the effect of the 24-hour photoperiod.

Murage et al. (1997) showed that photooxidative damage to leaf pigments seen under continuous lighting is evidenced by leaf chlorosis and a synchronized increase in antioxidant enzymes superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT). The increase in these enzymes is a response to reactive oxygen species (ROS) such as the superoxide anion (O_2^-) and hydrogen peroxide (H_2O_2). Biochar amendment has been shown to significantly decrease antioxidant enzymes SOD, CAT and POD activities in tomato under salt stress (*Solanum lycopersicum*) (Kul et al., 2021), and in safflower (*Carthamus tinctorius* L.), and under fluoride toxicity stress (Ghassemi-Golezani & Farhangi-Abriz, 2019). However, under salt stress, improvement in plant performance upon biochar application is due to an increase in soil porosity and a reduction in bulk density, thus reducing the stress experienced by plants resulting in a decrease in SOD, CAT and POD activities (Kul et al., 2021). Similarly, under fluoride stress biochar addition reduced the negative effects of fluoride toxicity by increasing soil pH and cation exchange capacity and decreasing the solubility of fluoride in the soil (Ghassemi-Golezani & Farhangi-Abriz, 2019). Under salt stress, biochar addition reduced the content of the plant stress hormones (abscisic acid (ABA), 1-aminocyclopropane-1-carboxylic acid (ACC), jasmonic acid (JA), and salicylic acid (SA) in common bean seedlings (Farhangi-Abriz & Torabian, 2018). Conversely, biochar addition increased the phytohormone indole-3-acetic acid (IAA) that regulates plant growth. A comprehensive study of over 1000 genes in biochar treated *Arabidopsis thaliana* and lettuce (*Lactuca sativa* L.) plants showed up-regulation in genes central for the promotion of growth seen in biochar addition (auxin and brassinosteroid). Crucially, down-regulation in genes related to plant immunity and defence (jasmonic and salicylic acid biosynthetic pathways) was also discovered with biochar addition (Viger et al., 2015). Tartaglia et al. (2020) also demonstrated a similar response to San Marzano tomato plants treated with biochar with a down-regulation of defence genes and up-regulation of a repressor gene of the JA signalling pathway.

The increased biomass and reduction in CL-induced leaf necrosis in combined biochar and fertilizer treatment is possibly due to an increase in nutrients provided by the fertilizer. Previous work has shown an increase in fertilization has reduced the leaf injury and increased yield in mini cucumber plants (Hao et al., 2012), however, Demers et al. (1998) concluded that leaf chloroses in tomato plants under continuous light were not associated with mineral nutrition problems. The mechanisms behind the role of light in nutrient absorption and assimilation remains poorly understood (J. Xu et al., 2021) and separating the effects of biochar and fertilizer addition on acidic soil properties and the effect of both these treatments on plants under continuous light and constant temperature conditions is complex.

6.4 STUDY LIMITATIONS

This study encountered several notable limitations that impacted the integrity and interpretability of the experiment:

1. Excessive Solid Fertilizer Usage:

At the outset of the experiment, an unintended overapplication of solid fertilizer occurred, leading to the death of all tomato plants within the fertilizer-only treatment group. Conversely, the tomato plants in the biochar and fertilizer treatment group survived, benefiting from a reduced fertilizer application rate, constituting 50% of that used in the fertilizer-only treatment group.

2. Control Lab Malfunction:

A significant limitation emerged due to a malfunction in the controlled laboratory environment, which subjected the tomato plants to an uninterrupted period of three months of continuous light exposure and constant temperature. This unforeseen circumstance rendered a drought stress experiment obselete, as an excess of confounding variables prevented any meaningful conclusions regarding the influence of biochar treatment on tomato plants under drought stress conditions.

3. Altered Experimental Design:

Originally, the experiment was designed to include distinct treatment groups, such as biochar-only treatment with a 4.2% w/w biochar concentration, fertilizer-only treatment with 4.2% w/w fertilizer, and combined biochar and fertilizer treatment groups at a 2.1% w/w biochar and 2.1% w/w fertilizer ratio. The latter, with its 50/50% ratio of biochar and fertilizer, aimed to investigate the potential of biochar to reduce fertilizer requirements while maintaining crop yield. The unforeseen plant losses within the fertilizer-only treatment group precluded the possibility of making this critical comparison. Additionally, time constraints exacerbated by the global COVID-19 pandemic prevented the restarting of the entire experiment with a reduction in fertilizer in the fertilizer only treatment groups.

These limitations are important to acknowledge as they underscore the challenges encountered during the experimental phase of the study. While they may have restricted the scope of the investigation, they offer insights into the effect of biochar on tomato plants grown under continuous light. Tomato plants exposed to continuous light develop a leaf injury indicated by yellowing spots and a mottled appearance which leads to a reduction in leaf chlorophyll content and necrosis (Arthur et al., 1930; Demers et al., 1998a; Hillman, 1956; Logendra et al., 1990). Although these observations were first made in the 1920s (Arthur et al., 1930), the mechanisms behind this continuous light induced leaf injury is still not fully understood. This is the first study to date showing evidence that biochar addition produces an increase in continuous light- induced leaf injury and necrosis in tomato plants.

6.5 CONCLUSION

Faecal sludge biochar treatment (4%w/w) significantly increased plant height, tomato yield and above ground biomass in Micro-tom tomato plants grown in acidic soil under continuous light and constant temperature. However, biochar addition (4%w/w) resulted in a significantly reduced number of leaves, and above ground biomass compared to the combined biochar (2% w/w) and fertilizer (2% w/w) treatment. These properties and visual evidence showed that biochar addition alone significantly enhanced continuous light--induced leaf injury and necrosis in Micro-tom tomato plants compared with the combined biochar (2% w/w) and fertilizer (2% w/w) treatment which alleviated CL-induced leaf chlorosis. It is possible that biochar addition results in an up-regulation of growth genes concurrent with a down-regulation in plant defence genes and pathways. However, further experimental work is needed to understand the mechanisms behind the variation in CL-induced leaf injury with different rates of biochar and fertilizer addition. Investigating the levels of growth and plant defence hormones in biochar treated tomato plants could help in finally understanding the mechanisms behind leaf chlorosis and necrosis caused by continuous lighting.

7 PUBLIC PERCEPTIONS ON FAECAL SLUDGE BIOCHAR AND BIOSOLIDS USE IN AGRICULTURE

Larissa Nicholas[1] Keith Hafacree[2] Ian Mabbett[1]

[1] Department of Chemistry, School of Engineering and Applied Science, Swansea University, Swansea, SA2 0PP, Wales, UK

[2] Geography Department, School of Science, Swansea University, Swansea, SA2 0PP, Wales, UK

Chapter Overview

Full-scale pyrolysis of faecal sludge in developing nations is a credible technology for the safe removal of pathogens from faecal sludge and the concurrent creation of biochar. There is huge potential for faecal sludge biochar to improve acidic, low nutrient, water constrained soils and crop yield in developing nations more at risk of climate change and food insecurity. However few research studies have been conducted into public acceptance of biochar as a soil enhancer in agriculture and specifically that of faecal sludge derived biochar. Unlike biochar, there have been numerous studies looking at the public's perception towards biosolids, but these studies focus on perceptions from farmers rather than the public. In this study of the public in Swansea, Wales, an online survey examines their awareness of, and comfort levels of eating food grown using biosolids, wood biochar and faecal sludge biochar. There was generally a positive attitude towards all three, albeit varying by gender and age most notably, but deployment of faecal sludge biochar must overcome a "disgust effect" related to its human faecal origins. This factor must be centrally considered when implementing management and policy decisions regarding the land application of biosolids and faecal sludge biochar in the future.

7.1 INTRODUCTION

Resource recovery and safe disposal of biological wastes is a major global environmental challenge, but one expressed differently in different parts of the world. Broadly speaking, in developing countries a lack of access to sewered water systems means that 4.5 billion people lack safely managed sanitation, relying on onsite sanitation facilities such as dry toilets, pit latrines or even open defecation, which is increasing in sub-Saharan Africa and Oceania (UNICEF & WHO, 2017).

Untreated sludge from pit latrines is often disposed of in the local environment, in the household compound (Jiménez et al., 2009a) or applied, untreated, as a fertilizer on agricultural land (Chandana & Rao, 2021). Such poor management of faecal sludge has led to negative public and environmental health outcomes, from eutrophication of surface water bodies to contamination of groundwater and soils (Gwenzi & Munondo, 2008), as well as poor social and economic development (Haller et al., 2007; Mara et al., 2010). Consequently, a more durable, economical, and sustainable approach is emerging to treat the sludge generated from onsite sanitation facilities(Strande et al., 2014a).

In developed nations, in contrast, sewage is carried though a waterborne system to a treatment plant, where it is processed via biochemical methods, such as anaerobic fermentation, or thermochemical methods, such as the addition of alkaline materials. The insoluble solid residue remaining after treatment is termed biosolids, or sewage sludge. As with faecal sludge, safe disposal of biosolids is an environmental challenge, the main methods being soil application, dumping at sea, landfilling and incineration (Sánchez-Monedero et al., 2004). Land application of biosolids aligns with the ethos of a circular economy, since nutrients and phosphorus from human waste are essential for continued global food security (Esrey et al., 2001). In 2009, there were around 20 million tonnes of municipal, commercial, and industrial organic wastes disposed in the UK alone (Thomas et al., 2009).

There are public health risks linked to biosolids, such as their pathogen and heavy metal content, even though it takes repeated applications to attain soil limit values. In the UK, maximum permissible concentrations of PTEs (Potentially Toxic Elements) in sewage sludge are given by Defra (Defra, 2018). In Europe, recent legislation (EU Directive 2018/851/EC) has resulted in a ban on landfilling and limited land application of sewage sludge, with the transition to a circular economy becoming a priority (European Parliament & European Council, 2018). Indeed, faecal sludge biochar and biosolids are waste products to be repurposed into resources as part of a circular economy, with the drive towards such an economy recently gaining momentum worldwide by nutrient and energy recovery (Drechsel et al., 2015a; Stahel, 2016). Biological wastes are now seen as a valuable source of phosphorus, a finite resource and an irreplaceable plant limiting nutrient (Steen, 1998). Almost 100% of fertilizer phosphorus is lost along the food chain, from farms to field to fork (Cordell et al., 2009), yet it is estimated that economically extractable mineral phosphorus will be scarce or even run out in approximately 50-100 years (Smil, 2000; Steen, 1998). Peak phosphorus may even occur as soon as 2030, so it is crucial we begin to recover it from waste for future global food security (Cordell et al., 2009).

Research over the last few years has focused on the drying and pyrolysis of faecal and sewage sludge to produce biochar, a nutrient-rich soil conditioner that can improve agricultural yields (Gaunt & Lehmann, 2008). It is a carbon-rich, charcoal-like product of the thermochemical process pyrolysis, which occurs at temperatures of 350-1000°C in the absence of oxygen (EBC, 2016). A major benefit of this process of dealing with faecal and sewage sludge is its elimination of harmful pathogens (Liu et al., 2014). Biochar differs from charcoal as its main use is as a soil amendment rather than fuel and it does not readily burn (Crombie et al., 2013). It's use to improve soil fertility and increase crop yield was inspired by *Terra Preta*, a dark, fertile soil of anthropogenic origin found in the Amazon basin, containing much higher nutrient levels and organic carbon than surrounding soils (Glaser et al., 2001).

Definitions

Sewage sludge: sludge generated during primary and secondary treatment of wastewater via sewer systems.

Biosolids: sewage sludge that has been treated at a centralized treatment plant and meets land application standards (NRC, 2002). Treatment is usually comprised of biochemical processes, such as anaerobic fermentation, or a thermochemical process, such as addition of alkaline materials.

Faecal sludge: sludge that has not been transported through a waterborne sewer system and originates from septic tanks, dry toilets and pit latrines.

FS (faecal sludge) biochar: a carbon-rich material produced from pyrolysis of dried faecal sludge which effectively destroys all its harmful pathogens.

In spite of clear present-day potential, very few research studies have been conducted to date into public acceptance of biochar as a soil enhancer in agriculture and of faecal sludge derived biochar specifically. Moreover, existing studies tend to focus on perceptions from farmers rather than the general public (Gwenzi et al., 2015b; Latawiec et al., 2017). Indeed, many of the public will not even have heard of biochar, let alone biochar produced from human biological waste. For example, a study published from 2017 even found that only 27% of Polish farmers surveyed were familiar with the term "biochar" (Latawiec et al., 2017).

With further reference to the importance of language, the term "biosolids" has increasingly been adopted after social science survey evidence suggested it elicited a more positive perception than the word "sludge" (Beecher, 2004; Powell, 1993). Unlike for biochar, there have been numerous studies looking at public perception of biosolids (Beecher et al., 2005; Mason-Renton & Luginaah, 2018; Naylor, 1997; Robinson et al., 2012). This is, in part, because biosolid land application relies on public acceptance of key issues around its health, safety and environmental impacts.

Whilst there are potentially many advantages to the reuse of human waste in agriculture, it is essential that socio-economic constraints such as negative perceptions and attitudes from the general public are addressed more fully than has been the case to date. Improving public understanding and knowledge of faecal sludge biochar and biosolids, and highlighting their benefits, will be crucial for future mass production of biochar and subsequent public acceptance. Reflecting this, the aim of the project from which the present chapter originates was to explore public attitudes towards faecal sludge biochar, wood biochar and biosolids land application with reference to differences in gender, age, residential area and issue awareness. A key objective was to collect information on public perceptions of exposure and risks towards consuming crops grown using faecal sludge biochar. Project results could help influence management and policy decisions regarding the reuse of biosolids and biochar as part of a sustainable resource strategy within a more circular economy.

This study was conducted, in part, due to covid lockdown restrictions in place at the time and with limited access to laboratories. An online survey provided an opportunity to collect data whilst still adhering to social distancing guidelines.

7.2 RESULTS

7.2.1 Profile of Respondents

Gender: 71% identified as female, 28% as male. This bias, which has often been noted for questionnaire responses (Curtin et al., 2000; Moore & Tarnai, 2002; Singer et al., 1999), was not ideal but at least 97 men were involved in the study.

Age: skewed slightly to the age 35-44 group (Table 7.1), with few in the 25-44 group. Other age groups were fairly evenly distributed. Overall, a good range of ages was covered. This lack of young adults was quite surprising as older individuals have often been found less likely to participate in questionnaires (Goyder, 1986; Kandel et al., 1983; Moore & Tarnai, 2002).

Table 7.1. *Profile of survey respondents including gender, age, residential location and frequency of organic food consumption.*

Profile of respondents		Number of respondents	Percentage of respondents
Gender	Female	249	71%
	Male	97	28%
Age group	18-24	20	5.7%
	25-34	54	15.5%
	35-44	94	26.9%
	45-54	59	16.9%
	55-64	56	16.0%
	65+	66	18.9%
Location	Rural	80	22.9%
	Suburban	121	34.7%
	Urban	148	42.4%
Frequency of organic food consumption	Every day	69	19.8%
	A few times a week	116	33.2%
	About once a week	30	8.6%
	A few times a month	36	10.3%
	Once a month	11	3.2%
	Less than once a month	44	12.6%
	Never	34	9.7%
	Other	9	2.3%

Location: the largest group lived in an urban area (Table 7.1), but suburban and rural locations were still well covered.

Organic food consumption: this was high amongst respondents, with 61.6% of respondents consuming organic food at least once a week (Table 7.1).

Carbon footprint: an overwhelming majority of participants (86.0%) stated that they "make an effort" to reduce their carbon footprint. Just 3.7% made no effort.
Both the high frequency of organic consumption and of attempting to reduce carbon footprints suggest that, overall, an interest in the survey topic was critical in persuading individuals to take part in the survey. They participated because it was an issue they felt strongly about, again not an uncommon or surprising finding (Bista, 2017; Porter & Whitcomb, 2005).

7.2.2 Awareness of Biosolids

Overall. in terms of general awareness of using biosolids (treated sewage sludge) in agriculture, 56.7% of respondents claimed to be unaware of this practice and 43.3% of respondents claimed to be aware. Even for a sample of people seemingly "on the case" with consuming organics and reducing carbon, therefore, the survey immediately reinforces the already-noted lack of popular awareness of biosolids. To get a greater sense of where this awareness is strongest and weakest, it will now be analysed by the key variables of gender, age, residential location, and whether or not organics are bought.

Gender (Table 7.2). A chi-square p value of 7.1×10^{-5} (dof 1) was significant at 95%: male respondents were markedly more aware of biosolid use than females.

Table 7.2 *Awareness of biosolid use cross-tabulated with gender*

		Aware of biosolids?	
		Yes	No
Gender	Male	60.8% (59)	39.2% (38)
	Female	36.5% (91)	63.5 (158)

Age (Table 7.3). A chi-square p value of 5.2×10^{-5} (dof 5) was significant at 95%: there was a significant difference in awareness of biosolid use by age group, with a general trend of such awareness increasing with age.

Table 7.3 *Awareness of biosolid use cross-tabulated with age.*

		Aware of biosolids?	
		Yes	No
Age Group (years)	18-24	20.0% (4)	80.0% (16)
	25-34	25.9% (14)	74.1% (40)
	35-44	35.1% (33)	64.9% (61)
	45-54	49.2% (29)	50.8% (30)
	55-64	51.8% (29)	48.2% (27)
	65+	63.6% (42)	36.4% (24)

Residential location (Table 7.4). A chi-square p value of 0.07 (dof 2) was not significant at 95%: a reduction of awareness as residential location got more urban was not statistically significant.

Table 7.4 *Awareness of biosolid use cross-tabulated with residential location.*

		Aware of biosolids?	
		Yes	No
Location	Rural	51.3 % (41)	48.8% (39)
	Suburban	46.3% (56)	53.7% (65)
	Urban	36.5% (54)	63.5% (94)

Organic food consumption (Table 7.5). A chi-square p value of 0.21 (dof 4) was not significant at 95%: awareness of biosolid use had no significant relation with organic consumption.

Table 7.5 Awareness of biosolid use cross-tabulated with frequency of organic food consumption.

		Aware of biosolids?	
		Yes	No
Frequency of organic food consumption	Every day	53.62% (37)	46.4% (32)
	At least once a week	41.1% (60)	58.9% (86)
	At least once a month	38.3% (18)	61.7% (29)
	Less than once a month	36.4(16)	63.6% (28)
	Never	52.9% (18)	47.1% (16)

In summary: awareness of biosolids was strongest in male respondents and increased with respondent age.

7.2.3 Attitude towards Eating Food Grown in Biosolids

Overall, the majority of respondents were generally okay with eating food grown with treated sewage sludge (biosolids) (Figure 7.1), with 65.9% at least slightly comfortable with the practice. Only 18.9% were uncomfortable or very uncomfortable with it. Again, it is not useful to discover who were most and least happy.

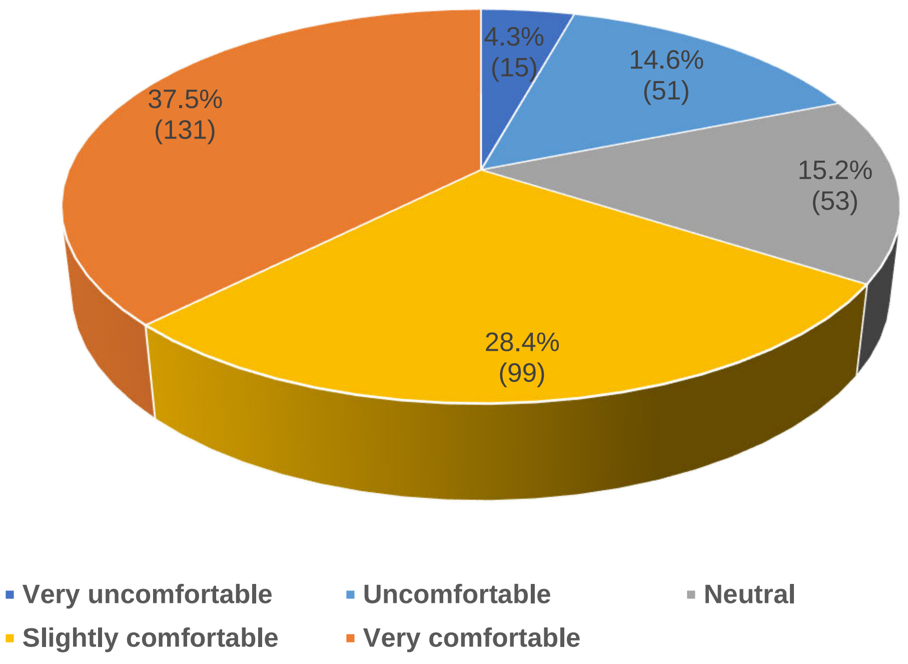

Figure 7.1 *Attitude towards eating food grown in biosolids.*

Gender (Table 7.6). A chi-square p value of 0.01 (dof 4) was significant at 95%: males were generally more comfortable with eating food grown in biosolids then females (32.1%).

Table 7.6 *Attitude towards eating food grown in biosolids cross-tabulated with gender.*

		Attitude towards eating food grown in biosolids				
		Very uncomfortable	Uncomfortable	Neutral	Slightly comfortable	Very comfortable
Gender	Female	4.4% (11)	15.3% (38)	17.3% (43)	30.9% (77)	32.1% (80)
	Male	4.1% (4)	12.4% (12)	9.3% (9)	21.6% (21)	52.6% (51)

Age (Table 7.7). A positive label was assigned to slightly comfortable/very comfortable and negative to very uncomfortable/uncomfortable to tighten up the table for robust statistical analysis. A chi-square p value of 0.12 (dof 10) was not significant at 95%: age of respondent was not strongly associated with comfortableness to eat food grown in biosolids.

__Table 7.7__ Attitude towards eating food grown in biosolids cross-tabulated with age.

		Attitude towards eating food grown in biosolids		
		Negative	**Neutral**	**Positive**
Age groups	18-24	15.0% (3)	20.0% (4)	65.0% (13)
	25-34	20.4% (11)	11.1% (6)	68.5% (37)
	35-44	20.2% (19)	14.9% (14)	64.9% (61)
	45-54	13.6% (8)	18.6% (11)	67.8% (40)
	55-64	33.9% (19)	10.7% (6)	55.4% (31)
	65+	9.1% (6)	18.2% (12)	72.7% (48)

Residential location (Table 7.8). A chi-square p value of 0.189 (dof 8) was not significant at 95%: where respondents lived was not strongly linked to comfort in eating food grown in biosolids.

__Table 7.8__ Attitude towards eating food grown in biosolids cross-tabulated with residential location.

		Attitude towards eating food grown in biosolids				
		Very uncomfortable	Uncomfortable	Neutral	Slightly comfortable	Very comfortable
Location	**Rural**	7.5% (6)	17.5% (14)	12.5% (10)	17.5% (14)	45.0% (36)
	Suburban	4.1% (5)	11.6% (14)	18.2% (22)	30.6% (37)	35.5% (43)
	Urban	2.7% (4)	15.5% (23)	14.2% (21)	32.4% (48)	35.1% (52)

Organic food consumption (Table 7.9). A positive label was assigned to slightly comfortable/very comfortable and negative to very uncomfortable/uncomfortable to tighten up the table and allow for robust statistical analysis. A chi-square p value of 0.22 (dof 8) was not significant at 95%: comfort in eating food grown in biosolids was not strongly linked to whether or not a respondent consumed organic food.

Table 7.9 *Attitude towards eating food grown in biosolids cross-tabulated with frequency of organic food consumption.*

		Attitude towards eating food grown in biosolids		
		Negative	**Neutral**	**Positive**
Frequency of organic food consumption	**Every day**	17.4% (12)	14.5% (10)	68.1% (47)
	At least once a week	21.2% (31)	11.0% (16)	67.8% (99)
	At least once a month	19.1% (9)	14.9% (7)	66.0% (31)
	Less than once a month	20.5% (9)	13.6% (6)	65.9% (29)
	Never	11.8% (4)	32.4% (11)	55.9% (19)

In summary: a positive attitude towards eating food grown in biosolids was strongest amongst male respondents.

7.2.4 Attitude towards Eating Food Grown in Wood Biochar

Overall, most respondents were very comfortable (68.5%) with consuming fruit and vegetables grown using wood biochar (Figure 7.2), with none being very uncomfortable. This again requires disaggregating further.

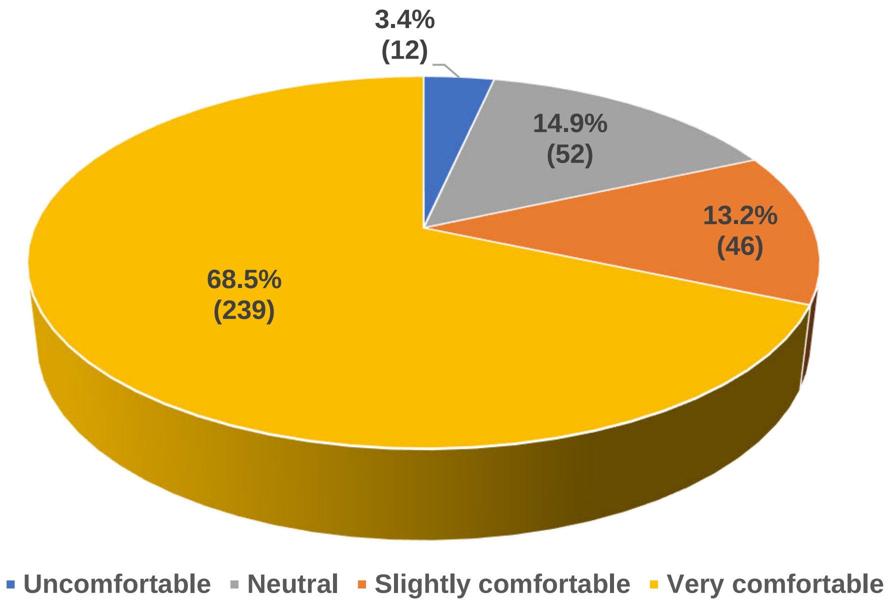

Figure 7.2 *Attitude towards eating food grown in wood biochar.*

Gender (Table 7.10). A chi-square p value of 0.016 (dof 3) was significant at 95%: males were generally more comfortable with eating food grown in wood biochar.

Table 7.10 *Attitude towards eating food grown in wood biochar cross-tabulated with gender.*

		Attitude towards eating food grown in wood biochar			
		Neutral	**Slightly comfortable**	**Uncomfortable**	**Very comfortable**
Gender	**Female**	14.9% (37)	15.7% (39)	4.0% (10)	65.5% (163)
	Male	14.4% (14)	6.2% (6)	2.1% (2)	77.3% (75)

Age (Table 7.11). After combining age groups to meet the assumptions of the chi-square test, a chi-square p value of 0.313 (dof 6) indicated no significant relationship between attitudes towards consuming food grown in wood biochar and respondent age. The majority of respondents from all age groups had a positive attitude towards wood biochar (81.7%).

Table 7.11 *Attitude towards eating food grown in wood biochar cross-tabulated with age.*

		Attitude towards eating food grown in wood biochar			
		Uncomfortable	**Neutral**	**Slightly comfortable**	**Very comfortable**
Age groups	**18-34**	5.4% (4)	13.5% (10)	10.8% (8)	70.3% (52)
	35-54	3.3% (5)	14.4% (22)	15.0% (23)	67.3% (103)
	over 55	2.5% (3)	16.4% (20)	12.3% (15)	68.9% (84)

Location (Table 7.12). A positive label was assigned to slightly comfortable/very comfortable and negative to very uncomfortable/uncomfortable for robust statistical analysis. A chi-square p value of 0.57 (dof 4) was not significant at 95%: attitude to eating food grown in wood biochar was not closely related to where respondents lived.

Table 7.12 *Attitude towards eating food grown in wood biochar cross-tabulated with residential location.*

		Attitude towards eating food grown in wood biochar		
		Negative	**Neutral**	**Positive**
Location	**Rural**	2.5% (2)	13.8% (11)	83.8% (67)
	Suburban	3.3% (4)	19.0% (23)	77.7% (94)
	Urban	4.1% (6)	12.2% (18)	83.8% (124)

Organic food consumption (Table 7.13). It was not possible to condense the data into groups that met the assumptions of a chi-square test. However, with respondents in all consumption categories having an overwhelmingly positive attitude towards wood biochar, it was clear that attitudes towards eating food grown in wood biochar were not strongly associated with frequency of eating organic food. However, it is worth noting that respondents who never consumed organic food had the lowest positive attitude towards wood biochar use (67.6%) compared to those who ate organic every day (91.3%).

Table 7.13 *Attitude towards eating food grown in wood biochar cross-tabulated with frequency of organic food consumption.*

		Attitude towards eating food grown in wood biochar		
		Negative	**Neutral**	**Positive**
Frequency of organic food consumption	**Every day**	0.0% (0)	8.7% (6)	91.3% (63)
	At least once a week	5.5% (8)	11.0% (16)	83.6% (122)
	At least once a month	2.1% (1)	21.3% (10)	76.6% (36)
	Less than once a month	2.3% (1)	15.9% (7)	81.8% 3(6)
	Never	5.9% (2)	26.5% (9)	67.6% (23)

In summary: males were generally more comfortable with eating food grown in wood biochar than females.

7.2.5 Attitude towards Eating Food Grown in Faecal Sludge Biochar

Overall (Figure 7.3), there was greater reluctance to eat food grown in faecal sludge biochar, with over a quarter of respondents (25.8%) expressing clear discomfort, even if over a third (35.2%) were still very comfortable in doing so. This again reiterates the "human waste" association's negative perception.

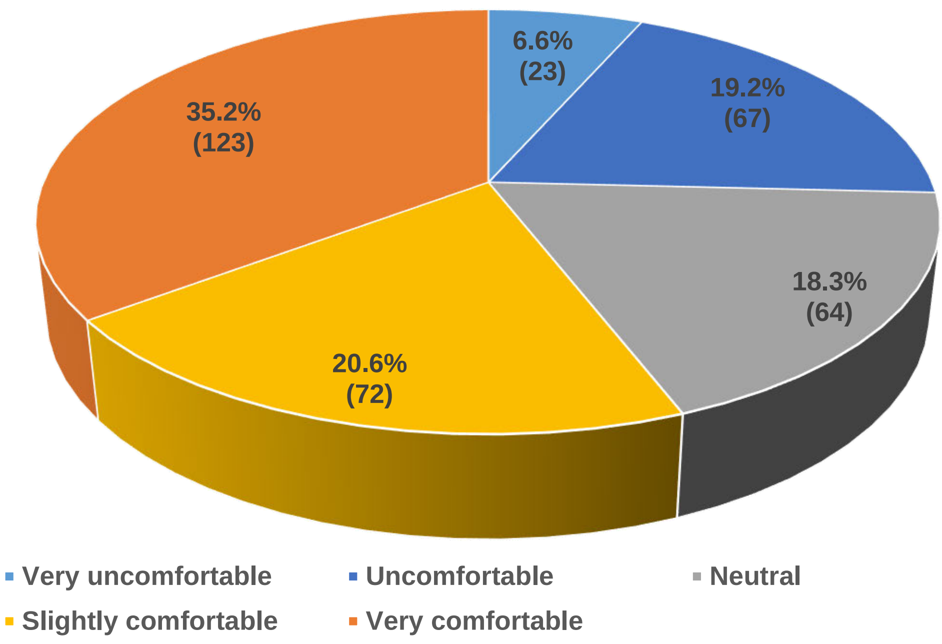

Figure 7.3 *Attitude towards eating food grown in faecal sludge biochar.*

Gender (Table 7.14). A chi-square p value of 0.00316 (dof 4) was significant at 95%: males were more comfortable overall in eating food grown in faecal sludge biochar than females.

Table 7.14 *Attitude towards eating food grown in faecal sludge biochar cross-tabulated with gender.*

		Attitudes towards eating food grown in sludge biochar				
		Very uncomfortable	**Uncomfortable**	**Neutral**	**Slightly comfortable**	**Very comfortable**
Gender	**Female**	7.2% (18)	21.7% (54)	19.3% (48)	22.5% (56)	29.3% (73)
	Male	5.2% (5)	11.3% (11)	15.5% (15)	16.5% (16)	51.5% (50)

Age (Table 7.15). A chi-square p value of 0.0045 (dof 10) was significant at 95%: older respondents were broadly happier with eating food grown in faecal sludge biochar, but it was not a straightforward relationship.

Table 7.15 *Attitude towards eating food grown in faecal sludge biochar cross-tabulated with age.*

		Attitudes towards eating food grown in sludge biochar		
		Negative	**Neutral**	**Positive**
Age group	**18-24**	65.0% (13)	10.0% (2)	25.0% (5)
	25-34	20.4% (11)	18.5% (10)	61.1% (33)
	35-44	28.7% (27)	17.0% (16)	54.3% (51)
	45-54	30.5% (18)	18.6% (11)	50.8% (30)
	55-64	23.2% (13)	16.1% (9)	60.7% (34)
	65+	12.1% (8)	24.2% (16)	63.6% (42)

Location (Table 7.16). A chi-square p value of 0.8866 (dof 8) was not significant at 95%: where respondents resided did not have a strong relation to attitude towards consuming food grown in faecal sludge biochar.

Table 7.16 *Attitude towards eating food grown in faecal sludge biochar cross-tabulated with residential location.*

		Attitudes towards eating food grown in sludge biochar				
		Very uncomfortable	Uncomfortable	Neutral	Slightly comfortable	Very comfortable
Location	Rural	7.5% (6)	18.8% (15)	13.8% (11)	20.0% (16)	40.0% (32)
	Suburban	5.8% (7)	17.4% (21)	19.8% (24)	24.0% (29)	33.1% (40)
	Urban	6.8% (10)	20.9% (31)	19.6% (29)	18.2% (27)	34.5% (51)

Organic food consumption (Table 7.17). A chi-square p value of 0.1971 (dof 8) was not significant at 95%: attitudes towards consuming food grown in faecal sludge biochar did not seem to be related to frequency of organic food consumption.

Table 7.17 *Attitude towards eating food grown in faecal sludge biochar cross-tabulated with frequency of organic food consumption.*

		Attitudes towards eating food grown in sludge biochar		
		Negative	**Neutral**	**Positive**
Frequency of organic food consumption	Every day	17.4% (12)	17.4% (12)	65.2% (45)
	At least once a week	26.0% (38)	14.4% (21)	59.6% (87)
	At least once a month	31.9% (15)	14.9% (7)	53.2% (25)
	Less than once a month	27.3% (12)	25.0% (11)	47.7% (21)
	Never	29.4% (10)	29.4% (10)	41.2% (14)

Wood versus sludge biochar (Table 7.18). A chi-square p value of 2.2 x10^{-16} (dof 12) was significant at 95%: those with a positive attitude towards wood biochar also tended to be positive towards faecal sludge biochar, and vice-versa.

Table 7.18 *Attitude towards eating food grown in faecal sludge biochar cross-tabulated with attitude towards eating food grown in wood biochar.*

		Attitudes towards eating food grown in faecal sludge biochar		
		Negative	**Neutral**	**Positive**
Attitudes towards eating food grown in wood biochar	**Negative**	75.0% (9)	0.0% (0)	25.0% (3)
	Neutral	40.4% (21)	51.9% (27)	7.7% (4)
	Positive	21.1% (60)	13.0% (37)	66.0% (188)

In summary: males, older people and those happy to eat food grown in wood biochar were happiest to eat food grown in faecal sludge biochar.

After measuring the public's "comfortableness" with eating food grown in faecal sludge biochar, a follow-up statement and further question was provided:
"Biochar produced from faecal sludge is perfectly safe to handle, has no odour and no harmful bacteria. Reading this information how comfortable now would you be eating fruit and vegetables that had been grown in this biochar?"
A Wilcoxon signed-rank test was used to examine if providing more information about biochar causes a significant shift in public perceptions. This confirmed that attitudes towards faecal sludge biochar significantly changed when more information regarding the safety of faecal sludge biochar was provided ($p = 2.2 \times 10^{-16}$).

7.2.6 Wariness of Sludge Biochar: the "Disgust Factor"

Studies related to sanitation and sewage sludge management have often noted a "squeamishness" and even a "taboo" around the whole topic (Black & Fawcett, 2008). Moreover, certain cultures find the handling of human waste repulsive or ritually polluting (faecophobic) (Jewitt, 2011). In some, even words associated with waste are distasteful (Esrey et al., 1998; Geest, 1998). However, any encultured desire to physically and mentally distance oneself from our biological wastes can have a major negative impact on the economic value of recoverable waste (Parizeau, 2015) and is a major challenge for such practices.

From the latter context and to explore further attitudes to faecal sludge biochar, the final survey question asked: "**What are the reasons (if any) that you would be wary of eating fruit and vegetables that had been grown in faecal sludge biochar?**" Whilst many respondents (36%) stated they had no issue with such consumption, approximately a quarter (84, 24.1%) indicated a strong "disgust effect". Responses included: "*Difficult to combat or neutralize a lifetime's negative imprint*", "*I don't know enough about it and the name 'faecal sludge' makes me feel queasy!*" and "*Simply psychological - the thought is revolting*". From all these answers a word cloud was produced (Figure 7.4). All statements where respondents indicated no wariness at all in consuming products grown in FS biochar were labelled "None". The minimum frequency of words expressing the disgust effect to be included was set at three, and filler words (about, all, more, just, need, like, any, enough, long, think, used, still, same, always, way, before, sure, see, currently, over, because, much, put, find, found, being) removed. Overall, the word cloud well illustrates how very many respondents felt at risk of coming to harm if they ate the food and, most of all, the emotional response of "disgust" explicitly.

Figure 7.4 *Word cloud showing reasons given by respondents expressing wariness in eating fruit and vegetables grown in faecal sludge biochar.*

A second word cloud – minimum frequency two, again with filler words removed - was then created from just the clear "disgust factor" statements (Figure 7.5) to identify which words were most frequently used to express this discomfort. Notably, many of the original statements here focused on the very words "faecal sludge":

- *I don't know enough about it and the name "faecal sludge" makes me feel queasy!*
- *I think it's mostly the wording. Faecal sludge sounds obviously disgusting and off putting and like no one would want to eat anything that had been in it.*
- *It's just the word faecal. Makes me think of dangerous bacteria*
- *It could do with some branding work. Maybe de-emphasis faecal?*

Many statements also showed wider evidence of "squeamishness" or, as one participant called it, the "ick factor". Yet, many also admitted that their attitude was not "logical" or "rational":

- *Just difficulty to shake the associations with "faecal sludge", even while trying to think about it rationally - a very visceral recoil away from associating "faecal" with food. I'd rather just not know!*
- *Just does not sound nice. Not really a rational answer*
- *It's probably profoundly illogical, but it just sounds unpleasant. Perhaps the disgust reaction is too ingrained - I think there's a linguistic aspect here, as "sludge" is such an unpleasant word. Nonetheless, I'm sure that with adequate reassurances and if it benefitted the environment (or at least wasn't as harmful as aggressive farming techniques using pesticides that deplete the bees, etc) it could be overcome!*
- *Logically I know it's safe but the thought of it has a bit of an ick factor*

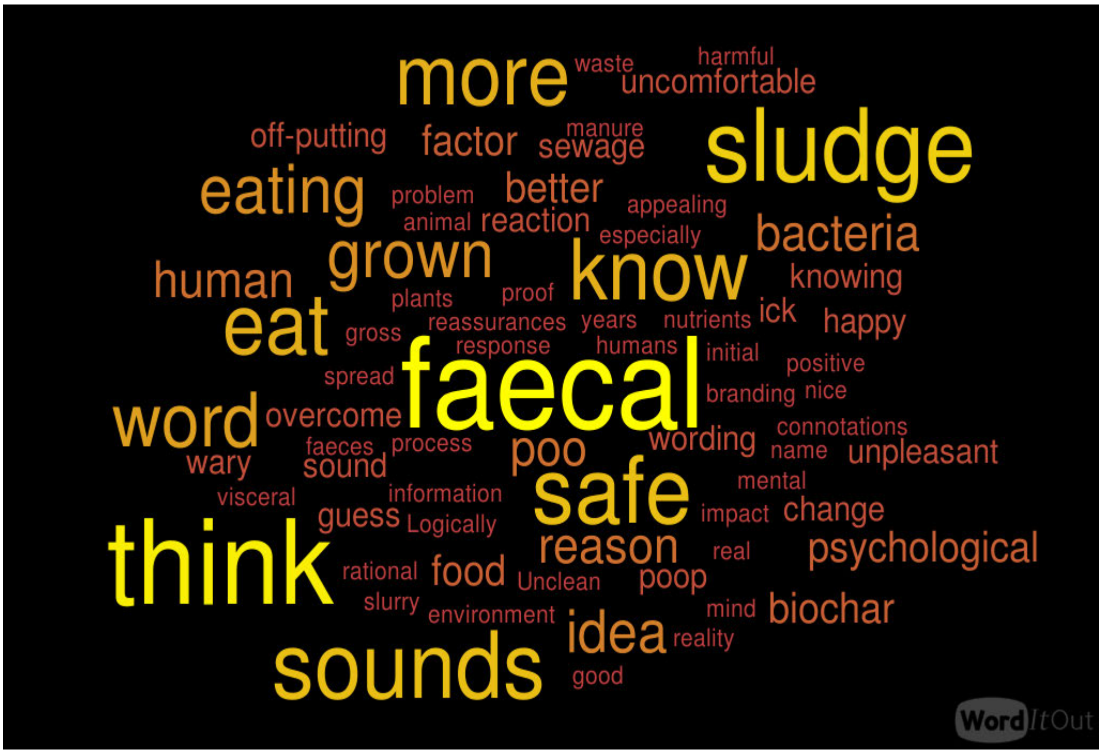

Figure 7.5 *Word cloud showing words that related to the "disgust factor" of consuming food grown in FS biochar.*

In summary: it is abundantly clear that it is imperative to engage with the “branding issue” for faecal sludge biochar is to become more readily accepted by the public.

7.3 Discussion

A first overall observation comes from the noted selectivity of the respondents. Cautiously, if women and older people are more interested in biosolids and biochar use, a challenge to be overcome if such use is to be increased and normalised is to engage men and younger adults more. This was despite a significantly higher percentage of male respondents stating awareness of biosolids, which may itself reflect previously noted higher level male self-confidence regarding science processes in subjects as diverse as medicine (Blanch et al., 2008) and computer science (Irani, 2004).

Focusing, second, on general attitudes to biosolid and biochar use, most participants showed a positive attitude towards biosolids use (65.9%), only 18.9% having a negative perception. However, negative perception towards FS biochar (25.8%) was higher, which may be related to unfamiliarity, lack of knowledge about this “new” product and also its “disgust factor”. The latter was supported by far lower negative attitudes towards the equally new and unfamiliar wood biochar (3.6%), which lacks a noted disgust factor. Interestingly, only 20% of those positive towards wood biochar were negative about FS biochar, suggesting some overall embracing of biochar is slowly emerging.

In terms of attitudes by gender, third, chi-squared testing confirmed a significant relationship between gender and awareness of biosolids and attitudes towards biosolids, FS biochar, and wood biochar, with men being consistently more positive. This was also in line with findings elsewhere showing differences in risk perception between genders (Steger & Witt, 1989) and differing attitudes towards science and technology (Flynn et al., 1994). In sum, those identifying as female appear less willing to consider new ideas and technologies with perceived health risks (Slovic, 2016; Steger & Witt, 1989). Specific issues demonstrating greater female risk perception include climate change, chemical pollution, bacteria in food (Flynn et al., 1994) and, recently, COVID-19 (Dryhurst et al., 2020). Most directly, a recent survey on biosolids' public risk perception concluded that there was a higher risk perception from females (Whitehouse et al., 2022). Generally, a key policy challenge is thus not only to get men more interested in the whole biosolids topic (noted above) but also to make women more positive about biosolids and biochar.

Turning, fourth, to perceptions of biosolids and biochar in relation to age, there was no significant difference in attitudes towards consuming food grown in wood biochar or biosolids, but use of FS biochar showed a significant effect. The overall feel was that older adults were more accepting of these new "technologies" than younger adults. Certainly, for FS biochar, the oldest age group (65+) had the greatest "very comfortable" percentage (47%) and the youngest age group (18-25) the lowest (15%). Thus, not only is there a challenge to get more younger adults engaged with biochar but their greater discomfort with the technologies has also to be overcome.

Fifth, where respondents lived in terms of how urban/rural showed no significant relationships with attitudes towards consuming food grown in biochar or biosolids. Clearly, there was no "closer to food production" impact, with no specific attention thus needing to be given to urban, suburban, or rural populations. Neither urban lack of biosolids / biochar application close to their homes nor rural residents' possibly negative perception of applications near where they reside (Robinson et al., 2012) came through.

Sixth, the survey collected data on the frequency participants consumed organic food to ascertain whether such consumers would be more willing to consume food grown in biochar and biosolids, perhaps as part of a broader critical perspective on the production of foodstuffs generally today. Findings were far from conclusive. On the one hand, respondents who consumed organic food every day had a very positive attitude (93%) towards wood biochar, with no negative responses recorded, whilst individuals who never consumed organic food had the lowest positivity percentage (69%) and a higher percentage viewing biochar unfavourably (6.9%). However, chi-square tests showed no overall statistically significant relationships between frequency of organic food consumption and attitude to biosolids, wood biochar or FS biochar. This again suggests, overall, that simple knowledge of biosolid and biochar usage and potential is the main initial step needed at present to allow these technologies to be more broadly embraced.

Finally, seventh, focusing specifically on FS biochar, approximately a quarter of respondents identified a “disgust effect” with it. This again reflects lack of knowledge and understanding about what it comprises, provoking a reflex-like rejection when “human waste” is mentioned, but also suggests a deeper cultural resistance to engaging, even just in words, with this every day and inevitable human product. Overcoming such an effect – often deeply engrained via childhood health and safety lessons of faecal products as dirty, harmful or disease containing - may be **the** most challenging task to address if FS biochar is to take its place alongside wood biochar and biosolids generally in the near future. Disgust, even if misdirected and sensationalised, is very real and must be taken into consideration, respected and addressed if the public are to get on board with land application of biosolids and FS biochar as a soil amendment (Naylor, 1997).

7.4 STUDY LIMITATIONS

Several limitations were encountered during the course of this research:

1. Gender Imbalance Among Survey Respondents:

In terms of the gender distribution of survey respondents, 71% identified as female, with 28% identifying as male. While the participation of at least 97 male respondents was achieved, this gender bias was not ideal. It is also worth noting that respondents' interest in the survey topic appeared to play a critical role in their engagement. For instance, 86% of those surveyed expressed active efforts to reduce their carbon footprint, suggesting that individuals participated because of their strong interest in the subject matter. While this is not an uncommon finding, it may represent a limitation of the study, as the sample may not fully represent broader demographics.

2. Omission of Key Variables:

The study did not include certain potentially relevant variables, such as the education level of the respondents. The absence of these variables may limit our understanding of how factors such as education impact perceptions of the presented issue.

3. Impact of the COVID-19 Pandemic:

A significant external factor, the COVID-19 pandemic, influenced the decision to conduct the survey research presented in this chapter. The decision to conduct an online survey during lockdown was driven by the necessity of bypassing laboratory access limitations while also collecting data on public perceptions and attitudes toward the use of faecal sludge biochar in crop cultivation. This study's limitation lies in its geographic scope, as it was conducted in the UK, where sewage sludge is more prevalent due to the presence of sewered systems. A more comprehensive survey of this nature would be better suited for regions in developing nations where faecal sludge is the dominant waste product.

These limitations are acknowledged as they may have influenced the study's outcomes and should be considered when interpreting the findings. Future research endeavours may seek to address these limitations for a more comprehensive understanding of the subject matter.

7.5 CONCLUSION

In conclusion, this chapter has given some indication of the appreciation of and attitudes towards use of biosolids, wood biochar and faecal sludge biochar from a diverse cross-section of Swansea residents. It revealed a wide range of attitudes and feelings about these technologies, now recognized within the scientific community as having much potential within a future sorely needed sustainable resource strategy within a more circular economy but still in need of more popular knowledge and understanding. Indeed, the immediate challenge this chapter strongly suggests is the need to make more people – some groups especially – more knowledgeable about these technologies and, most especially for faecal sludge biochar, overcome a “disgust factor” that further separates an environmentally benign technology from the public.

8 CONCLUSION

8.1 INTRODUCTION

The work presented here expands our current understanding of the characteristics of faecal sludge biochar and its application as a soil amendment in agriculture. The main objective of this study was to characterise faecal sludge biochars produced at three community scale sludge treatment plants in India and use these findings to investigate how the biochar properties affect soil properties and crop yield of (*Solanum lycopersicum* L.*)* cultivar Micro-Tom.

To achieve this, a thorough laboratory analysis of the chemical and physical properties of the three faecal sludge biochars was performed. A plant growth experiment on the effect of biochar with and without fertilizer on soil properties, plant parameters and fruit yield of on (*Solanum lycopersicum* L.) cultivar Micro-Tom was performed in an outdoor glasshouse. A second experiment on the impact of biochar with and without fertilizer on soil properties, plant parameters and fruit yield of (*Solanum lycopersicum* L.) cultivar Micro-Tom was performed in a controlled environment laboratory under a 24-hour lighting period and constant temperature.

Finally, a study was conducted investigating public perceptions of faecal sludge biochar, wood biochar and biosolids and determining whether gender, age, and location factor into perceptions and risks associated with the consumption of crops grown in these specific soil amendments.

The following sections summarise the findings of the research project and recommendations for further research are suggested.

8.2 BIOCHAR CHARACTERIZATION

All three faecal sludge biochars had a high ash content, high pH, low carbon content, negative surface charge and low specific surface areas and pore volumes. The similarity of FTIR spectra between biochars signifies a uniformity of the organic component of all three biochars. Warangal biochar had a significantly higher ash content and pH compared to the Narsapur and Wai biochar. There were also differences in XRD spectra between biochars. These differences could be related to possible contamination of faecal sludge in the containment structure by sand or grit.

The variability of these faecal sludge biochar properties highlights the differences between small-scall laboratory and full-scale "real world" biochar production. Control over every single variable in large-scale faecal sludge biochar production is difficult and routine inspections of every containment structure at every location would be time-consuming. However, the pH and ash content of the biochars could be monitored periodically at the treatment plant. The low surface areas and porosity of these biochars could prove detrimental in its end use a soil amendment as these properties relate to water holding capacity and microbial activity. However, increasing the porosity of faecal sludge biochar is possible through techniques such as chemical and physical activation. Overall, the properties of these biochars, in particular the high alkalinity, highlight their potential use as soil amendment particularly with acidic soil. The potential liming effect of these biochars could contribute to increased agricultural productivity especially in developing nations where the use of inorganic fertilizer on smallholder farmers is much lower. Future work should determine the biochars total and plant available macro-and micronutrient concentrations

8.3 FAECAL SLUDGE BIOCHAR AS A SOIL AMENDMENT

Commercial, large -scale faecal sludge biochar addition to acidic soil increased crop yield, fruit number, plant height and plant biomass and also reduced water runoff in Micro-Tom tomatoes compared to control soil. Biochar treatment produced a fruit yield of tomato cv. Micro-Tom approximately 1,060% greater compared to that of control soil conditions. The combination of biochar and fertilizer treatment together, however, produced plants with the greatest leaf length, plant height, tomato yield, and biomass. The combined application of biochar and fertilizer produced a tomato yield 2,980% greater than that of control soil conditions. It is possible that the biochar induced a liming effect which increased nutrient availability and is more evident in the combined biochar and fertilizer treatment, causing the bioavailability of nutrients within the fertilizer to be enhanced. The high CEC of biochar itself is also crucial, and likely had a positive effect on the sandy, low CEC soil, limiting nutrient leaching and improving nutrient retention resulting in a greater crop yield. The results of this study also highlight the importance of both the soils physical and chemical properties and those of the biochar that is applied. It is important to note the limitations of this study including the limited number of replicates, which was in part due to the Covid – 19 pandemic. This resulted in lack of access to university glasshouses, specialized irrigation equipment and support which reduced the number of replicates in the study. Also, it's important to highlight that this study suffered from a lack of technician support which could have aided in resolving issues with the pH and electrical conductivity meters used.

In conclusion it suggested that a tailored approach involving matching soil types to biochars with appropriate characteristics and properties is essential especially in areas where fertilizer alone is not enough.

8.4 EFFECT OF FAECAL SLUDGE BIOCHAR ADDITION ON TOMATOES GROWN UNDER CONTINUOUS LIGHT

Faecal sludge biochar significantly increased plant height, tomato yield and above ground biomass in an acidic, low nutrient soil under continuous light conditions. However, biochar (4% w/w) addition resulted in greater continuous light-induced leaf injury compared to the combined biochar (2%w/w) and fertilizer (2%w/w) treatment. This indicates that either nutrients from the fertilizer can alleviate the effects of continuous light induced leaf injury or that biochar addition on its own exacerbates the effect of continuous lighting on tomato plants. This is in contrast to other studies where biochar addition has helped the management of stress in plants under drought stress, salt stress, high temperature stress and heavy metal toxicity. However, further experimental work utilizing different rates of biochar and fertilizer addition is needed to further understand the effects of biochar on tomato plants grown under continuous light conditions.

8.5 PUBLIC PERCEPTION OF FAECAL SLUDGE BIOCHAR

There are potentially many advantages to the reuse of human waste in agriculture and research shows that faecal sludge biochar addition can improve crop yield. It is, however, crucial that socio-economic constraints including negative perceptions and attitudes from public consumers is addressed. In the survey conducted as part of this research project approximately 1/4 of respondents identified a “disgust effect” regarding faecal sludge biochar. This disgust effect, related to sanitation and sewage sludge management, has also been described in terms of squeamishness” and “taboo”. The cultural need to physically and mentally distance oneself from our biological wastes can have a detrimental effect on the economic value of recoverable waste. These attitudes and perceptions must be taken into consideration and addressed to enable the public to get on board with land application of faecal sludge biochar to increase crop yield. It was concluded that females have a much greater perception of risk towards the use of faecal sludge biochar and biosolids compared to males and that wood biochar elicited a much lower perception of risk than FS biochar. Also, age plays a significant part in perceptions of FS biochar with those in the oldest age group having the most positive attitude towards FS biochar. Therefore, in the future it is critical to consider gender differences, issue awareness, age and the “disgust factor” when implementing management and policy decisions regarding the land application of biosolids and FS biochar (H. L. Nicholas, Halfacree, et al., 2022).

8.6 FUTURE WORK

Further analysis of the physico-chemical properties of the faecal sludge biochars discussed in **Chapter 4** needs to be conducted. Specifically, the determination of the heavy metal content via inductively coupled plasma atomic emission spectroscopy (ICP-AES) is crucial to ensure these biochars adhere to the accepted upper thresholds set by the International Biochar Initiative (IBI, 2015) for use as agricultural soil amendments.

Determination of the biochars total and plant available macro-and micronutrient concentrations would also be useful in determining their applicability as a soil amendment. Extraction and column leaching experiments should be conducted to investigate the amount of nitrogen (N), phosphorus (P), and potassium (K) as well as the water-soluble contents of the nutrients in the biochars. Micro-nutrients such as silicon, calcium, iron, and zinc could also be determined via ICP-AES.

Surface area and porosity measurements were conducted using N_2 and CO_2 adsorptive gas. However, the adsorption of water in biochar could follow a different mechanism than for N_2 and CO_2. The water holding capacity of the biochar could be determined by measuring the adsorption isotherm with water via Dynamic Vapor Sorption (DVS) to provide a more accurate assessment of the water holding capacity in the biochar.

Whilst results from the greenhouse experiment (**Chapter 5**) are promising further research needs to be conducted looking at the effect of faecal sludge biochar on soil properties. A more thorough analysis of the effect of biochar addition on the chemical properties of acidic soil such as cation exchange capacity (CEC), and exchangeable acidity should be conducted to further investigate the liming potential of these biochars. In **Chapter 5** the water runoff from the biochar treatment was significantly lower than the control and the fertilizer treatments. Further investigation into the water holding capacity of these biochars is warranted. This can be achieved by measuring bulk density, porosity and water holding capacity in the control soil and the biochar amended soil at the end of a pot trial experiment. The effect of these biochars on soil microorganisms is another important area of investigation and future work could look at changes in microbial biomass, community composition and diversity after faecal sludge biochar treatment.

Measuring the available nutrients present in the soil after biochar addition could also aid in determining the potential of faecal sludge biochar as slow-release fertilizer.

It is possible that the liming effect from faecal sludge biochar discussed in **Chapter 5** is short-lived; therefore, longer-term field studies are needed to assess the duration of the reported positive liming effects of faecal sludge biochar addition on acidic soil and the reported increase in yield. These field trials should be conducted in India in areas local to the faecal sludge treatment plants. Many of the chemical, physical and biological soil tests already discussed could be conducted at a larger- scale. The benefit of field trials allows us to better understand the longevity of biochar within the soil and whether an increase in crop yield is seen over longer-time scales. A 3–5-year field trial would establish the re-application rates of biochar needed to maintain healthy soil and increased crop yield.

Further work focusing on the impact of faecal sludge biochar treatment on different crop types (cereal grasses, root crops) should also be studied, as well as different soil types. The high alkalinity of these biochars lend themselves to benefit acidic soils, however, it is important to investigate these biochars with other soil types combined with different crops.

The FTIR and XRD analysis (**Chapter 4**) indicate that the faecal sludge biochars studied here have relatively high concentrations of silicon. To date there are few studies that have investigated whether silicon in biochar can play a role increased plant growth (Rizwan et al., 2018) even though Si is primarily a major inorganic constituent of biochar; and can alleviate abiotic and biotic stresses of plants (Wang et al., 2019). Future work could look at whether silicon in biochar can play a role in mitigating abiotic stresses by investigating the impact of biochar application on crops grown under drought stress and high salinity conditions.

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Further investigation of the effect of biochar treatment on tomato plants grown under continuous light conditions (**Chapter 6)** should be conducted. Repeating the study described in **Chapter 6** but using different rates of biochar and fertilizer addition would help differentiate the effects of biochar from that of the fertilizer. The fertilizer treated plants in **Chapter 6** died due to overuse of fertilizer so reducing the rate of fertilizer to 2% w/w and reducing the rate of biochar to 2% w/w and consequently using a combined biochar (2% w/w) and fertilizer (2% w/w) treatment would help establish the extent of CL-induced leaf injury from each treatment. In particular using a biochar rate in the combined biochar and fertilizer treatment equal to the biochar rate in the biochar treatment group would further our understanding of whether the alleviation of leaf chlorosis seen in the combined biochar and fertilizer treatment group is due to the addition of fertilizer or a reduction in biochar application.

A property commonly used for detecting stress in plants is the Fv/Fm ratio of variable to maximum fluorescence after dark-adaptation and represents maximum potential quantum efficiency of Photosystem II. The Hansatech Handy PEA device can measure the maximum potential quantum efficiency of Photosystem II by using LEDs focused onto a leaf surface. Repeating the continuous light study with larger cultivars of tomato (*Solanum lycopersicum* San Marzano cultivar) would enable stress to be measured in each treatment group throughout the study. A more robust suite of analyses should be conducted, specifically looking at plant stress. These should include measuring the concentrations of chlorophylls and total carotenoids in leaf tissue and measuring reactive oxygen species (ROS) present such as H_2O_2. Enzyme extraction and assay analysis can also be conducted for antioxidant enzymes superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT).

Chapter 7 evaluated whether gender difference, age, differences, residential area and issue awareness affected public attitudes towards the use of faecal sludge biochar to grow crops. Future research should focus on conducting a similar survey focusing on sewage sludge biochar as this would be more applicable to residents in the global north. In the global north public perceptions regarding the use of sewage sludge biochar to grow crops are becoming increasingly relevant. This is due to new EU legislation (Directive (EU) 2018/850) that introduces restrictions on landfilling from 2030 of all waste that is suitable for recycling or other material or energy recovery. This directive aimed at underpinning the EU's transition to a circular economy is the driver behind the increased interest from wastewater companies in converting sewage sludge into biochar.

Similarly, a more comprehensive survey focusing on faecal sludge biochar can be conducted in regions in developing nations where onsite sanitation is prevalent. Also surveying the attitudes of farmers to using faecal sludge biochar in areas local to the community scale faecal sludge treatment facilities could also be crucial in addressing negative perceptions and ensuring the utilization of faecal sludge biochar to improve crop yields and degraded soils. Future research could investigate whether small-holder farmers attitudes change after using the biochar themselves and could be linked in with longer-term field trials of biochar application that are sorely needed.

8.7 CONCLUDING REMARKS

The major finding from this research is that large scale produced faecal sludge biochar application to acidic soil significantly improves crop yield, both with and without fertilizer. Producing a valuable product from faecal sludge can mitigate some of the worst effects of the sanitation crisis by preventing the indiscriminate disposal of pathogen containing raw faecal sludge into the environment. The benefits are numerous including the recovery of nutrients from waste and the mitigation of climate change whilst increasing crop yields.

Faecal sludge biochar addition improves fertilizer retention which is of great benefit to farmers in developing nations where the use of inorganic fertilizer has historically been low. The results from this study demonstrate that faecal sludge biochar can be used either as an alternative to fertilizer when fertilizer is not readily available or in combination with fertilizer to further increase enhance yields. The water holding capacity of biochar also benefits areas more at risk of increasing droughts from climate change and increasing water scarcity driven by rapid population growth.

Faecal sludge biochar as part of a circular economy can revolutionize the agricultural industry and can play a pivotal role in the water-energy-food nexus. It has enormous potential to improve soil health, reduce water demand and increase agricultural productivity in developing nations faced with rising water scarcity, increasing pressure on natural resources, and growing food insecurity.

REFERENCES

Abbas, T., Rizwan, M., Ali, S., Adrees, M., Mahmood, A., Zia-ur-Rehman, M., Ibrahim, M., Arshad, M., & Qayyum, M. F. (2018). Biochar application increased the growth and yield and reduced cadmium in drought stressed wheat grown in an aged contaminated soil. *Ecotoxicology and Environmental Safety*, *148*, 825–833. https://doi.org/10.1016/j.ecoenv.2017.11.063

Abbas, T., Rizwan, M., Ali, S., Zia-ur-Rehman, M., Farooq Qayyum, M., Abbas, F., Hannan, F., Rinklebe, J., & Sik Ok, Y. (2017). Effect of biochar on cadmium bioavailability and uptake in wheat (Triticum aestivum L.) grown in a soil with aged contamination. *Ecotoxicology and Environmental Safety*, *140*(February), 37–47. https://doi.org/10.1016/j.ecoenv.2017.02.028

Abbasi, G. H., Akhtar, J., Ahmad, R., Jamil, M., Anwar-ul-Haq, M., Ali, S., & Ijaz, M. (2015). Potassium application mitigates salt stress differentially at different growth stages in tolerant and sensitive maize hybrids. *Plant Growth Regulation*, *76*(1), 111–125. https://doi.org/10.1007/s10725-015-0050-1

Agrafioti, E., Bouras, G., Kalderis, D., & Diamadopoulos, E. (2013). Biochar production by sewage sludge pyrolysis. *Journal of Analytical and Applied Pyrolysis*, *101*, 72–78. https://doi.org/10.1016/j.jaap.2013.02.010

Ahmad, M., Rajapaksha, A. U., Lim, J. E., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Lee, S. S., & Ok, Y. S. (2014). Biochar as a sorbent for contaminant management in soil and water: A review. *Chemosphere*, *99*, 19–33. https://doi.org/10.1016/j.chemosphere.2013.10.071

Akhtar, S. S., Li, G., Andersen, M. N., & Liu, F. (2014). Biochar enhances yield and quality of tomato under reduced irrigation. *Agricultural Water Management*, *138*, 37–44. https://doi.org/10.1016/j.agwat.2014.02.016

Alloway, B. J., & Jackson, A. P. (1991). The behaviour of heavy metals in sewage sludge-amended soils. *Science of the Total Environment, The*, *100*(C), 151–176. https://doi.org/10.1016/0048-9697(91)90377-Q

Alvarenga, P., Mourinha, C., Farto, M., Palma, P., Sengo, J., Morais, M. C., & Cunha-Queda, C. (2016). Ecotoxicological assessment of the potential impact on soil porewater, surface and groundwater from the use of organic wastes as soil amendments. *Ecotoxicology and Environmental Safety*, *126*, 102–110. https://doi.org/10.1016/j.ecoenv.2015.12.019

Al-Wabel, M. I., Al-Omran, A., El-Naggar, A. H., Nadeem, M., & Usman, A. R. A. (2013). Pyrolysis temperature induced changes in characteristics and chemical composition of biochar produced from conocarpus wastes. *Bioresource Technology*, *131*, 374–379. https://doi.org/10.1016/j.biortech.2012.12.165

Amenaghawon, A. N., Anyalewechi, C. L., Okieimen, C. O., & Kusuma, H. S. (2021). Biomass pyrolysis technologies for value-added products: a state-of-the-art review. *Environment, Development and Sustainability*, *23*(10), 14324–14378. https://doi.org/10.1007/s10668-021-01276-5

Andriessen, N., Ward, B. J., & Strande, L. (2019). To char or not to char? Review of technologies to produce solid fuels for resource recovery from faecal sludge. *Journal of Water Sanitation and Hygiene for Development*, *9*(2), 210–224. https://doi.org/10.2166/washdev.2019.184

Antal, M. J., & Grønli, M. (2003). The art, science, and technology of charcoal production. *Industrial and Engineering Chemistry Research*, *42*(8), 1619–1640. https://doi.org/10.1021/ie0207919

Appiah-Effah, E., Duku, G. A., Dwumfour-Asare, B., Manu, I., & Nyarko, K. B. (2020). Toilet chemical additives and their effect on faecal sludge characteristics. *Heliyon*, *6*(9), e04998. https://doi.org/10.1016/j.heliyon.2020.e04998

Appiah-effah, E., Nyarko, K. B., & Awuah, E. S. I. (2014). Characterization of Public Toilet Sludge From Peri-Urban and Rural Areas of Ashanti Region of Ghana. *Journal of Applied Sciences in Environmental Sanitation*, *9*(3), 175–184.

Appiah-Effah, E., Nyarko, K. B., Gyasi, S. F., & Awuah, E. (2014). Faecal sludge management in low income areas: A case study of three districts in the Ashanti region of Ghana. *Journal of Water Sanitation and Hygiene for Development*, *4*(2), 189–199. https://doi.org/10.2166/washdev.2014.126

Arthur, J. M., Guthrie, J. D., & Newell, J. M. (1930). Some Effects of Artificial Climates on the Growth and Chemical Composition of Plants. *American Journal of Botany*, *17*(5), 416. https://doi.org/10.2307/2435930

Artiola, J. F., Rasmussen, C., & Freitas, R. (2012). Effects of a biochar-amended alkaline soil on the growth of romaine lettuce and bermudagrass. *Soil Science*, *177*(9), 561–570. https://doi.org/10.1097/SS.0b013e31826ba908

ASTM D 1762-84. (2011). Standard Test Method for Chemical Analysis of Wood Charcoal. *ASTM International*, *84*(Reapproved 2007), 1–2. https://doi.org/10.1520/D1762-84R07.2

Atkinson, C. J., Fitzgerald, J. D., & Hipps, N. A. (2010). Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: A review. *Plant and Soil*, *337*(1), 1–18. https://doi.org/10.1007/s11104-010-0464-5

Ato Armah, F., Ekumah, B., Oscar Yawson, D., Odoi, J. O., Afitiri, A.-R., & Esi Nyieku, F. (2018). Access to improved water and sanitation in sub-Saharan Africa in a quarter century. *Heliyon*, *4*, e00931. https://doi.org/10.1016/j.heliyon.2018

Awad, Y. M., Ok, Y. S., Abrigata, J., Beiyuan, J., Beckers, F., Tsang, D. C. W., & Rinklebe, J. (2018). Pine sawdust biomass and biochars at different pyrolysis temperatures change soil redox processes. *Science of the Total Environment*, *625*, 147–154. https://doi.org/10.1016/j.scitotenv.2017.12.194

Awere, E., Appiah Obeng, P., Asirifua Obeng, P., & Bonoli, A. (2020). Characterization of Faecal Sludge from Pit Latrines to Guide Management Solutions in Cape Coast, Ghana. *Journal of Geography, Environment and Earth Science International*, *February*, 1–13. https://doi.org/10.9734/jgeesi/2020/v24i130189

Bagreev, A., Bandosz, T. J., & Locke, D. C. (2001). Pore structure and surface chemistry of adsorbents obtained by pyrolysis of sewage sludge-derived fertilizer. *Carbon*, *39*(13), 1971–1979. https://doi.org/10.1016/S0008-6223(01)00026-4

Bai, S. H., Omidvar, N., Gallart, M., Kämper, W., Tahmasbian, I., Farrar, M. B., Singh, K., Zhou, G., Muqadass, B., Xu, C.-Y., Koech, R., Li, Y., Nguyen, T. T. N., & van Zwieten, L. (2022). Combined effects of biochar and fertilizer applications on yield: A review and meta-analysis. *Science of The Total Environment*, *808*, 152073. https://doi.org/10.1016/j.scitotenv.2021.152073

Bai, X., Li, Z., Zhang, Y., Ni, J., Wang, X., & Zhou, X. (2018). Recovery of Ammonium in Urine by Biochar Derived from Faecal Sludge and its Application as Soil Conditioner. *Waste and Biomass Valorization*, *9*(9), 1619–1628. https://doi.org/10.1007/s12649-017-9906-0

Baiamonte, G., De Pasquale, C., Marsala, V., Cimò, G., Alonzo, G., Crescimanno, G., & Conte, P. (2015). Structure alteration of a sandy-clay soil by biochar amendments. *Journal of Soils and Sediments*, *15*(4), 816–824. https://doi.org/10.1007/s11368-014-0960-y

Banik, C., Lawrinenko, M., Bakshi, S., & Laird, D. A. (2018). Impact of Pyrolysis Temperature and Feedstock on Surface Charge and Functional Group Chemistry of Biochars. *Journal of Environmental Quality*, *47*(3), 452–461. https://doi.org/10.2134/jeq2017.11.0432

Barani, V., Hegarty-Craver, M., Rosario, P., Madhavan, P., Perumal, P., Sasidaran, S., Basil, M., Raj, A., Berg, A. B., Stowell, A., Heaton, C., & Grego, S. (2018). Characterization of fecal sludge as biomass feedstock in the southern Indian state of Tamil Nadu. *Gates Open Research*, *2*, 52. https://doi.org/10.12688/gatesopenres.12870.1

Barry, D., Barbiero, C., Briens, C., & Berruti, F. (2019). Pyrolysis as an economical and ecological treatment option for municipal sewage sludge. *Biomass and Bioenergy*, *122*(January), 472–480. https://doi.org/10.1016/j.biombioe.2019.01.041

Bassan, M., Tchonda, T., Yiougo, L., Zoellig, H., Mahamane, I., Mbéguéré, M., & Strande, L. (2013). Characterization of faecal sludge during dry and rainy seasons in Ouagadougou, Burkina Faso. *36th WEDC International Conference: Delivering Water, Sanitation and Hygiene Services in an Uncertain Environment*, *September 2011*, 1–6.

Batool, A., Taj, S., Rashid, A., Khalid, A., Qadeer, S., Saleem, A. R., & Ghufran, M. A. (2015). Potential of soil amendments (Biochar and gypsum) in increasing water use efficiency of abelmoschus esculentus L. Moench. *Frontiers in Plant Science*, *6*(September), 1–13. https://doi.org/10.3389/fpls.2015.00733

Baveye, P., McBride, M. B., Bouldin, D., Hinesly, T. D., Dahdoh, M. S. A., & Abdel-Sabour, M. F. (1999). Mass balance and distribution of sludge-borne trace elements in a silt loam soil following long-term applications of sewage sludge. *Science of the Total Environment*, *227*(1), 13–28. https://doi.org/10.1016/S0048-9697(98)00396-9

Beck, D. A., Johnson, G. R., & Spolek, G. A. (2011). Amending greenroof soil with biochar to affect runoff water quantity and quality. *Environmental Pollution*, *159*(8–9), 2111–2118. https://doi.org/10.1016/j.envpol.2011.01.022

Beecher, N. (2004). Public Perception of Biosolids Recycling:Developing Public Participation and Earning Trust. *Water Intelligence Online*, *3*. https://doi.org/10.2166/9781780404318

Beecher, N., Harrison, E., Goldstein, N., McDaniel, M., Field, P., & Susskind, L. (2005). Risk perception, risk communication, and stakeholder involvement for biosolids management and research. *Journal of Environmental Quality*, *34*(1), 122–128. https://doi.org/10.2134/jeq2005.0122a

Belmonte, B. A., Benjamin, M. F. D., & Tan, R. R. (2017). Biochar systems in the water-energy-food nexus: the emerging role of process systems engineering. *Current Opinion in Chemical Engineering*, *18,* 32–37. https://doi.org/10.1016/j.coche.2017.08.005

Bergbäck, B., Johansson, K., & Mohlander, U. (2001). Urban metal flows–A case study of Stockholm. Review and conclusions. *Water, Air, and Soil Pollution: Focus*, *1*, 3–24.

Bhateria, R., & Jain, D. (2016). Water quality assessment of lake water: a review. *Sustainable Water Resources Management*, *2*(2), 161–173. https://doi.org/10.1007/s40899-015-0014-7

Bhowmik, D., Kumar, K. P. S., Paswan, S., & Srivastava, S. (2012). Tomato-A Natural Medicine and Its Health Benefits. *Journal of Pharmacognosy and Phytochemistry*, *1*(1), 33–43.

Bista, K. (2017). Examining Factors Impacting Online Survey Response Rates in Educational Research: Perceptions of Graduate Students. *Online Submission*, *13*(2), 63–74.

Black, M., & Fawcett, B. (2008). The Last Taboo: Opening the Door on the Global Sanitation Crisis. *Management of Environmental Quality: An International Journal*, *19*(6). https://doi.org/10.1108/meq.2008.08319fae.002

Blanch, D. C., Hall, J. A., Roter, D. L., & Frankel, R. M. (2008). Medical student gender and issues of confidence. *Patient Education and Counseling*, *72*(3), 374–381. https://doi.org/10.1016/j.pec.2008.05.021

Blanco-Canqui, H. (2017). Biochar and Soil Physical Properties. *Soil Science Society of America Journal*, *81*(4), 687–711. https://doi.org/10.2136/sssaj2017.01.0017

Bleuler, M., Gold, M., Strande, L., & Schönborn, A. (2021). Pyrolysis of Dry Toilet Substrate as a Means of Nutrient Recycling in Agricultural Systems: Potential Risks and Benefits. *Waste and Biomass Valorization*, *12*(7), 4171–4183. https://doi.org/10.1007/s12649-020-01220-0

Bridgwater, A. V. (2012). Review of fast pyrolysis of biomass and product upgrading. *Biomass and Bioenergy*, *38*, 68–94. https://doi.org/10.1016/j.biombioe.2011.01.048

Bridle, T. R., & Pritchard, D. (2004). Energy and nutrient recovery from sewage sludge via pyrolysis. *Water Science and Technology*, *50*(9), 169–175. https://doi.org/10.2166/wst.2004.0562

Brownsort, P., & Mašek, O. (2009). Biomass Pyrolysis Processes: Performance Parameters and their Influence on Biochar System Benefits. *SchoolofGeoSciences*, *MSc.*, 84.

Brunauer, S., Emmett, P. H., & Teller, E. (1938). Adsorption of Gases in Multimolecular Layers. *Journal of the American Chemical Society*, *60*(2), 309–319. https://doi.org/10.1021/ja01269a023

Cairns, S., Todd, A., Robertson, I., Byrne, P., & Dunlop, T. (2022). Treatment of mine water for the fast removal of zinc and lead by wood ash amended biochar.

Environmental Science: Advances, *1*(4), 506–516. https://doi.org/10.1039/D2VA00085G

Calderón, F. J., McCarty, G. W., & Reeves, J. B. (2006). Pyrolisis-MS and FT-IR analysis of fresh and decomposed dairy manure. *Journal of Analytical and Applied Pyrolysis*, *76*(1–2), 14–23. https://doi.org/10.1016/j.jaap.2005.06.009

Campos, M. L., Carvalho, R. F., Benedito, V. A., & Peres, L. E. P. (2010). Small and remarkable. *Plant Signaling & Behavior*, *5*(3), 267–270. https://doi.org/10.4161/psb.5.3.10622

Cantrell, K. B., Hunt, P. G., Uchimiya, M., Novak, J. M., & Ro, K. S. (2012). Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. *Bioresource Technology*, *107*(January 2019), 419–428. https://doi.org/10.1016/j.biortech.2011.11.084

Carrington, E.-G. (2001). Evaluation of sludge treatments for pathogen reduction. In *European Commission*.

Castan, S., Sigmund, G., Hüffer, T., & Hofmann, T. (2019). Biochar particle aggregation in soil pore water: The influence of ionic strength and interactions with pyrene. *Environmental Science: Processes and Impacts*, *21*(10), 1722–1728. https://doi.org/10.1039/c9em00277d

Chan, K. Y., Van Zwieten, L., Meszaros, I., Downie, A., & Joseph, S. (2007). Agronomic values of greenwaste biochar as a soil amendment. *Australian Journal of Soil Research*, *45*(8), 629–634. https://doi.org/10.1071/SR07109

Chan, Y. K., & Xu, Z. (2009). Biochar: nutrient properties and their enhancement J. Lehmann, S. Joseph (Eds.), Biochar for Environmental Management: Science and Technology, (2009), pp. 67-84. In J. Lehmann & S. Joseph (Eds.), *Biochar for Environmental Management: Science and Technology* (pp. 67–84). Earthscan.

Chanaka Udayanga, W. D., Andrei, V., Apostolos, G., Yen Nan, L., Grzegorz, L., Xiao, H., & Teik-Thye, L. (2019). Insights into the speciation of heavy metals during pyrolysis of industrial sludge. *Science of The Total Environment*, *691*, 232–242. https://doi.org/10.1016/j.scitotenv.2019.07.095

Chandana, N., & Rao, B. (2021). Status of sustainable sanitation chain in rural, semi-urban, and urban regions: a case study of Maharashtra, India. *Journal of Water, Sanitation and Hygiene for Development*, *11*(1), 112–125. https://doi.org/10.2166/washdev.2020.020

Chen, B., Zhou, D., & Zhu, L. (2008). Transitional adsorption and partition of nonpolar and polar aromatic contaminants by biochars of pine needles with different pyrolytic temperatures. *Environmental Science and Technology*, *42*(14), 5137–5143. https://doi.org/10.1021/es8002684

Chen, T., Zhang, Y., Wang, H., Lu, W., Zhou, Z., Zhang, Y., & Ren, L. (2014). Influence of pyrolysis temperature on characteristics and heavy metal adsorptive performance of biochar derived from municipal sewage sludge. *Bioresource Technology*, *164*, 47–54. https://doi.org/10.1016/j.biortech.2014.04.048

Cheng, C. H., Lehmann, J., Thies, J. E., Burton, S. D., & Engelhard, M. H. (2006). Oxidation of black carbon by biotic and abiotic processes. *Organic Geochemistry*, *37*(11), 1477–1488. https://doi.org/10.1016/j.orggeochem.2006.06.022

Chintala, R., Schumacher, T. E., Mcdonald, L. M., Clay, D. E., Malo, D. D., Papiernik, S. K., Clay, S. A., & Julson, J. L. (2014). Phosphorus sorption and availability from biochars and soil/biochar mixtures. *Clean - Soil, Air, Water*, *42*(5), 626–634. https://doi.org/10.1002/clen.201300089

Chorazy, T., Čáslavský, J., Žvaková, V., Raček, J., & Hlavínek, P. (2020). Characteristics of Pyrolysis Oil as Renewable Source of Chemical Materials and Alternative Fuel from the Sewage Sludge Treatment. *Waste and Biomass Valorization*, *11*(8), 4491–4505. https://doi.org/10.1007/s12649-019-00735-5

Cisse, L., Mrabet, T., Abdelkader, R., & Mazini, A. (2004). *World Phosphate Production : Overview and Prospects Abstract , however , is always phosphate rock for direct processing and direct application was estimated to 125*. *15*, 21–25.

Claoston, N., Samsuri, A. W., Ahmad Husni, M. H., & Mohd Amran, M. S. (2014). Effects of pyrolysis temperature on the physicochemical properties of empty fruit bunch and rice husk biochars. *Waste Management and Research*, *32*(4), 331–339. https://doi.org/10.1177/0734242X14525822

Coates, J. (2004). Encyclopedia of Analytical Chemistry -Interpretation of Infrared Spectra, A Practical Approach. *Encyclopedia of Analytical Chemistry*, 1–23.

Cofie, O., Kone, D., Rothenberger, S., Moser, D., & Zubruegg, C. (2009). Co-composting of faecal sludge and organic solid waste for agriculture: Process dynamics. *Water Research*, *43*(18), 4665–4675. https://doi.org/10.1016/j.watres.2009.07.021

Cordell, D., Drangert, J. O., & White, S. (2009). The story of phosphorus: Global food security and food for thought. *Global Environmental Change*, *19*(2), 292–305. https://doi.org/10.1016/j.gloenvcha.2008.10.009

Crombie, K., Mašek, O., Cross, A., & Sohi, S. (2015a). Biochar - synergies and trade-offs between soil enhancing properties and C sequestration potential. *GCB Bioenergy*, *7*(5), 1161–1175. https://doi.org/10.1111/gcbb.12213

Crombie, K., Mašek, O., Cross, A., & Sohi, S. (2015b). Biochar - synergies and trade-offs between soil enhancing properties and C sequestration potential. *GCB Bioenergy*, *7*(5), 1161–1175. https://doi.org/10.1111/gcbb.12213

Crombie, K., Mašek, O., Sohi, S. P., Brownsort, P., & Cross, A. (2013). The effect of pyrolysis conditions on biochar stability as determined by three methods. *GCB Bioenergy*. https://doi.org/10.1111/gcbb.12030

Cunningham, M., Gold, M., & Strande, L. (2016). *Literature Review: Slow pyrolysis of faecal sludge*. 85.

Curtin, R., Presser, S., & Singer, E. (2000). The effects of response rate changes on the index of consumer sentiment. *Public Opinion Quarterly*, *64*(4), 413–428. https://doi.org/10.1086/318638

Dad, K., Wahid, A., Khan, A. A., Anwar, A., Ali, M., Sarwar, N., Ali, S., Ahmad, A., Ahmad, M., Khan, K. A., Ansari, M. J., Gulshan, A. B., & Mohammed, A. A. (2019). Nutritional status of different biosolids and their impact on various growth parameters of wheat (Triticum aestivum L.). *Saudi Journal of Biological Sciences*, *26*(7), 1423–1428. https://doi.org/10.1016/j.sjbs.2018.09.001

Das, S. K., & Mukherjee, I. (2014). Influence of microbial community on degradation of flubendiamide in two Indian soils. *Environmental Monitoring and Assessment*, *186*(5), 3213–3219. https://doi.org/10.1007/s10661-013-3611-7

Davis, W. M., Erickson, C. L., Johnston, C. T., Delfino, J. J., & Porter, J. E. (1999). Quantitative Fourier Transform Infrared spectroscopic investigation humic substance functional group composition. *Chemosphere*, *38*(12), 2913–2928. https://doi.org/10.1016/S0045-6535(98)00486-X

Deacon, G. B., & Phillips, R. J. (1980). Deacon G Phillips R. *Coord. Chem. Rev.*, *33*, 227–250.

Defra. (2018). *Sewage sludge in agriculture: code of practice for England, Wales and Northern Ireland*. https://www.gov.uk/government/publications/sewage-sludge-in-agriculture-code-of-practice/sewage-sludge-in-agriculture-code-of-practice-for-england-wales-and-northern-ireland

DeLuca, T. H., MacKenzie, M. D., & Gundale, M. J. (2012). Biochar effects on soil nutrient transformations. *Biochar for Environmental Management: Science and Technology*, *January*, 251–270. https://doi.org/10.4324/9781849770552

Demers, D. A., Dorais, M., Wien, C. H., & Gosselin, A. (1998a). Effects of supplemental light duration on greenhouse tomato (Lycopersicon esculentum Mill.) plants and fruit yields. *Scientia Horticulturae*, *74*(4), 295–306. https://doi.org/10.1016/S0304-4238(98)00097-1

Demers, D. A., Dorais, M., Wien, C. H., & Gosselin, A. (1998b). Effects of supplemental light duration on greenhouse tomato (Lycopersicon esculentum Mill.) plants and fruit yields. *Scientia Horticulturae*, *74*(4), 295–306. https://doi.org/10.1016/S0304-4238(98)00097-1

Demers, D. A., & Gosselin, A. (1991). *Productivite Du Poivron Cultiv6 En Serre*. *594*, 587–594.

Dillman, D., Smyth, J., & Christian, L. (2014). *Internet, phone, mail, and mixed-mode surveys: The tailored design method*. John Wiley & Sons.

Dorais, M., Yelle, S., & Gosselin, A. (1996). Influence of extended photoperiod on photosynthate partitioning and export in tomato and pepper plants. *New Zealand*

Journal of Crop and Horticultural Science, *24*(1), 29–37. https://doi.org/10.1080/01140671.1996.9513932

Downie, A., Crosky, A., & Munroe, P. (2009). Physical properties of biochar. In J. Lehmann and S. Joseph (ed.) (Ed.), *Biochar for environmental management* (pp. 13–32). Earthscan.

Drechsel, P., Qadir, M., & Wichelns, D. (2015a). *Wastewater* (P. Drechsel, M. Qadir, & D. Wichelns, Eds.). Springer Netherlands. https://doi.org/10.1007/978-94-017-9545-6

Drechsel, P., Qadir, M., & Wichelns, D. (2015b). Wastewater: Economic asset in an urbanizing world. *Wastewater: Economic Asset in an Urbanizing World*, 1–282. https://doi.org/10.1007/978-94-017-9545-6

Dryhurst, S., Schneider, C. R., Kerr, J., Freeman, A. L. J., Recchia, G., van der Bles, A. M., Spiegelhalter, D., & van der Linden, S. (2020). Risk perceptions of COVID-19 around the world. *Journal of Risk Research*, *0*(0), 1–13. https://doi.org/10.1080/13669877.2020.1758193

EBC. (2016). Guidelines for a Sustainable Production of Biochar. *European Biochar Foundation (EBC)*, *SeptemberECB*, 1–22. https://doi.org/10.13140/RG.2.1.4658.7043

EEC. (1986). 91/692/EEC Council Directive of 12 June 1986 on the Protection of the Environment, and in Particular of the Soil, when Sewage Sludge Is Used in Agriculture. *EEC*.

Ellen MacArthur Foundation. (2015). An Approach to Measuring Circularity. *Circular Indicators: An Approach to Measuring Circularity. Methodology*, *23*(1), 159–161.

Ellerbrock, R. H., & Gerke, H. H. (2021). FTIR spectral band shifts explained by OM–cation interactions. *Journal of Plant Nutrition and Soil Science*, *184*(3), 388–397. https://doi.org/10.1002/jpln.202100056

Enders, A., Hanley, K., Whitman, T., Joseph, S., & Lehmann, J. (2012). Characterization of biochars to evaluate recalcitrance and agronomic performance. *Bioresource Technology, 114,* 644–653. https://doi.org/10.1016/j.biortech.2012.03.022

Enders, A., & Lehmann, J. (2015). Proximate analyses for characterising biochars. *Biochar: A Guide to Analytical Methods,* 9–22.

Esrey, S. A., Andersson, I., Hillers, A., & Sawyer, R. (2001). Ecological sanitation for food security. In *Water Resources*.

Esrey, S. A., Gough, J., Rapaport, D., Sawyer, R., Simpson-Hebert, M., Varga, J., & Winblad, U. (1998). *Ecological Sanitation*. 100.

European Biochar Foundation. (2016). Guidelines for a Sustainable Production of Biochar. *European Biochar Foundation (EBC), August*, 1–22.

European Comission. (2001). Part 2: regulatory report. In *Disposal and recycling routes for sewage sludge* (Vol. 0, Issue 75).

European Commission. (1986). Protection of the Environment, and in particular of the soil, when sewage sludge is used in agriculture. *Official Journal of the European Communities*, *4*(7), 6–12.

European Commission. (2018a). A European Strategy for Plastics. *European Comission*, *July*, 24. https://doi.org/10.1021/acs.est.7b02368

European Commission. (2018b). A monitoring framework for the circular economy. COM(2018) 29 final.16.1.2018. *COM/2018/29 Final*, *29*(final), 1–11.

European Parliament, & European Council. (2018). Directive (EU) 2018/851 of the European Parliament - Waste Framework Directive 2.0 (WFD 2.0). *Official Journal of the European Union, 1907*, (L-150/109-140).

Fahad, S., Hussain, S., Saud, S., Tanveer, M., Bajwa, A. A., Hassan, S., Shah, A. N., Ullah, A., Wu, C., Khan, F. A., Shah, F., Ullah, S., Chen, Y., & Huang, J. (2015). A biochar application protects rice pollen from high-temperature stress. *Plant Physiology and Biochemistry, 96,* 281–287. https://doi.org/10.1016/j.plaphy.2015.08.009

Falaras, P. (1999). Cottonseed Oil Bleaching by Acid-Activated Montmorillonite. *Clay Minerals, 34*(2), 221–232. https://doi.org/10.1180/claymin.1999.034.2.02

Fanyin-Martin, A., Tamakloe, W., Antwi, E., Ami, J., Awarikabey, E., Apatti, J., Mensah, M., & Chandran, K. (2017). Chemical characterization of faecal sludge in the Kumasi metropolis, Ghana. *Gates Open Research*, *1*, 12. https://doi.org/10.12688/gatesopenres.12757.1

FAO. (2008). Climate Change , Water and Food Security Technical Background Document From the Expert Consultation Held on. *Security*, *February*, 18.

FAO. (2011). Energy-smart food for people and climate. Issue Paper. *Food and Agriculture Organization of the United Nations.*, 66.

FAO, IFAD, UNICEF, WFP, & WHO. (2021). The State of Food Security and Nutrition in the World 2021. In *The State of Food Security and Nutrition in the World 2021*. FAO. https://doi.org/10.4060/cb4474en

Farhangi-Abriz, S., & Torabian, S. (2017). Antioxidant enzyme and osmotic adjustment changes in bean seedlings as affected by biochar under salt stress. *Ecotoxicology and Environmental Safety*, *137*, 64–70. https://doi.org/10.1016/j.ecoenv.2016.11.029

Farhangi-Abriz, S., & Torabian, S. (2018). Biochar Increased Plant Growth-Promoting Hormones and Helped to Alleviates Salt Stress in Common Bean Seedlings. *Journal of Plant Growth Regulation*, *37*(2), 591–601. https://doi.org/10.1007/s00344-017-9756-9

Farmer, V. C. (1974). *Chapter 1 Vibrational Spectroscopy in Mineral Chemistry*. 1–10.

Farrell, M., Kuhn, T. K., Macdonald, L. M., Maddern, T. M., Murphy, D. V., Hall, P. A., Singh, B. P., Baumann, K., Krull, E. S., & Baldock, J. A. (2013). Microbial utilisation of biochar-derived carbon. *Science of the Total Environment*, *465*, 288–297. https://doi.org/10.1016/j.scitotenv.2013.03.090

Feng, H., Zheng, M., Dong, H., Xiao, Y., Hu, H., Sun, Z., Long, C., Cai, Y., Zhao, X., Zhang, H., Lei, B., & Liu, Y. (2015). Three-dimensional honeycomb-like hierarchically structured carbon for high-performance supercapacitors derived from high-ash-content sewage sludge. *Journal of Materials Chemistry A*, *3*(29), 15225–15234. https://doi.org/10.1039/c5ta03217b

Fidjeland, J. (2015). *Sanitisation of faecal sludge by ammonia : treatment technology for safe reuse in agriculture*.

Fijalkowski, K., Rorat, A., Grobelak, A., & Kacprzak, M. J. (2020). *Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID- 19 . The COVID-19 resource centre is hosted on Elsevier Connect , the company ' s public news and information . January*.

Flynn, J., Slovic, P., & Mertz, C. K. (1994). Gender, Race, and Perception of Environmental Health Risks. *Risk Analysis*, *14*(6), 1101–1108. https://doi.org/10.1111/j.1539-6924.1994.tb00082.x

Fonts, I., Gea, G., Azuara, M., Ábrego, J., & Arauzo, J. (2012). Sewage sludge pyrolysis for liquid production: A review. *Renewable and Sustainable Energy Reviews*, *16*(5), 2781–2805. https://doi.org/10.1016/j.rser.2012.02.070

Fuertes, A. B., Arbestain, M. C., Sevilla, M., MacIá-Agulló, J. A., Fiol, S., López, R., Smernik, R. J., Aitkenhead, W. P., Arce, F., & MacIas, F. (2010). Chemical and structural properties of carbonaceous products obtained by pyrolysis and hydrothermal carbonisation of corn stover. *Australian Journal of Soil Research*, *48*(6–7), 618–626. https://doi.org/10.1071/SR10010

Fytili, D., & Zabaniotou, A. (2008). Utilization of sewage sludge in EU application of old and new methods-A review. *Renewable and Sustainable Energy Reviews*, *12*(1), 116–140. https://doi.org/10.1016/j.rser.2006.05.014

Galvín, R. M., López, J. M. C., & Mellado, J. M. R. (2009). Chemical characterization of biosolids from three Spanish WWTPs: Transfer of organics and metallic pollution from urban wastewater to biosolids. *Clean - Soil, Air, Water*, *37*(1), 52–59. https://doi.org/10.1002/clen.200800154

Gascó, G., Méndez, A., & Gascó, J. M. (2005). Preparation of carbon-based adsorbents from sewage sludge pyrolysis to remove metals from water. *Desalination*, *180*(1–3), 245–251. https://doi.org/10.1016/j.desal.2005.01.006

Gaskin, J. W., Speir, A., Morris, L. M., Ogden, L., Harris, K., Lee, D., & Das, K. C. (2007). *Potential for Pyrolysis Char To Affect Soil Moisture and*.

Gaskin, J. W., Steiner, C., Harris, K., Das, K. C., & Bibens, B. (2008a). *EFFECT OF LOW-TEMPERATURE PYROLYSIS CONDITIONS ON BIOCHAR FOR AGRICULTURAL USE*. *51*(6), 2061–2069.

Gaskin, J. W., Steiner, C., Harris, K., Das, K. C., & Bibens, B. (2008b). Effect of Low-Temperature Pyrolysis Conditions on Biochar for Agricultural Use. *Transactions of the ASABE*, *51*(6), 2061–2069. https://doi.org/10.13031/2013.25409

Gaunt, J. L., & Lehmann, J. (2008). Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. *Environmental Science and Technology*, *42*(11), 4152–4158. https://doi.org/10.1021/es071361i

Geest, S. Van Der. (1998). Akan Shit: Getting Rid of Dirt in Ghana. *Anthropology Today*, *14*(3), 8. https://doi.org/10.2307/2783049

Ghassemi-Golezani, K., & Farhangi-Abriz, S. (2019). Biochar alleviates fluoride toxicity and oxidative stress in safflower (Carthamus tinctorius L.) seedlings. *Chemosphere*, *223*, 406–415. https://doi.org/10.1016/j.chemosphere.2019.02.087

Gil, R., Bojacá, C. R., & Schrevens, E. (2019). Understanding the heterogeneity of smallholder production systems in the Andean tropics – The case of Colombian tomato growers. *NJAS - Wageningen Journal of Life Sciences*, *88*(September 2018), 1–9. https://doi.org/10.1016/j.njas.2019.02.002

Glaser, B., Haumaier, L., Guggenberger, G., & Zech, W. (2001). The 'Terra Preta' phenomenon: A model for sustainable agriculture in the humid tropics. *Naturwissenschaften*. https://doi.org/10.1007/s001140000193

Glaser, B., Lehmann, J., & Zech, W. (2002). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - A review. *Biology and Fertility of Soils*, *35*(4), 219–230. https://doi.org/10.1007/s00374-002-0466-4

Glaser, B., & Lehr, V. I. (2019). Biochar effects on phosphorus availability in agricultural soils: A meta-analysis. *Scientific Reports*, *9*(1), 1–9. https://doi.org/10.1038/s41598-019-45693-z

Glaser, B., Wiedner, K., Seelig, S., Schmidt, H.-P., & Gerber, H. (2015). Biochar organic fertilizers from natural resources as substitute for mineral fertilizers. *Agronomy for Sustainable Development*, *35*(2), 667–678. https://doi.org/10.1007/s13593-014-0251-4

Globig, S., Rosen, I., & Janes, H. W. (1997). CONTINUOUS LIGHT EFFECTS ON PHOTOSYNTHESIS AND CARBON METABOLISM IN TOMATO. *Acta Horticulturae*, *418*, 141–152. https://doi.org/10.17660/ActaHortic.1997.418.19

Gold, M., Cunningham, M., Bleuler, M., Arnheiter, R., Schönborn, A., Niwagaba, C., & Strande, L. (2018). Operating parameters for three resource recovery options from slow-pyrolysis of faecal sludge. *Journal of Water, Sanitation and Hygiene for Development*, *8*(4), 707–717. https://doi.org/10.2166/washdev.2018.009

Gondek, K., Mierzwa-Hersztek, M., Kopeć, M., Sikora, J., Lošák, T., & Grzybowski, P. (2019). Sewage Sludge Biochar Effects on Phosphorus Mobility in Soil and Accumulation in Plant. *Ecological Chemistry and Engineering S*, *26*(2), 367–381. https://doi.org/10.1515/eces-2019-0026

Goyder, J. (1986). Surveys on Surveys: Limitations and Potentialities. *The Public Opinion Quarterly*, *50*(1), 27–41.

Graber, E., Singh, B., K, H., & Lehmann, J. (2017). Determination of Cation Exchange Capacity in Biochar. In B. Singh, M. Camps-Arbestain, & J. Lehmann (Eds.), *Biochar: A Guide to Analytical Methods.* (pp. 74-84.). Csiro Publishing.

Graham, J. P., & Polizzotto, M. L. (2013). Pit Latrines and Their Impacts on Groundwater Quality: A Systematic Review. *Environmental Health Perspectives*, *121*(5), 521–530. https://doi.org/10.1289/ehp.1206028

Gross, A., Bromm, T., & Glaser, B. (2021). Soil Organic Carbon Sequestration after Biochar Application: A Global Meta-Analysis. *Agronomy*, *11*(12), 2474. https://doi.org/10.3390/agronomy11122474

Grossman, J. M., O'Neill, B. E., Tsai, S. M., Liang, B., Neves, E., Lehmann, J., & Thies, J. E. (2010). Amazonian Anthrosols Support Similar Microbial Communities that Differ Distinctly from Those Extant in Adjacent, Unmodified Soils of the Same Mineralogy. *Microbial Ecology*, *60*(1), 192–205. https://doi.org/10.1007/s00248-010-9689-3

Günther, F. (1997). Hampered effluent accumulation process: Phosphorus management and societal structure. *Ecological Economics*, *21*(2), 159–174. https://doi.org/10.1016/S0921-8009(96)00100-0

Gupta, S., Kua, H. W., & Low, C. Y. (2018). Use of biochar as carbon sequestering additive in cement mortar. *Cement and Concrete Composites*, *87*, 110–129. https://doi.org/10.1016/j.cemconcomp.2017.12.009

Gwenzi, W., Chaukura, N., Mukome, F. N. D., Machado, S., & Nyamasoka, B. (2015a). Biochar production and applications in sub-Saharan Africa: Opportunities, constraints, risks and uncertainties. *Journal of Environmental Management*, *150*, 250–261. https://doi.org/10.1016/j.jenvman.2014.11.027

Gwenzi, W., Chaukura, N., Mukome, F. N. D., Machado, S., & Nyamasoka, B. (2015b). Biochar production and applications in sub-Saharan Africa: Opportunities, constraints, risks and uncertainties. *Journal of Environmental Management*, *150*, 250–261. https://doi.org/10.1016/j.jenvman.2014.11.027

Gwenzi, W., & Munondo, R. (2008). Long-term impacts of pasture irrigation with treated sewage effluent on nutrient status of a sandy soil in Zimbabwe. *Nutrient Cycling in Agroecosystems*, *82*(2), 197–207. https://doi.org/10.1007/s10705-008-9181-3

Gwenzi, W., Muzava, M., Mapanda, F., & Tauro, T. P. (2016). Comparative short-term effects of sewage sludge and its biochar on soil properties, maize growth and uptake of nutrients on a tropical clay soil in Zimbabwe. *Journal of Integrative Agriculture*, *15*(6), 1395–1406. https://doi.org/10.1016/S2095-3119(15)61154-6

Hale, S. E., Alling, V., Martinsen, V., Mulder, J., Breedveld, G. D., & Cornelissen, G. (2013). The sorption and desorption of phosphate-P, ammonium-N and nitrate-N in cacao shell and corn cob biochars. *Chemosphere*, *91*(11), 1612–1619. https://doi.org/10.1016/j.chemosphere.2012.12.057

Haller, L., Hutton, G., & Bartram, J. (2007). Estimating the costs and health benefits of water and sanitation improvements at global level. *Journal of Water and Health*, *5*(4), 467–480. https://doi.org/10.2166/wh.2007.008

Hammes, K. and Schmidt, M. W. I. (2009). Changes of biochar in soil. In J. Lehmann & S. and Joseph (Eds.), *Biochar for Environmental Management.* (pp. 169–182). Earthscan, London.

Hao, X., Zheng, J. M., Little, C., & Khosla, S. (2012). LED inter-lighting in year-round greenhouse mini-cucumber production. *Acta Horticulturae*, *956*, 335–340. https://doi.org/10.17660/ActaHortic.2012.956.38

Haque, M. S., de Sousa, A., Soares, C., Kjaer, K. H., Fidalgo, F., Rosenqvist, E., & Ottosen, C.-O. (2017). Temperature Variation under Continuous Light Restores Tomato Leaf Photosynthesis and Maintains the Diurnal Pattern in Stomatal Conductance. *Frontiers in Plant Science*, *8*. https://doi.org/10.3389/fpls.2017.01602

Harmanto, Salokhe, V. M., Babel, M. S., & Tantau, H. J. (2005). Water requirement of drip irrigated tomatoes grown in greenhouse in tropical environment. *Agricultural Water Management*, *71*(3), 225–242. https://doi.org/10.1016/j.agwat.2004.09.003

Haynes, R. J., Murtaza, G., & Naidu, R. (2009). Chapter 4 Inorganic and Organic Constituents and Contaminants of Biosolids. Implications for Land Application. In *Advances in Agronomy* (Vol. 104). https://doi.org/10.1016/S0065-2113(09)04004-8

Heinss, U., Larmie, Seth. A., & Martin, S. (1998). Solids Separation and Pond Systems Treatment of Faecal Sludges In the Tropics: Lessons Learnt and Recommendations for Preliminary Design. *Development*, *05*.

Heinss, U., & Strauss, M. (1999). Management of Sludges from On-site Sanitation: Co-treatment of Faecal Sludge and Wastewater in Tropical Climates. *EAWAG/SANDEC- Water and Sanitation in Developing Countries*, *January*, 1–7.

Hemming, S., Bakker, J. C., Campen, J. B., & Kempkes, F. L. K. (2019). *Sustainable use of energy in greenhouses* (pp. 445–492). https://doi.org/10.19103/AS.2019.0052.07

Herath, H. M. S. K., Camps-Arbestain, M., & Hedley, M. (2013). Effect of biochar on soil physical properties in two contrasting soils: An Alfisol and an Andisol. *Geoderma*, *209–210*, 188–197. https://doi.org/10.1016/j.geoderma.2013.06.016

Hiemenz, P. C., & Rajagopalan, R. (Eds.). (1997). *Principles of Colloid and Surface Chemistry, Revised and Expanded* (3rd ed.). CRC Press. htt. https://doi.org/org/10.1201/9781315274287

Hill, N., Brierley, J., & MacDougall, R. (2017). *How to Measure Customer Satisfaction*. Routledge. https://doi.org/10.4324/9781315253107

Hillman, W. S. (1956). Injury of Tomato Plants by Continuous Light and Unfavorable Photoperiodic Cycles. *American Journal of Botany*, *43*(2), 89. https://doi.org/10.2307/2438816

Hornung, A., & Seifert, H. (2006). Rotary Kiln Pyrolysis of Polymers Containing Heteroatoms. *Feedstock Recycling and Pyrolysis of Waste Plastics: Converting Waste Plastics into Diesel and Other Fuels*, 549–567. https://doi.org/10.1002/0470021543.ch20

Hossain, M. K., Strezov, V., Chan, K. Y., Ziolkowski, A., & Nelson, P. F. (2010). *Influence of pyrolysis temperature on production and nutrient properties of wastewater sludge biochar*. https://doi.org/10.1016/j.jenvman.2010.09.008

Hossain, M. K., Strezov, V., & Nelson, P. F. (2015). Comparative Assessment of the Effect of Wastewater Sludge Biochar on Growth, Yield and Metal Bioaccumulation of Cherry Tomato. *Pedosphere*, *25*(5), 680–685. https://doi.org/10.1016/S1002-0160(15)30048-5

Hossain, M. K., Strezov, V., Yin Chan, K., & Nelson, P. F. (2010). Agronomic properties of wastewater sludge biochar and bioavailability of metals in production of cherry tomato (Lycopersicon esculentum). *Chemosphere*, *78*(9), 1167–1171. https://doi.org/10.1016/j.chemosphere.2010.01.009

Hossain, M. K., Strezov Vladimir, V., Chan, K. Y., Ziolkowski, A., & Nelson, P. F. (2011). Influence of pyrolysis temperature on production and nutrient properties of wastewater sludge biochar. *Journal of Environmental Management*, *92*(1), 223–228. https://doi.org/10.1016/j.jenvman.2010.09.008

Hurd, R. G., & Thornley, J. H. M. (1974). An analysis of the growth of young tomato plants in water culture at different light integrals and CO2 concentrations: I. Physiological aspects. *Annals of Botany*, *38*(2), 375–388. https://doi.org/10.1093/oxfordjournals.aob.a084821

IBI. (2015). *Standardized Product Definition and Product Testing Guidelines for Biochar 7 That Is Used in Soil*. https://www.biochar-international.org/wp-content/uploads/2018/04/IBI_Biochar_Standards_V2.1_Final.pdf

Ibrahim, M., Li, G., Chan, F. K. S., Kay, P., Liu, X.-X., Firbank, L., & Xu, Y.-Y. (2019). Biochars effects potentially toxic elements and antioxidant enzymes in Lactuca sativa L. grown in multi-metals contaminated soil. *Environmental Technology & Innovation*, *15*, 100427. https://doi.org/10.1016/j.eti.2019.100427

Ippolito, J. A., Laird, D. A., & Busscher, W. J. (2012). Environmental Benefits of Biochar. *Journal of Environmental Quality*, *41*(4), 967–972. https://doi.org/10.2134/jeq2012.0151

Irani, L. (2004). Understanding gender and confidence in CS course culture. *ACM SIGCSE Bulletin*, *36*(1), 195–199. https://doi.org/10.1145/1028174.971371

Ishii, T., & Kadoya, K. (1994). Effects of charcoal as a soil conditioner on citrus growth and vesicular-arbuscular mycorrhizal development. *Journal of the Japanese Society for Horticultural Science*, *63*(3), 529–535. https://doi.org/10.2503/jjshs.63.529

Jeffery, S., Verheijen, F. G. A., van der Velde, M., & Bastos, A. C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems and Environment*, *144*(1), 175–187. https://doi.org/10.1016/j.agee.2011.08.015

Jewitt, S. (2011). Geographies of shit: Spatial and temporal variations in attitudes towards human waste. *Progress in Human Geography*, *35*(5), 608–626. https://doi.org/10.1177/0309132510394704

Jiang, W., Saxena, A., Song, B., Ward, B. B., Beveridge, T. J., & Myneni, S. C. B. (2004). Elucidation of functional groups on gram-positive and gram-negative bacterial surfaces using infrared spectroscopy. *Langmuir*, *20*(26), 11433–11442. https://doi.org/10.1021/la049043+

Jiménez, B., Drechsel, P., Koné, D., Bahri, A., Raschid-Sally, L., & Qadir, M. (2009a). Wastewater, sludge and excreta use in developing countries: An overview. *Wastewater Irrigation and Health: Assessing and Mitigating Risk in Low-Income Countries*, 3–27. https://doi.org/10.4324/9781849774666

Jiménez, B., Drechsel, P., Koné, D., Bahri, A., Raschid-Sally, L., & Qadir, M. (2009b). Wastewater, sludge and excreta use in developing countries: An overview. *Wastewater Irrigation and Health: Assessing and Mitigating Risk in Low-Income Countries*, 3–27. https://doi.org/10.4324/9781849774666

Jin, H., Arazo, R. O., Gao, J., Capareda, S., & Chang, Z. (2014). Leaching of heavy metals from fast pyrolysis residues produced from different particle sizes of sewage sludge. *Journal of Analytical and Applied Pyrolysis*, *109*, 168–175. https://doi.org/10.1016/j.jaap.2014.06.016

Johannes Lehmann. (2007). Bio-Energy in the Black. *Frontiers in Ecology and the Environment*, *5*(September), 381–387.

Jonsson, H., Stintzing, A. R., Vinneras, B., & Salomon, E. (2004). EcoSanRes Publications Series-Guidelines on the use of urine and faeces in Crop Production. *Journal of Indian Water Works Association*, *37*(4), 293–295.

Joseph, S., Kammann, C. I., Shepherd, J. G., Conte, P., Schmidt, H. P., Hagemann, N., Rich, A. M., Marjo, C. E., Allen, J., Munroe, P., Mitchell, D. R. G., Donne, S., Spokas, K., & Graber, E. R. (2018). Microstructural and associated chemical changes during the composting of a high temperature biochar: Mechanisms for nitrate, phosphate and other nutrient retention and release. *Science of the Total Environment*, *618*(November 2017), 1210–1223. https://doi.org/10.1016/j.scitotenv.2017.09.200

Kajitvichyanukul, P., Ananpattarachai, J., Amuda, O. S., Alade, A. O., Hung, Y.-T., & Wang, L. K. (2008). Landfilling Engineering and Management. In *Biosolids Engineering and Management* (pp. 415–442). Humana Press. https://doi.org/10.1007/978-1-59745-174-1_8

Kamran, M., Malik, Z., Parveen, A., Huang, L., Riaz, M., Bashir, S., Mustafa, A., Abbasi, G. H., Xue, B., & Ali, U. (2020). Ameliorative Effects of Biochar on Rapeseed (Brassica napus L.) Growth and Heavy Metal Immobilization in Soil

Irrigated with Untreated Wastewater. *Journal of Plant Growth Regulation*, *39*(1), 266–281. https://doi.org/10.1007/s00344-019-09980-3

Kandel, D., Raveis, V., & Logan, J. (1983). Sex differences in the characteristics of members lost to a longitudinal panel: A speculative research note. *Public Opinion Quarterly*, *47*(4), 567–575. https://doi.org/10.1086/268813

Karan, S. K., Woolf, D., Azzi, E. S., Sundberg, C., & Wood, S. A. (2023). Potential for biochar carbon sequestration from crop residues: A global spatially explicit assessment. *GCB Bioenergy*, *15*(12), 1424–1436. https://doi.org/10.1111/gcbb.13102

Katzin, D., Marcelis, L. F. M., & van Mourik, S. (2021). Energy savings in greenhouses by transition from high-pressure sodium to LED lighting. *Applied Energy*, *281*, 116019. https://doi.org/10.1016/j.apenergy.2020.116019

Keiluweit, M., Nico, P. S., Johnson, M., & Kleber, M. (2010). Dynamic molecular structure of plant biomass-derived black carbon (biochar). *Environmental Science and Technology*, *44*(4), 1247–1253. https://doi.org/10.1021/es9031419

Kengne, I. M., Soh Kengne, E., Akoa, A., Bemmo, N., Dodane, P. H., & Koné, D. (2011). Vertical-flow constructed wetlands as an emerging solution for faecal sludge dewatering in developing countries. *Journal of Water Sanitation and Hygiene for Development*, *1*(1), 13–19. https://doi.org/10.2166/washdev.2011.001

Khan, S., Chao, C., Waqas, M., Arp, H. P. H., & Zhu, Y. G. (2013). Sewage sludge biochar influence upon rice (Oryza sativa L) yield, metal bioaccumulation and greenhouse gas emissions from acidic paddy soil. *Environmental Science and Technology*, *47*(15), 8624–8632. https://doi.org/10.1021/es400554x

Kim, P., Johnson, A., Edmunds, C. W., Radosevich, M., Vogt, F., Rials, T. G., & Labbé, N. (2011). Surface functionality and carbon structures in lignocellulosic-derived biochars produced by fast pyrolysis. *Energy and Fuels*, *25*(10), 4693–4703. https://doi.org/10.1021/ef200915s

Kinney, T. J., Masiello, C. A., Dugan, B., Hockaday, W. C., Dean, M. R., Zygourakis, K., & Barnes, R. T. (2012). Hydrologic properties of biochars produced at different temperatures. *Biomass and Bioenergy*, *41*, 34–43. https://doi.org/10.1016/j.biombioe.2012.01.033

Kistler, R. C., Brunner, P. H., & Widmer, F. (1987). Behavior of Chromium, Nickel, Copper, Zinc, Cadmium, Mercury, and Lead during the Pyrolysis of Sewage Sludge. *Environmental Science and Technology*, *21*(7), 704–708. https://doi.org/10.1021/es00161a012

Klasson, K. T., Lima, I. M., & Boihem, L. L. (2009). Poultry manure as raw material for mercury adsorbents in gas applications. *Journal of Applied Poultry Research*, *18*(3), 562–569. https://doi.org/10.3382/japr.2009-00011

Koetlisi, K. A., & Muchaonyerwa, P. (2017). Biochar Types from Latrine Waste and Sewage Sludge Differ in Physico-Chemical Properties and Cadmium Adsorption. *American Journal of Applied Sciences*, *14*(11), 1039–1048. https://doi.org/10.3844/ajassp.2017.1039.1048

Koné, D., & Strauss, M. (2004). Low-Cost Options for Treating Faecal Sludges (FS) in Developing Countries – Challenges and Performance *. *9th International IWA Specialist Group Conference on Wetlans Systems for Water Pollution Control and the 6th International IWA Specialist Group Conference on Waste Stabilisation Ponds*, *January 2004*, 7.

Koottatep, T., Surinkul, N., Polprasert, C., Kamal, A. S. M., Koné, D., Montangero, A., Heinss, U., & Strauss, M. (2005). Treatment of septage in constructed wetlands in tropical climate: Lessons learnt from seven years of operation. *Water Science and Technology*, *51*(9), 119–126. https://doi.org/10.2166/wst.2005.0301

Kramer, R. W., Kujawinski, E. B., & Hatcher, P. G. (2004). Identification of black carbon derived structures in a volcanic ash soil humic acid by fourier transform ion cyclotron resonance mass spectrometry. *Environmental Science and Technology*, *38*(12), 3387–3395. https://doi.org/10.1021/es030124m

Krueger, B. C., Fowler, G. D., Templeton, M. R., & Moya, B. (2020). Resource recovery and biochar characteristics from full-scale faecal sludge treatment and co-treatment with agricultural waste. *Water Research*, *169*, 115253. https://doi.org/10.1016/j.watres.2019.115253

Kuffour, A. R., Awuah, E., Anyemedu, F. O. K., Strauss, M., Koné, D., & Cofie, O. (2009). Effect of using different particle sizes of sand as filter media for dewatering faecal sludge. *Desalination*, *248*(1–3), 308–314. https://doi.org/10.1016/j.desal.2008.05.121

Kul, R., Arjumend, T., Ekinci, M., Yildirim, E., Turan, M., & Argin, S. (2021). Biochar as an organic soil conditioner for mitigating salinity stress in tomato. *Soil Science and Plant Nutrition*, *00*(00), 1–14. https://doi.org/10.1080/00380768.2021.1998924

La Notte, L., Giordano, L., Calabrò, E., Bedini, R., Colla, G., Puglisi, G., & Reale, A. (2020). Hybrid and organic photovoltaics for greenhouse applications. *Applied Energy*, *278*, 115582. https://doi.org/10.1016/j.apenergy.2020.115582

Laird, D. A., Brown, R. C., Amonette, J. E., & Lehmann, J. (2009). Review of the pyrolysis platform for coproducing bio-oil and biochar. *Biofuels, Bioproducts and Biorefining*, *3*(5), 547–562. https://doi.org/10.1002/bbb.169

Laird, D. A., Fleming, P., Davis, D. D., Horton, R., Wang, B., & Karlen, D. L. (2010a). Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. *Geoderma*, *158*(3–4), 443–449. https://doi.org/10.1016/j.geoderma.2010.05.013

Laird, D. A., Fleming, P., Davis, D. D., Horton, R., Wang, B., & Karlen, D. L. (2010b). Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. *Geoderma*, *158*(3–4), 443–449. https://doi.org/10.1016/j.geoderma.2010.05.013

Lalander, C. H., Hill, G. B., & Vinnerås, B. (2013). Hygienic quality of faeces treated in urine diverting vermicomposting toilets. *Waste Management*, *33*(11), 2204–2210. https://doi.org/10.1016/j.wasman.2013.07.007

Lama, S. L., Samal, M., & Luitel, S. Water, 17. (2022). CHARACTERIZATION OF FAECAL SLUDGE AND DESIGN OF FAECAL SLUDGE TREATMENT PLANT IN DHULIKHEL MUNICIPALITY. In *Sanitation for all by 2030. Every year, the World Water Day highlights a specific aspect of freshwater.* (p. 17).

Lambers, H., Chapin, F. S., & Pons, T. L. (2008). Plant physiological ecology: Second edition. *Plant Physiological Ecology: Second Edition*, *October*, 1–604. https://doi.org/10.1007/978-0-387-78341-3

Lamin-Samu, A. T., Farghal, M., Ali, M., & Lu, G. (2021). Morpho-Physiological and Transcriptome Changes in Tomato Anthers of Different Developmental Stages under Drought Stress. *Cells*, *10*(7), 1809. https://doi.org/10.3390/cells10071809

Larissa Nicholas, H., Devine, A., Robertson, I., & Mabbett, I. (2023). Perspective Chapter: Agronomic Properties of Biochar from Slow Pyrolysis of Human Waste. In *Sustainable Use of Biochar [Working Title]*. IntechOpen. https://doi.org/10.5772/intechopen.1002187

Latawiec, A. E., Królczyk, J. B., Kuboń, M., Szwedziak, K., Drosik, A., Polańczyk, E., Grotkiewicz, K., & Strassburg, B. B. N. (2017). Willingness to adopt biochar in agriculture: The producer's perspective. *Sustainability (Switzerland)*, *9*(4), 1–13. https://doi.org/10.3390/su9040655

Leave no one behind. (2023). *Nature Water*, *1*(9), 751–751. https://doi.org/10.1038/s44221-023-00137-x

Lehmann, J., & Joseph, S. (2012a). Biochar for Environmental Management. In *Biochar for Environmental Management*. https://doi.org/10.4324/9781849770552

Lehmann, J., & Joseph, S. (2012b). Biochar for environmental management: An introduction. *Biochar for Environmental Management: Science and Technology*, *1*, 1–12. https://doi.org/10.4324/9781849770552

Lehmann, J., & Joseph, S. (2015). Biochar for Environmental Management. In *Biochar for Environmental Management* (2nd ed.).

Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota - A review. *Soil Biology and Biochemistry*, *43*(9), 1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022

Leng, R. A., Preston, T. R., & Inthapanya, S. (2012). Biochar reduces enteric methane and improves growth and feed conversion in local 'Yellow' cattle fed cassava root chips and fresh cassava foliage. *Livestock Research for Rural Development*, *24*(11), 1–8.

Lenth, R. V., Buerkner, P., Herve, M., Love, J., Miguez, F., Riebl, H., Singmann, H., & 2022. (2022). *emmeans: estimated marginal means, aka least-squares mean. R Package Version 1(7): 3.* https://cran.r-project.org/web/packages/emmeans/index.html

Li, R., Zhang, Z., Li, Y., Teng, W., Wang, W., & Yang, T. (2015). Transformation of apatite phosphorus and non-apatite inorganic phosphorus during incineration of sewage sludge. *Chemosphere*, *141*, 57–61. https://doi.org/10.1016/j.chemosphere.2015.05.094

Li, Y. hua, Li, H. bo, Xu, X. yang, Xiao, S. yao, Wang, S. qi, & Xu, S. cong. (2017). Fate of nitrogen in subsurface infiltration system for treating secondary effluent. *Water Science and Engineering*, *10*(3), 217–224. https://doi.org/10.1016/j.wse.2017.10.002

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B., Skjemstad, J. O., Thies, J., Luizão, F. J., Petersen, J., & Neves, E. G. (2006). Black Carbon Increases Cation Exchange Capacity in Soils. *Soil Science Society of America Journal*, *70*(5), 1719–1730. https://doi.org/10.2136/sssaj2005.0383

Liu, T., Liu, B., & Zhang, W. (2014). Nutrients and heavy metals in biochar produced by sewage sludge pyrolysis: Its application in soil amendment. *Polish Journal of Environmental Studies*, *23*(1), 271–275.

Liu, X., Li, Z., Zhang, Y., Feng, R., & Mahmood, I. B. (2014). Characterization of human manure-derived biochar and energy-balance analysis of slow pyrolysis process. *Waste Management*, *34*(9), 1619–1626. https://doi.org/10.1016/J.WASMAN.2014.05.027

Logendra, S., Putman, J. D., & Janes, H. W. (1990). The influence of light period on carbon partitioning, translocation and growth in tomato. *Scientia Horticulturae*, *42*(1–2), 75–83. https://doi.org/10.1016/0304-4238(90)90149-9

Lou, L., Luo, L., Wang, L., Cheng, G., Xu, X., Hou, J., Xun, B., Hu, B., & Chen, Y. (2011). The influence of acid demineralization on surface characteristics of black carbon and its sorption for pentachlorophenol. *Journal of Colloid and Interface Science*, *361*(1), 226–231. https://doi.org/10.1016/j.jcis.2011.05.015

Lu, H., Zhang, W., Wang, S., Zhuang, L., Yang, Y., & Qiu, R. (2013). Characterization of sewage sludge-derived biochars from different feedstocks and pyrolysis temperatures. *Journal of Analytical and Applied Pyrolysis*, *102*, 137–143. https://doi.org/10.1016/j.jaap.2013.03.004

Lua, A. C., Yang, T., & Guo, J. (2004). Effects of pyrolysis conditions on the properties of activated carbons prepared from pistachio-nut shells. *Journal of Analytical and Applied Pyrolysis*, *72*(2), 279–287. https://doi.org/10.1016/j.jaap.2004.08.001

MacCarthy, D. S., Darko, E., Nartey, E. K., Adiku, S. G. K., & Tettey, A. (2020). Integrating biochar and inorganic fertilizer improves productivity and profitability of irrigated rice in Ghana, West Africa. *Agronomy*, *10*(6), 1–23. https://doi.org/10.3390/agronomy10060904

MacKerron, G. J., Egerton, C., Gaskell, C., Parpia, A., & Mourato, S. (2009). Willingness to pay for carbon offset certification and co-benefits among (high-)flying young adults in the UK. *Energy Policy*, *37*(4), 1372–1381. https://doi.org/10.1016/j.enpol.2008.11.023

Mahdavian, M., & Wattanapongsakorn, N. (2017). Optimizing greenhouse lighting for advanced agriculture based on real time electricity market price. *Mathematical Problems in Engineering*, *2017*. https://doi.org/10.1155/2017/6862038

Mamera, M., van Tol, J. J., Aghoghovwia, M. P., Nhantumbo, A. B. J. C., Chabala, L. M., Cambule, A., Chalwe, H., Mufume, J. C., & Rafael, R. B. A. (2021). Potential Use of Biochar in Pit Latrines as a Faecal Sludge Management Strategy to Reduce Water Resource Contaminations: A Review. *Applied Sciences*, *11*(24), 11772. https://doi.org/10.3390/app112411772

Mango, N., Mapemba, L., Tchale, H., Makate, C., Dunjana, N., & Lundy, M. (2015). Comparative analysis of tomato value chain competitiveness in selected areas of Malawi and Mozambique. *Cogent Economics and Finance*, *3*(1). https://doi.org/10.1080/23322039.2015.1088429

Mansoor, S., Kour, N., Manhas, S., Zahid, S., Wani, O. A., Sharma, V., Wijaya, L., Alyemeni, M. N., Alsahli, A. A., El-Serehy, H. A., Paray, B. A., & Ahmad, P. (2021). Biochar as a tool for effective management of drought and heavy metal toxicity. *Chemosphere*, *271*, 129458. https://doi.org/10.1016/j.chemosphere.2020.129458

Mara, D. (2013). Domestic wastewater treatment in developing countries. In *Domestic Wastewater Treatment in Developing Countries* (Issue January 2013). https://doi.org/10.4324/9781849771023

Mara, D., Lane, J., Scott, B., & Trouba, D. (2010). Sanitation and Health. *PLoS Medicine*, *7*(11), e1000363. https://doi.org/10.1371/journal.pmed.1000363

Mason-Renton, S. A., & Luginaah, I. (2018). Conceptualizing waste as a resource: Urban biosolids processing in the rural landscape. *Canadian Geographer*, *62*(2), 266–281. https://doi.org/10.1111/cag.12454

Matsuda, R., Ozawa, N., & Fujiwara, K. (2014). Leaf photosynthesis, plant growth, and carbohydrate accumulation of tomato under different photoperiods and diurnal temperature differences. *Scientia Horticulturae, 170*, 150–158. https://doi.org/10.1016/j.scienta.2014.03.014

McAvoy, R. J., & Janes, H. W. (1984). the Use of High Pressure Sodium Lights in Greenhouse Tomato Crop Production. In *Acta Horticulturae* (Issue 148, pp. 877–888). https://doi.org/10.17660/actahortic.1984.148.115

McLaughlin, M. J. (1984). Phosphorus Considerations. *South African Journal of Plant and Soil*, *1*(1), 1–3. https://doi.org/10.1080/02571862.1984.10634104

Meissner, R., Jacobson, Y., Melamed, S., Levyatuv, S., Shalev, G., Ashri, A., Elkind, Y., & Levy, A. (1997). A new model system for tomato genetics. *The Plant Journal*, *12*(6), 1465–1472. https://doi.org/10.1046/j.1365-313x.1997.12061465.x

Mekuria, W., & Noble, A. (2013). The Role of Biochar in Ameliorating Disturbed Soils and Sequestering Soil Carbon in Tropical Agricultural Production Systems International Water Management Institute (IWMI), 127 Sunil Mawatha , Pelawatte ,. *Applied and Environmental Soil Science*, *2013*.

Méndez, A., Gómez, A., Paz-Ferreiro, J., & Gascó, G. (2012). Effects of sewage sludge biochar on plant metal availability after application to a Mediterranean soil. *Chemosphere*, *89*(11), 1354–1359. https://doi.org/10.1016/j.chemosphere.2012.05.092

Méndez, A., Tarquis, A. M., Saa-Requejo, A., Guerrero, F., & Gascó, G. (2013). Influence of pyrolysis temperature on composted sewage sludge biochar priming effect in a loamy soil. *Chemosphere*, *93*(4), 668–676. https://doi.org/10.1016/j.chemosphere.2013.06.004

Metcalf, L., Eddy, H. P., & Tchobanoglous, G. (2004). *Wastewater engineering : treatment, disposal, and reuse* (fourth ed). McGraw-Hill Publishing Company Ltd.,.

Miller, G., Suzuki, Nn., Ciftci-Yilmaz, S., & Mittler, R. (2010). Reactive oxygen species homeostasis and signalling during drought and salinity stresses. *Plant, Cell & Environment*, *33*(4), 453–467. https://doi.org/10.1111/j.1365-3040.2009.02041.x

Mittler, R., Vanderauwera, S., Gollery, M., & Van Breusegem, F. (2004). Reactive oxygen gene network of plants. *Trends in Plant Science*, *9*(10), 490–498. https://doi.org/10.1016/j.tplants.2004.08.009

Mokaya, R., & Jones, W. (1995). Pillared clays and pillared acid-activated clays: A comparative-study of physical, acidic, and catalytic properties. In *Journal of Catalysis* (Vol. 153, Issue 1, pp. 76–85). https://doi.org/10.1006/jcat.1995.1109

Montusiewicz, A., Lebiocka, M., Rozej, A., Zacharska, E., & Pawłowski, L. (2010). Freezing/thawing effects on anaerobic digestion of mixed sewage sludge. *Bioresource Technology*, *101*(10), 3466–3473. https://doi.org/10.1016/j.biortech.2009.12.125

Moore, D. L., & Tarnai, J. (2002). Evaluating nonresponse error in mail surveys. In *Survey nonresponse*.

Moreno-Jiménez, E., Esteban, E., & Peñalosa, J. M. (2012). The fate of arsenic in soil-plant systems. In *Reviews of Environmental Contamination and Toxicology* (Vol. 215). https://doi.org/10.1007/978-1-4614-1463-6_1

Mulcahy, D. N., Mulcahy, D. L., & Dietz, D. (2013). Biochar soil amendment increases tomato seedling resistance to drought in sandy soils. *Journal of Arid Environments*, *88,* 222–225. https://doi.org/10.1016/j.jaridenv.2012.07.012

Munera-Echeverri, J. L., Martinsen, V., Strand, L. T., Zivanovic, V., Cornelissen, G., & Mulder, J. (2018). Cation exchange capacity of biochar: An urgent method modification. *Science of The Total Environment*, *642*, 190–197. https://doi.org/10.1016/J.SCITOTENV.2018.06.017

Murage, E. N., & Masuda, M. (1997). Response of pepper and eggplant to continuous light in relation to leaf chlorosis and activities of antioxidative enzymes. *Scientia Horticulturae*, *70*(4), 269–279. https://doi.org/10.1016/S0304-4238(97)00078-2

Nabiul Afrooz, A. R. M., & Boehm, A. B. (2017). Effects of submerged zone, media aging, and antecedent dry period on the performance of biochar-amended biofilters in removing fecal indicators and nutrients from natural stormwater. *Ecological Engineering*, *102*, 320–330. https://doi.org/10.1016/j.ecoleng.2017.02.053

Naylor, L. (1997). Biosolids-Meeting the Challenge for Public Acceptance: The Municipal Agricultural Interface. *70th National Conference Water Environment Federation*, *February*, 1–13.

Ngoune Tandzi, L., Mutengwa, C., Ngonkeu, E., & Gracen, V. (2018). Breeding Maize for Tolerance to Acidic Soils: A Review. *Agronomy*, *8*(6), 84. https://doi.org/10.3390/agronomy8060084

Nicholas, H. L., Devine, A., Robertson, I., & Mabbett, I. (2023). The Effect of Faecal Sludge Biochar on the Growth and Yield of Tomato (Solanum lycopersicum L.) Cultivar Micro-Tom. *Agronomy*, *13*(5), 1233. https://doi.org/10.3390/agronomy13051233

Nicholas, H. L., Halfacree, K. H., & Mabbett, I. (2022). Public Perceptions of Faecal Sludge Biochar and Biosolids Use in Agriculture. *Sustainability*, *14*(22), 15385. https://doi.org/10.3390/su142215385

Nicholas, H. L., Mabbett, I., Apsey, H., & Robertson, I. (2022a). Physico-chemical properties of waste derived biochar from community scale faecal sludge treatment plants. *Gates Open Research*, *6*, 96. https://doi.org/10.12688/gatesopenres.13727.2

Nicholas, H. L., Mabbett, I., Apsey, H., & Robertson, I. (2022b). Physico-chemical properties of waste derived biochar from community scale faecal sludge treatment plants. *Gates Open Research*, *6*, 96. https://doi.org/10.12688/gatesopenres.13727.1

Nicholas, H., Winrow, E., Devine, A., Robertson, I., & Mabbett, I. (2023). Faecal sludge pyrolysis as a circular economic approach to waste management and nutrient recovery. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-023-04219-4

Nigussie, A., Kissi, E., Misganaw, M., & Ambaw, G. (2012). Effect of Biochar Application on Soil Properties and Nutrient Uptake of Lettuces (Lactuca sativa) Grown in Chromium Polluted Soils. *& Environ. Sci*, *12*(3), 369376.

Niwagaba, C. B., Mbéguéré, M., & Strande, L. (2014a). Faecal sludge quantification, characterisation and treatment objectives. In D. B. (Editor) Linda Strande, Mariska Ronteltap (Ed.), *Faecal Sludge Management: Systems Approach for Implementation and Operation* (pp. 19–44). IWA Publishing.

Niwagaba, C. B., Mbéguéré, M., & Strande, L. (2014b). Faecal sludge quantification, characterisation and treatment objectives. Faecal Sludge Management: Systems approach for implementation and operation, 19-44. In *Faecal Sludge Management: Systems approach for implementation and operation* (pp. 19–44).

Njenga, P., Willilo, S., & Hine, J. (2015). First Mile Transport Challenges for Smallholder Tomato Farmers along Ihimbo-Itimbo Road, Kilolo District Tanzania Final Report Safe and sustainable transport for rural communities. *International Forum for Rural Transport and Development, October*, 35.

Novak, J., Lima, I., Xing, B., Gaskin, J., Steiner, C., Das, K., Ahmedna, M., Rehrah, D., Watts, D., & Busscher, W. (2009). Characterization of designer biochar produced at different temperatures and their effects on a loamy sand. *Annals of Environmental Science*, *3*(1), 195–206.

Novak, J. M., Busscher, W. J., Laird, D. L., Ahmedna, M., Watts, D. W., & Niandou, M. A. S. (2009). Impact of biochar amendment on fertility of a southeastern coastal plain soil. *Soil Science*, *174*(2), 105–112. https://doi.org/10.1097/SS.0b013e3181981d9a

Novak, J. M., Busscher, W. J., Watts, D. W., Amonette, J. E., Ippolito, J. A., Lima, I. M., Gaskin, J., Das, K. C., Steiner, C., Ahmedna, M., Rehrah, D., & Schomberg, H. (2012). Biochars impact on soil-moisture storage in an ultisol and two aridisols. *Soil Science*, *177*(5), 310–320. https://doi.org/10.1097/SS.0b013e31824e5593

Nyamapfene, K. W. (1991). *The soils of Zimbabwe* (Vol. 1). Nehanda Publishers.

Oguntunde, P. G., Fosu, M., Ajayi, A. E., & van de Giesen, N. (2004). Effects of charcoal production on maize yield, chemical properties and texture of soil. *Biology and Fertility of Soils*, *39*(4), 295–299. https://doi.org/10.1007/s00374-003-0707-1

Omondi, M. O., Xia, X., Nahayo, A., Liu, X., Korai, P. K., & Pan, G. (2016). Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data. *Geoderma*, *274*, 28–34. https://doi.org/10.1016/j.geoderma.2016.03.029

Parizeau, K. (2015). Urban political ecologies of informal recyclers[U+05F3] health in Buenos Aires, Argentina. *Health and Place*, *33*, 67–74. https://doi.org/10.1016/j.healthplace.2015.02.007

Park, J. H., Choppala, G. K., Bolan, N. S., Chung, J. W., & Chuasavathi, T. (2011). Biochar reduces the bioavailability and phytotoxicity of heavy metals. *Plant and Soil*, *348*(1–2), 439–451. https://doi.org/10.1007/s11104-011-0948-y

Paz-Ferreiro, J., Nieto, A., Méndez, A., Askeland, M. P. J., & Gascó, G. (2018). Biochar from biosolids pyrolysis: A review. *International Journal of Environmental Research and Public Health*, *15*(5). https://doi.org/10.3390/ijerph15050956

Peech, M., Alexander, L. T., Dean, L. A., & Reed, J. F. (1947). *Methods of Soil Analysis for Soil Fertility Investigations*.

Pepper, I. L., Brooks, J. P., & Gerba, C. P. (2006). Pathogens in Biosolids. *Advances in Agronomy*, *90*(06), 1–41. https://doi.org/10.1016/S0065-2113(06)90001-7

Perkins, G. (2018). Integration of biocrude production from fast pyrolysis of biomass with solar PV for dispatchable electricity production. *Clean Energy*. https://doi.org/10.1093/ce/zky013

Pham, M. D., Hwang, H., Park, S. W., Cui, M., Lee, H., & Chun, C. (2019). Leaf chlorosis, epinasty, carbohydrate contents and growth of tomato show different responses to the red/blue wavelength ratio under continuous light. *Plant Physiology and Biochemistry*, *141*, 477–486. https://doi.org/10.1016/j.plaphy.2019.06.004

Pokhrel, S. P., Milke, M. W., Bello-Mendoza, R., Buitrón, G., & Thiele, J. (2018). Use of solid phosphorus fractionation data to evaluate phosphorus release from waste activated sludge. *Waste Management*, *76*, 90–97. https://doi.org/10.1016/j.wasman.2018.03.008

Porter, S. R., & Whitcomb, M. E. (2005). Non-response in student surveys: The role of demographics, engagement and personality. *Research in Higher Education*, *46*(2), 127–152. https://doi.org/10.1007/s11162-004-1597-2

Powell, T. (1993). Communications plan on biosolids. In *Water Environ. Federation*.

Qian, L., & Chen, B. (2013). Dual role of biochars as adsorbents for aluminum: The effects of oxygen-containing organic components and the scattering of silicate particles. *Environmental Science and Technology*, *47*(15), 8759–8768. https://doi.org/10.1021/es401756h

Rehrah, D., Reddy, M. R., Novak, J. M., Bansode, R. R., Schimmel, K. A., Yu, J., Watts, D. W., & Ahmedna, M. (2014). Production and characterization of biochars from agricultural by-products for use in soil quality enhancement. *Journal of Analytical and Applied Pyrolysis*, *108*, 301–309. https://doi.org/10.1016/j.jaap.2014.03.008

Ricker-Gilbert, J. (2020). Inorganic Fertiliser Use Among Smallholder Farmers in Sub-Saharan Africa: Implications for Input Subsidy Policies. In *The Role of Smallholder Farms in Food and Nutrition Security* (pp. 81–98). Springer International Publishing. https://doi.org/10.1007/978-3-030-42148-9_5

Rizwan, M., Rehman, M. Z. U., Ali, S., Abbas, T., Maqbool, A., & Bashir, A. (2018). Biochar is a potential source of silicon fertilizer: An overview. In *Biochar from*

Biomass and Waste: Fundamentals and Applications (Issue November). Elsevier Inc. https://doi.org/10.1016/B978-0-12-811729-3.00012-1

Robinson, K. G., Robinson, C. H., Raup, L. A., & Markum, T. R. (2012). Public attitudes and risk perception toward land application of biosolids within the south-eastern United States. *Journal of Environmental Management*, *98*(1), 29–36. https://doi.org/10.1016/j.jenvman.2011.12.012

Rombel, A., Krasucka, P., & Oleszczuk, P. (2022). Sustainable biochar-based soil fertilizers and amendments as a new trend in biochar research. *Science of The Total Environment*, *816*, 151588. https://doi.org/10.1016/j.scitotenv.2021.151588

Ronsse, F., van Hecke, S., Dickinson, D., & Prins, W. (2013). Production and characterization of slow pyrolysis biochar: Influence of feedstock type and pyrolysis conditions. *GCB Bioenergy*, *5*(2), 104–115. https://doi.org/10.1111/gcbb.12018

Sadeghi, S. H., Hazbavi, Z., & Harchegani, M. K. (2016). Controllability of runoff and soil loss from small plots treated by vinasse-produced biochar. *Science of The Total Environment*, *541*, 483–490. https://doi.org/10.1016/j.scitotenv.2015.09.068

Sainju, U. M., Dris, R., & Singh, B. (2003). Mineral nutrition of tomato. *Food, Agriculture & Environment*, *1*(2), 176–184.

Salinger, M. J., Sivakumar, M. V. K., & Motha, R. (2005). *REDUCING VULNERABILITY OF AGRICULTURE AND FORESTRY TO CLIMATE VARIABILITY AND CHANGE : WORKSHOP SUMMARY AND RECOMMENDATIONS Climate change and variability , drought and other climate-related extremes have a direct influence on the quantity and quality of* . 341–362.

Samsuri, A. W., Sadegh-Zadeh, F., & Seh-Bardan, B. J. (2013). Adsorption of As(III) and As(V) by Fe coated biochars and biochars produced from empty fruit bunch and rice husk. *Journal of Environmental Chemical Engineering*, *1*(4), 981–988. https://doi.org/10.1016/j.jece.2013.08.009

Sánchez-Monedero, M. A., Mondini, C., De Nobili, M., Leita, L., & Roig, A. (2004). Land application of biosolids. Soil response to different stabilization degree of the treated organic matter. *Waste Management*, *24*(4), 325–332. https://doi.org/10.1016/j.wasman.2003.08.006

Sax, L. J., Gilmartin, S. K., & Bryant, A. N. (2003). ASSESSING RESPONSE RATES AND NONRESPONSE BIAS IN WEB AND PAPER SURVEYS , , Vol 44 n°4, 2003, p409-432. *Research in Higher Education*, *44*(4), 409–432.

Schimmelpfennig, S., & Glaser, B. (2012). One Step Forward toward Characterization: Some Important Material Properties to Distinguish Biochars. *Journal of Environmental Quality*, *41*(4), 1001–1013. https://doi.org/10.2134/jeq2011.0146

Schoebitz, L., Bassan, M., Ferré, A., Vu, T. H. A., Nguyen, V. A., & Strande, L. (2014). Conference paper: FAQ: faecal sludge quantification and characterization – field trial of methodology in Hanoi, Vietnam. *37th WEDC International Conference*, 1–6.

Septien, S., Mirara, S. W., Makununika, B. S. N., Singh, A., Pocock, J., Velkushanova, K., & Buckley, C. A. (2020). Effect of drying on the physical and chemical properties of faecal sludge for its reuse. *Journal of Environmental Chemical Engineering*, *8*(1), 103652. https://doi.org/10.1016/j.jece.2019.103652

Shahrokh Abadi, M. H., Delbari, A., Fakoor, Z., & Baedi, J. (2015). Effects of annealing temperature on infrared spectra of SiO2 extracted from rice husk. *Journal of Ceramic Science and Technology*, *6*(1), 41–45. https://doi.org/10.4416/JCST2014-00028

Shao, M., Liu, W., Zhou, C., Wang, Q., & Li, B. (2022). Alternation of temporally overlapped red and blue light under continuous irradiation affected yield, antioxidant capacity and nutritional quality of purple-leaf lettuce. *Scientia Horticulturae*, *295*. https://doi.org/10.1016/j.scienta.2021.110864

Sharma, R. K., Wooten, J. B., Baliga, V. L., Lin, X., Chan, W. G., & Hajaligol, M. R. (2004). Characterization of chars from pyrolysis of lignin. *Fuel*, *83*(11–12), 1469–1482. https://doi.org/10.1016/j.fuel.2003.11.015

Sheahan, M., & Barrett, C. B. (2017). Ten striking facts about agricultural input use in Sub-Saharan Africa. *Food Policy*, *67*, 12–25. https://doi.org/10.1016/j.foodpol.2016.09.010

Sing, K. S. W., & Williams, R. T. (2004). Physisorption hysteresis loops and the characterization of nanoporous materials. *Adsorption Science and Technology*, *22*(10), 773–782. https://doi.org/10.1260/0263617053499032

Singer, E., Groves, R. M., & Corning, A. (1999). Differential Incentives: Beliefs about Practices, Perceptions of Equity, and Effects on Survey Participation. *Public Opinion Quarterly*, *63*(2), 251–260. https://doi.org/10.1086/297714

Singh, B., Dolk, M. M., Shen, Q., & Camps-Arbestain, M. (2017). Biochar pH, electrical conductivity and liming potential. *Biochar: A Guide to Analytical Methods*, *June 2018*, 23–38. https://doi.org/10.13040/IJPSR.0975-8232.5(2).607-1

Singh, B., Singh, B. P., & Cowie, A. L. (2010a). Characterisation and evaluation of biochars for their application as a soil amendment. *Australian Journal of Soil Research*, *48*(6–7), 516–525. https://doi.org/10.1071/SR10058

Singh, B., Singh, B. P., & Cowie, A. L. (2010b). Characterisation and evaluation of biochars for their application as a soil amendment. *Australian Journal of Soil Research*, *48*(6–7), 516–525. https://doi.org/10.1071/SR10058

Singh, S., Mohan, R. R., Rathi, S., & Raju, N. J. (2017). Technology options for faecal sludge management in developing countries: Benefits and revenue from reuse. *Environmental Technology & Innovation*, *7*, 203–218. https://doi.org/10.1016/j.eti.2017.02.004

Sivakumar, R., & Srividhya, S. (2016). Impact of drought on flowering, yield and quality parameters in diverse genotypes of tomato (Solanum lycopersicum L.). *Advances in Horticultural Science*, *30*(1), 3–11. https://doi.org/10.13128/ahs-18696

Slovic, P. (2016). Trust, emotion, sex, politics and science: Surveying the risk-assessment battlefield. *The Perception of Risk*, *19*(4), 390–412. https://doi.org/10.1111/j.1539-6924.1999.tb00439.x

Smider, B., & Singh, B. (2014). Agronomic performance of a high ash biochar in two contrasting soils. *Agriculture, Ecosystems and Environment*, *191*, 99–107. https://doi.org/10.1016/j.agee.2014.01.024

Smil, V. (2000). *PHOSPHORUS IN THE ENVIRONMENT : Natural Flows and Human Interferences*. 53–88.

Snel, M., & Shordt, K. (2005). The evidence to support hygiene, sanitation and water in schools. *Waterlines, 23*(3), 2–5.

Socrates, G. (2001). *Infrared and Raman Characteristic Group Frequencies* (3rd ed.). John Wiley & Sons.

Sohi, S. P., Krull, E., Lopez-Capel, E., & Bol, R. (2010). *A Review of Biochar and Its Use and Function in Soil* (pp. 47–82). https://doi.org/10.1016/S0065-2113(10)05002-9

Solankey, S. S., Singh, R. K., Baranwal, D. K., & Singh, D. K. (2015). Genetic Expression of Tomato for Heat and Drought Stress Tolerance: An Overview. *International Journal of Vegetable Science*, *21*(5), 496–515. https://doi.org/10.1080/19315260.2014.902414

Sommers, L. E. (1977). Chemical Composition of Sewage Sludges and Analysis of Their Potential Use as Fertilizers. *Journal of Environmental Quality*, *6*(2), 225–232. https://doi.org/10.2134/jeq1977.00472425000600020026x

Song, W., & Guo, M. (2012a). Quality variations of poultry litter biochar generated at different pyrolysis temperatures. *Journal of Analytical and Applied Pyrolysis*, *94*, 138–145. https://doi.org/10.1016/j.jaap.2011.11.018

Song, W., & Guo, M. (2012b). Quality variations of poultry litter biochar generated at different pyrolysis temperatures. *Journal of Analytical and Applied Pyrolysis*, *94*, 138–145. https://doi.org/10.1016/j.jaap.2011.11.018

Song, X. D., Xue, X. Y., Chen, D. Z., He, P. J., & Dai, X. H. (2014). Application of biochar from sewage sludge to plant cultivation: Influence of pyrolysis temperature and biochar-to-soil ratio on yield and heavy metal accumulation. *Chemosphere*, *109*, 213–220. https://doi.org/10.1016/j.chemosphere.2014.01.070

Sörme, L., & Lagerkvist, R. (2002). Sources of heavy metals in urban wastewater in Stockholm. *Science of the Total Environment*, *298*(1–3), 131–145. https://doi.org/10.1016/S0048-9697(02)00197-3

Sousa, A. A. T. C., & Figueiredo, C. C. (2016). Sewage sludge biochar: Effects on soil fertility and growth of radish. *Biological Agriculture and Horticulture*, *32*(2), 127–138. https://doi.org/10.1080/01448765.2015.1093545

Spokas, K. A. (2010). Review of the stability of biochar in soils: predictability of O:C molar ratios. *Carbon Management*, *1*(2), 289–303. https://doi.org/10.4155/cmt.10.32

Spokas, K. A., Cantrell, K. B., Novak, J. M., Archer, D. W., Ippolito, J. A., Collins, H. P., Boateng, A. A., Lima, I. M., Lamb, M. C., McAloon, A. J., Lentz, R. D., & Nichols, K. A. (2012). Biochar: A Synthesis of Its Agronomic Impact beyond Carbon Sequestration. *Journal of Environmental Quality*, *41*(4), 973–989. https://doi.org/10.2134/jeq2011.0069

Srinivasan, P., Sarmah, A. K., Smernik, R., Das, O., Farid, M., & Gao, W. (2015). A feasibility study of agricultural and sewage biomass as biochar, bioenergy and biocomposite feedstock: Production, characterization and potential applications. *Science of the Total Environment*, *512–513*, 495–505. https://doi.org/10.1016/j.scitotenv.2015.01.068

Stahel, W. R. (2016). The circular economy. *Nature*, *531*(7595), 435–438. https://doi.org/10.1038/531435a

Steen, I. (1998). Phosphorus availability in the 21st century : Management of a non-renewable resource. *Phosphorus Potassium*, *217*(Cl), 25–31.

Steger, M. A. E., & Witt, S. L. (1989). Gender Differences in Environmental Orientations: A Comparison of Publics and Activists in Canada and the U. S. *The Western Political Quarterly*, *42*(4), 627. https://doi.org/10.2307/448646

Steinbeiss, S., Gleixner, G., & Antonietti, M. (2009). Effect of biochar amendment on soil carbon balance and soil microbial activity. *Soil Biology and Biochemistry*, *41*(6), 1301–1310. https://doi.org/10.1016/j.soilbio.2009.03.016

Stoknes, P. E., Soldal, O. B., Hansen, S., Kvande, I., & Skjelderup, S. W. (2021). Willingness to Pay for Crowdfunding Local Agricultural Climate Solutions. *Sustainability*, *13*(16), 9227. https://doi.org/10.3390/su13169227

Strande, L., Brdjanovic, D., & Ronteltap, M. (2014a). *Faecal Sludge Management: Systems Approach for Implementation and Operation* (D. Brdjanovic & M. Ronteltap, Eds.). IWA Publishing.

Strande, L., Brdjanovic, D., & Ronteltap, M. (2014b). *Faecal Sludge Management: Systems Approach for Implementation and Operation* (D. Brdjanovic & M. Ronteltap, Eds.). IWA Publishing.

Strauss, M., Montangero, A., Sandec, E. /, & Management, D. W. (2002). Feacal Sludge Management Review of Practices, Problems and Initiatives Capacity Building for Effective. *Duebendorf, Water and Sanitation in Developing Countries EAWAG/SANDEC*.

Stuart, B. H. (2004). *Infrared Spectroscopy: Fundamentals and Applications*. John Wiley & Sons, Ltd. https://doi.org/10.1002/0470011149

Sun, J., He, F., Shao, H., Zhang, Z., & Xu, G. (2016). Effects of biochar application on Suaeda salsa growth and saline soil properties. *Environmental Earth Sciences*, *75*(8), 1–6. https://doi.org/10.1007/s12665-016-5440-9

Sun, S., Huang, X., Lin, J., Ma, R., Fang, L., Zhang, P., Qu, J., Zhang, X., & Liu, Y. (2018). Study on the effects of catalysts on the immobilization efficiency and mechanism of heavy metals during the microwave pyrolysis of sludge. *Waste Management*, *77*, 131–139. https://doi.org/10.1016/j.wasman.2018.04.046

Tag, A. T., Duman, G., Ucar, S., & Yanik, J. (2016). Effects of feedstock type and pyrolysis temperature on potential applications of biochar. *Journal of Analytical and Applied Pyrolysis*, *120*, 200–206. https://doi.org/10.1016/j.jaap.2016.05.006

Tartaglia, M., Arena, S., Scaloni, A., Marra, M., & Rocco, M. (2020). Biochar Administration to San Marzano Tomato Plants Cultivated Under Low-Input Farming Increases Growth, Fruit Yield, and Affects Gene Expression. *Frontiers in Plant Science*, *11*(August), 1–11. https://doi.org/10.3389/fpls.2020.01281

Tayler, K. (2018). *Faecal Sludge and Septage Treatment*. Practical Action Publishing. https://doi.org/10.3362/9781780449869

Tchobanoglous, G., Burton, F. L., & Stensel, H. D. (2003). Wastewater Engineering, Treatment and Reuse. In M. & EDDY (Ed.), *Wastewater Engineering, Treatment and Reuse* (4th ed.). McGraw-Hill Companies, Inc.

Thies, J. E., & Rillig, M. C. (2009). Characteristics of biochar: biological properties. In J. Lehmann & S. Joseph (Eds.), *Biochar for Environmental Management.* (pp. 85–105). Earthscan.

Thomas, C., Lane, A., Oreszczyn, S., Schiller, F., & Yoxon, M. (2009). *Attitudes to the use of organic waste resources to land*. *October*.

Thommes, M., Kaneko, K., Neimark, A. V., Olivier, J. P., Rodriguez-Reinoso, F., Rouquerol, J., & Sing, K. S. W. (2015). Physisorption of gases, with special reference to the evaluation of surface area and pore size distribution (IUPAC Technical Report). *Pure and Applied Chemistry*, *87*(9–10), 1051–1069. https://doi.org/10.1515/pac-2014-1117

Tian, Y., Cui, L., Lin, Q., Li, G., & Zhao, X. (2019). The sewage sludge biochar at low pyrolysis temperature had better improvement in urban soil and turf grass. *Agronomy*, *9*(3). https://doi.org/10.3390/agronomy9030156

Tian, Y., Zhang, J., Zuo, W., Chen, L., Cui, Y., & Tan, T. (2013). Nitrogen conversion in relation to NH3 and HCN during microwave pyrolysis of sewage sludge. *Environmental Science and Technology*, *47*(7), 3498–3505. https://doi.org/10.1021/es304248j

Tomczyk, A., Sokołowska, Z., & Boguta, P. (2020). Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. *Reviews in Environmental Science and Biotechnology*, *19*(1), 191–215. https://doi.org/10.1007/s11157-020-09523-3

Toor, R. K., Lister, C. E., & Savage, G. P. (2005). Antioxidant activities of New Zealand-grown tomatoes. *International Journal of Food Sciences and Nutrition*, *56*(8), 597–605. https://doi.org/10.1080/09637480500490400

Uchimiya, M., Wartelle, L. H., Klasson, K. T., Fortier, C. A., & Lima, I. M. (2011). Influence of pyrolysis temperature on biochar property and function as a heavy metal sorbent in soil. *Journal of Agricultural and Food Chemistry*, *59*(6), 2501–2510. https://doi.org/10.1021/jf104206c

Ulrich, B. A., Loehnert, M., & Higgins, C. P. (2017). Improved contaminant removal in vegetated stormwater biofilters amended with biochar. *Environmental Science: Water Research and Technology*, *3*(4), 726–734. https://doi.org/10.1039/c7ew00070g

UN. (2015). *Transforming our world: the 2030 Agenda for Sustainable Development, United Nations, New York*. https://sustainabledevelopment.un.org/post2015/transformingourworld%0A

UNICEF & WHO. (2020). *State of the World's Sanitation: An urgent call to transform sanitation for better health, environments, economies and societies*.

UNICEF, & WHO. (2017). Progress on Drinking Water, Sanitation and Hygiene - Joint Monitoring Programme 2017 Update and SDG Baselines. *Who*, 66. https://doi.org/10.1111 / tmi.12329

UN-Water. (2021). Summary Progress Update 2021 : SDG 6 — water and sanitation for all. *UN-Water Integrated Monitoring Initiative*, 1–58.

Uzoma, K. C., Inoue, M., Andry, H., Fujimaki, H., Zahoor, A., & Nishihara, E. (2011). Effect of cow manure biochar on maize productivity under sandy soil condition. *Soil Use and Management*, *27*(2), 205–212. https://doi.org/10.1111/j.1475-2743.2011.00340.x

Van Vuuren, D. P., Bouwman, A. F., & Beusen, A. H. W. (2010). Phosphorus demand for the 1970-2100 period: A scenario analysis of resource depletion. *Global Environmental Change*, *20*(3), 428–439. https://doi.org/10.1016/j.gloenvcha.2010.04.004

Velez-Ramirez, A. I., Van Ieperen, W., Vreugdenhil, D., & Millenaar, F. F. (2011). Plants under continuous light. *Trends in Plant Science*, *16*(6), 310–318. https://doi.org/10.1016/j.tplants.2011.02.003

Velez-Ramirez, A. I., Van Ieperen, W., Vreugdenhil, D., Van Poppel, P. M. J. A., Heuvelink, E., & Millenaar, F. F. (2014a). A single locus confers tolerance to continuous light and allows substantial yield increase in tomato. *Nature Communications*, *5*. https://doi.org/10.1038/ncomms5549

Velez-Ramirez, A. I., Van Ieperen, W., Vreugdenhil, D., Van Poppel, P. M. J. A., Heuvelink, E., & Millenaar, F. F. (2014b). A single locus confers tolerance to continuous light and allows substantial yield increase in tomato. *Nature Communications*, *5*. https://doi.org/10.1038/ncomms5549

Velez-Ramirez, A. I., Vreugdenhil, D., Millenaar, F. F., & van Ieperen, W. (2019). Phytochrome a protects tomato plants from injuries induced by continuous light. *Frontiers in Plant Science*, *10*(January), 1–11. https://doi.org/10.3389/fpls.2019.00019

Viger, M., Hancock, R. D., Miglietta, F., & Taylor, G. (2015). More plant growth but less plant defence? First global gene expression data for plants grown in soil amended with biochar. *GCB Bioenergy*, *7*(4), 658–672. https://doi.org/10.1111/gcbb.12182

von Uexküll, H., & Mutert, E. (1995). Global extent, development and economic impact of acid soils. In *Plant–Soil Interactions at Low pH: Principles and Management.* (pp. 5–19). Kluwer Academic Publishers.

Wahb-Allah, M. A., Alsadon, A. A., & Ibrahim, A. A. (2011). Drought tolerance of several tomato genotypes under greenhouse conditions. *World Applied Sciences Journal*, *15*(7), 933–940.

Wang, H., Brown, S. L., Magesan, G. N., Slade, A. H., Quintern, M., Clinton, P. W., & Payn, T. W. (2008). Technological options for the management of biosolids. *Environmental Science and Pollution Research*, *15*(4), 308–317. https://doi.org/10.1007/s11356-008-0012-5

Wang, S., Zhang, H., Huang, H., Xiao, R., Li, R., & Zhang, Z. (2020). Influence of temperature and residence time on characteristics of biochars derived from agricultural residues: A comprehensive evaluation. *Process Safety and Environmental Protection*, *139*, 218–229. https://doi.org/10.1016/j.psep.2020.03.028

Wang, X., Li, C., Zhang, B., Lin, J., Chi, Q., & Wang, Y. (2016). Migration and risk assessment of heavy metals in sewage sludge during hydrothermal treatment combined with pyrolysis. *Bioresource Technology*, *221*, 560–567. https://doi.org/10.1016/j.biortech.2016.09.069

Wang, Y., Xiao, X., Xu, Y., & Chen, B. (2019). Environmental Effects of Silicon within Biochar (Sichar) and Carbon-Silicon Coupling Mechanisms: A Critical Review. *Environmental Science and Technology*, *53*(23), 13570–13582. https://doi.org/10.1021/acs.est.9b03607

Wang, Z., Liu, S., Liu, K., Ji, S., Wang, M., & Shu, X. (2021). Effect of temperature on pyrolysis of sewage sludge: Biochar properties and environmental risks from heavy metals. *E3S Web of Conferences*, *237*. https://doi.org/10.1051/e3sconf/202123701040

Waqas, M., Li, G., Khan, S., Shamshad, I., Reid, B. J., Qamar, Z., & Chao, C. (2015). Application of sewage sludge and sewage sludge biochar to reduce polycyclic aromatic hydrocarbons (PAH) and potentially toxic elements (PTE) accumulation in tomato. *Environmental Science and Pollution Research*, *22*(16), 12114–12123. https://doi.org/10.1007/s11356-015-4432-8

Weber, K., & Quicker, P. (2018a). Properties of biochar. *Fuel*, *217*(January), 240–261. https://doi.org/10.1016/j.fuel.2017.12.054

Weber, K., & Quicker, P. (2018b). Properties of biochar. *Fuel*, *217*(January), 240–261. https://doi.org/10.1016/j.fuel.2017.12.054

Wei, R., Li, H., Chen, Y., Hu, Y., Long, H., Li, J., & Xu, C. C. (2022). Environmental Issues Related to Bioenergy. In *Comprehensive Renewable Energy* (pp. 92–106). Elsevier. https://doi.org/10.1016/B978-0-12-819727-1.00011-X

Wen, B., Zhang, J. J., Zhang, S. Z., Shan, X. Q., Khan, S. U., & Xing, B. (2007). Phenanthrene sorption to soil humic acid and different humin fractions. *Environmental Science and Technology*, *41*(9), 3165–3171. https://doi.org/10.1021/es062262s

Whitehouse, S., Tsigaris, P., Wood, J., & Fraser, L. H. (2022). Biosolids in Western Canada: A Case Study on Public Risk Perception and Factors Influencing Public

Attitudes. *Environmental Management*, *69*(1), 179–195. https://doi.org/10.1007/s00267-021-01540-4

WHO. (2017). *Updates fact sheet on Diarrhoeal diseases.* . Geneva: World Health Organization;

WHO. (2020a). *Global Health Estimates 2020: Deaths by Cause, Age, Sex, by Country and by Region, 2000-2019*.

WHO. (2020b). 'Progress on household drinking water, sanitation and hygiene 2000-2020: five years into the SDGs.' In *Sanitation and hygiene*.

WHO and UNICEF. (2023). *Progress on Household Drinking Water, Sanitation and Hygiene W*. http://apps.who.int/bookorders.

WHO, & UNICEF. (2017). *Progress on household drinking water, sanitation and hygiene 2000-2017. Special focus on inequalities. New York: United Nations Children's Fund (UNICEF) and World Health Organization, 2019.*

Woldetsadik, D., Drechsel, P., Marschner, B., Itanna, F., & Gebrekidan, H. (2018). Effect of biochar derived from faecal matter on yield and nutrient content of lettuce (Lactuca sativa) in two contrasting soils. *Environmental Systems Research*, *6*(1). https://doi.org/10.1186/s40068-017-0082-9

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*. https://doi.org/10.1038/ncomms1053

World Bank. (2015a). Ending Poverty and Hunger by 2030 An Agenda for the global food system. Second Edition with foreword. *Ending Poverty and Hunger by 2030*, *May*(Second Edition), 3–6.

World Bank. (2015b). Ending Poverty and Hunger by 2030 An Agenda for the global food system. Second Edition with foreword. *Ending Poverty and Hunger by 2030*, *May*(Second Edition), 3–6.

WWAP. (2018). The United Nations world water development report 2018: Nature-Based Solutions for Water. In *Unesco*.

Xu, G., Yang, X., & Spinosa, L. (2015). Development of sludge-based adsorbents: Preparation, characterization, utilization and its feasibility assessment. *Journal of Environmental Management*, *151*, 221–232. https://doi.org/10.1016/j.jenvman.2014.08.001

Xu, J., Guo, Z., Jiang, X., Ahammed, G. J., & Zhou, Y. (2021). Light regulation of horticultural crop nutrient uptake and utilization. *Horticultural Plant Journal*, *7*(5), 367–379. https://doi.org/10.1016/j.hpj.2021.01.005

Xu, X., Cao, X., Zhao, L., & Sun, T. (2014). Comparison of sewage sludge- and pig manure-derived biochars for hydrogen sulfide removal. *Chemosphere*, *111*, 296–303. https://doi.org/10.1016/j.chemosphere.2014.04.014

Yang, F., LEE, X. qing, & Wang, B. (2015). Characterization of biochars produced from seven biomasses grown in three different climate zones. *Chinese Journal of Geochemistry*, *34*(4), 592–600. https://doi.org/10.1007/s11631-015-0072-4

Yao, Y., Gao, B., Inyang, M., Zimmerman, A. R., Cao, X., Pullammanappallil, P., & Yang, L. (2011). Biochar derived from anaerobically digested sugar beet tailings: Characterization and phosphate removal potential. *Bioresource Technology*, *102*(10), 6273–6278. https://doi.org/10.1016/j.biortech.2011.03.006

Ye, L., Camps-Arbestain, M., Shen, Q., Lehmann, J., Singh, B., & Sabir, M. (2020). Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls. *Soil Use and Management*, *36*(1), 2–18. https://doi.org/10.1111/sum.12546

You, J., Sun, L., Liu, X., Hu, X., & Xu, Q. (2019). Effects of sewage sludge biochar on soil characteristics and crop yield in loamy sand soil. *Polish Journal of Environmental Studies*, *28*(4), 2973–2980. https://doi.org/10.15244/pjoes/93294

Yu, H., Zou, W., Chen, J., Chen, H., Yu, Z., Huang, J., Tang, H., Wei, X., & Gao, B. (2019). Biochar amendment improves crop production in problem soils: A review. *Journal of Environmental Management*, *232*, 8–21. https://doi.org/10.1016/j.jenvman.2018.10.117

Yu, X., Tian, X., Lu, Y., Liu, Z., Guo, Y., Chen, J., Li, C., Zhang, M., & Wan, Y. (2018). Combined effects of straw-derived biochar and bio-based polymer-coated urea on nitrogen use efficiency and cotton yield. *Chemical Speciation &*

Bioavailability, *30*(1), 112–122. https://doi.org/10.1080/09542299.2018.1518730

Yu, X.-Y., Ying, G.-G., & Kookana, R. S. (2009). Reduced plant uptake of pesticides with biochar additions to soil. *Chemosphere*, *76*(5), 665–671. https://doi.org/10.1016/j.chemosphere.2009.04.001

Yuan, H., Lu, T., Wang, Y., Chen, Y., & Lei, T. (2016). Sewage sludge biochar: Nutrient composition and its effect on the leaching of soil nutrients. *Geoderma*, *267*, 17–23. https://doi.org/10.1016/j.geoderma.2015.12.020

Yuan, J. H., Xu, R. K., Wang, N., & Li, J. Y. (2011). Amendment of Acid Soils with Crop Residues and Biochars. *Pedosphere*, *21*(3), 302–308. https://doi.org/10.1016/S1002-0160(11)60130-6

Yuan, J. H., Xu, R. K., & Zhang, H. (2011a). The forms of alkalis in the biochar produced from crop residues at different temperatures. *Bioresource Technology*, *102*(3), 3488–3497. https://doi.org/10.1016/j.biortech.2010.11.018

Yuan, J. H., Xu, R. K., & Zhang, H. (2011b). The forms of alkalis in the biochar produced from crop residues at different temperatures. *Bioresource Technology*, *102*(3), 3488–3497. https://doi.org/10.1016/j.biortech.2010.11.018

Zhang, J., Lü, F., Zhang, H., Shao, L., Chen, D., & He, P. (2015). Multiscale visualization of the structural and characteristic changes of sewage sludge biochar oriented towards potential agronomic and environmental implication. *Scientific Reports*, *5*, 1–8. https://doi.org/10.1038/srep09406

Zhang, X., Wang, H., He, L., Lu, K., Sarmah, A., Li, J., Bolan, N. S., Pei, J., & Huang, H. (2013). Using biochar for remediation of soils contaminated with heavy metals and organic pollutants. *Environmental Science and Pollution Research*, *20*(12), 8472–8483. https://doi.org/10.1007/s11356-013-1659-0

Zhang, Y., Chen, T., Liao, Y., Reid, B. J., Chi, H., Hou, Y., & Cai, C. (2016). Modest amendment of sewage sludge biochar to reduce the accumulation of cadmium into rice(Oryza sativa L.): A field study. *Environmental Pollution*, *216*, 819–825. https://doi.org/10.1016/j.envpol.2016.06.053

Zhao, L., Cao, X., Mašek, O., & Zimmerman, A. (2013). Heterogeneity of biochar properties as a function of feedstock sources and production temperatures. *Journal of Hazardous Materials*, *256–257*, 1–9. https://doi.org/10.1016/j.jhazmat.2013.04.015

Zielińska, A., Oleszczuk, P., Charmas, B., Skubiszewska-Zięba, J., & Pasieczna-Patkowska, S. (2015). Effect of sewage sludge properties on the biochar characteristic. *Journal of Analytical and Applied Pyrolysis*, *112*, 201–213. https://doi.org/10.1016/j.jaap.2015.01.025

Zorpas, A. A., Kapetanios, E., Zorpas, G. A., Karlis, P., Vlyssides, A., Haralambous, I., & Loizidou, M. (2000). Compost produced from organic fraction of municipal solid waste, primary stabilized sewage sludge and natural zeolite. *Journal of Hazardous Materials*, *77*(1–3), 149–159. https://doi.org/10.1016/S0304-3894(00)00233-8

Zuidgeest, M., Hendriks, M., Koopman, L., Spreeuwenberg, P., & Rademakers, J. (2011). A Comparison of a Postal Survey and Mixed-Mode Survey Using a Questionnaire on Patients' Experiences With Breast Care. *Journal of Medical Internet Research*, *13*(3), e68. https://doi.org/10.2196/jmir.1241

Zuma, L., Velkushanova, K., & Buckley, C. (2015). Chemical and thermal properties of VIP latrine sludge. *Water SA*, *41*(4), 534–540. https://doi.org/10.4314/wsa.v41i4.13

APPENDICES

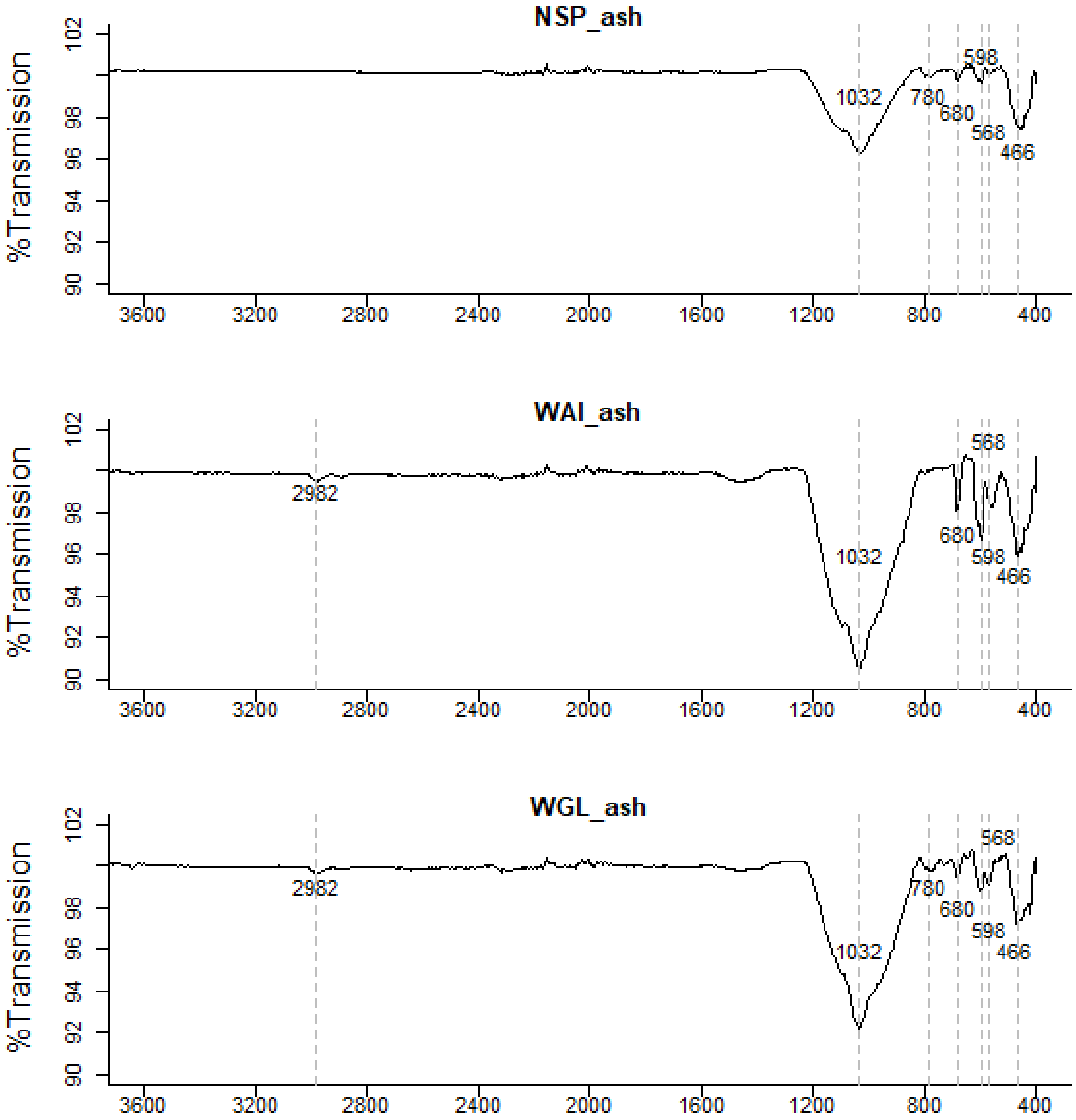
1 - SUPPLEMENTARY INFORMATION CHAPTER 4

FTIR Results

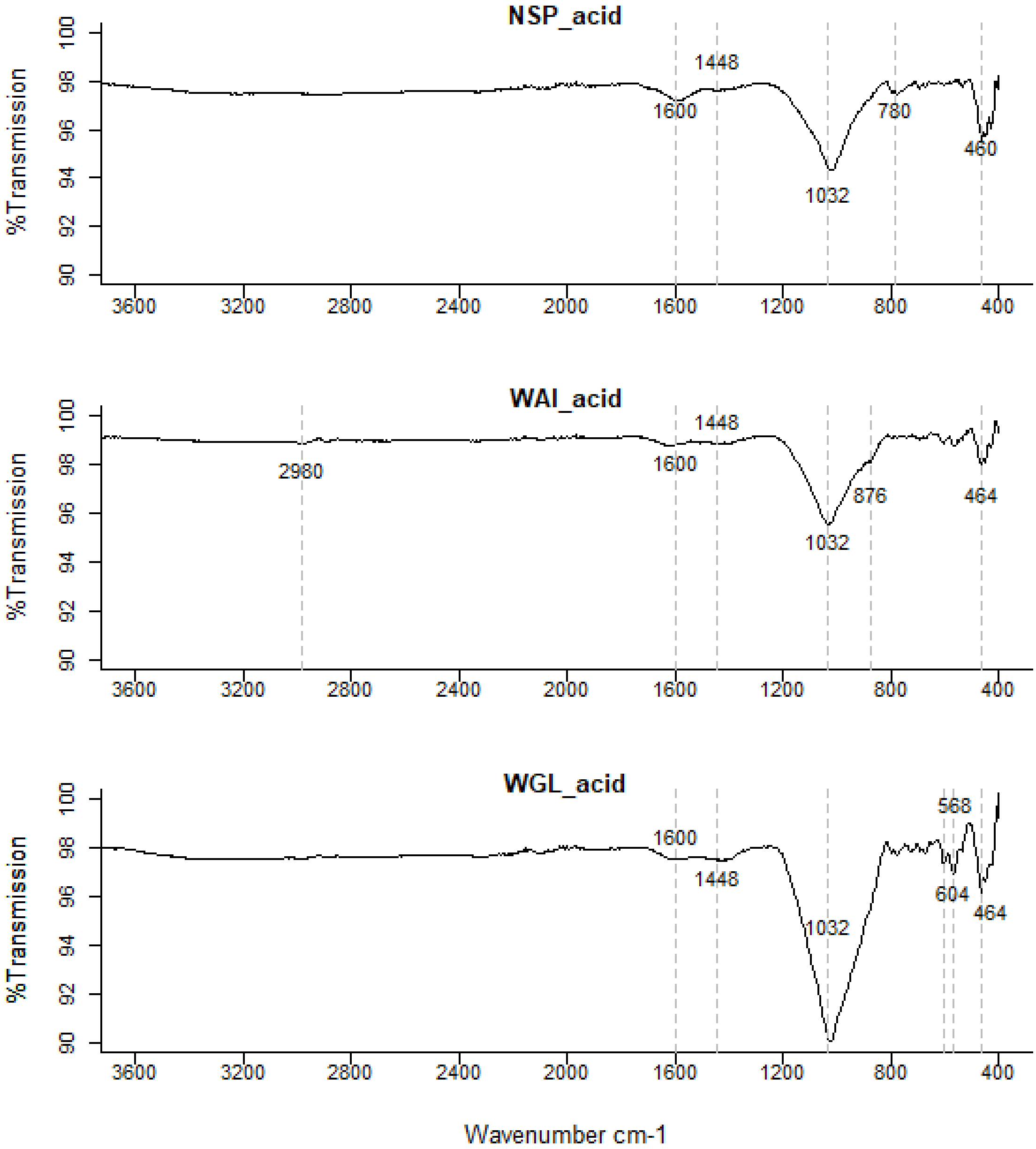
Supplementary Table 1 *FTIR spectral band assignments of biochar*

Wavenumbers (cm^{-1})	Characteristic vibrations	Reference
3670 - 3650	ν(OH) from non-hydrogen bonded O-H groups	(Sharma et al., 2004)
3600 - 3200	ν(OH) from sorbed water and hydrogen-bonded biochar O-H groups	(Keiluweit et al., 2010)
~2980	2990-2950 cm^{-1} asymmetric aliphatic ν(CH) from terminal $–CH_3$ groups	(Socrates, 2001)
~2890	2870-2890 $cm^{-1\ symmetric}$ aliphatic ν(CH) from terminal $–CH_3$ groups	(Socrates, 2001)
2700-2100	P-OH groups produce one or two broad bands in the 2700 -2100 region 2100 – 2250 cm^{-1} C≡C bonds 2100 – 2360 cm^{1} Silane Si-H 2100 – 2270 cm^{-1} Dimides, Azides and Ketenes	(Stuart, 2004)
1700	ν(C=O) from carboxylic acids amides, esters and ketones 1740- 1650	(Socrates, 2001)
1540 - 1650	C═O stretching vibrations for amides, aromatic C=C stretching and carboxylate anion vibrations.	(Calderón et al., 2006)
1580 - 1600	vibration of C=C bonds	(Davis et al., 1999)
1424	Carbonate ($ν_3$; asymmetric stretch)	(Socrates, 2001)
1200- 950	P–O (asymmetric and symmetric stretching of $PO_2$and $P(OH)_2$ in phosphate)	(Jiang et al., 2004)
1100-1000	Si-O-Si asymmetric stretching	(Falaras, 1999)
1020 - 1030	C–O stretching of ethers and primary amine C–N stretches	(Keiluweit et al., 2010) (Claoston et al., 2014)
~875	Out-of-plane bending for CO_3^{2-} and – ν(M-O-H) O-H bending bands from clay minerals associated with biochar	(Zhao et al., 2013) (Farmer, 1974)
796 and 780	quartz doublet	(Farmer, 1974)
462-464	Si-O-Si	(Qian & Chen, 2013)

452	Si-O rocking	Abadri, et al., 2015

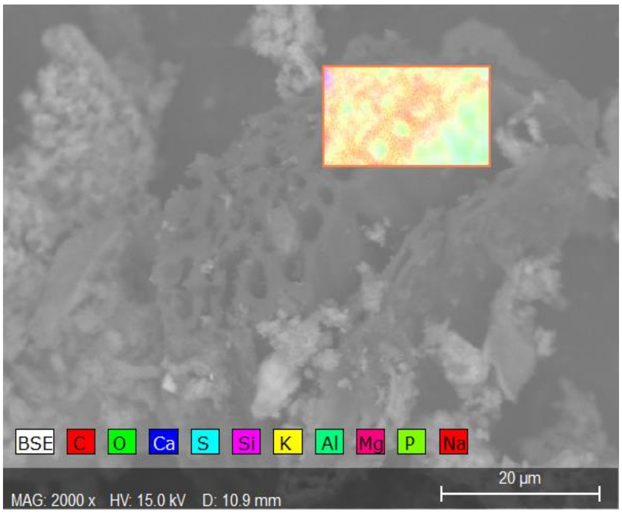


Supplementary Figure 2 *FTIR spectra of ashed NSP biochar, ashed WAI biochar, and ashed WGL biochar.*



Supplementary Figure 3 *FTIR spectra of deashed (acid washed) NSP, WAI and WGL biochar*

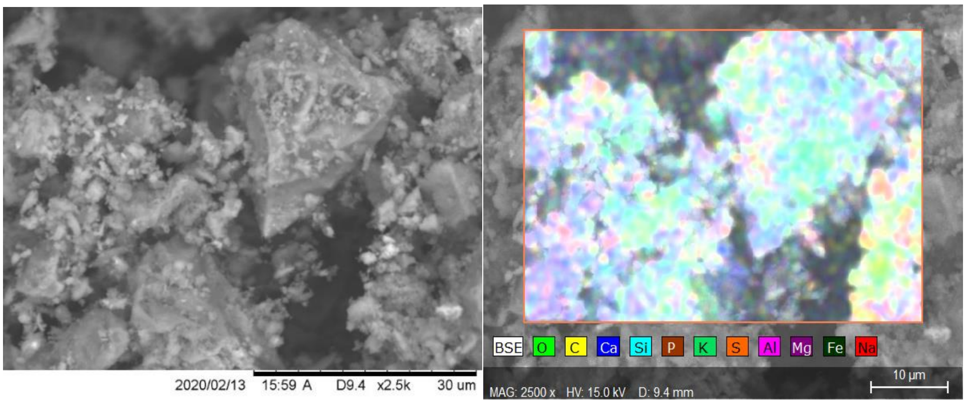
SEM/EDX



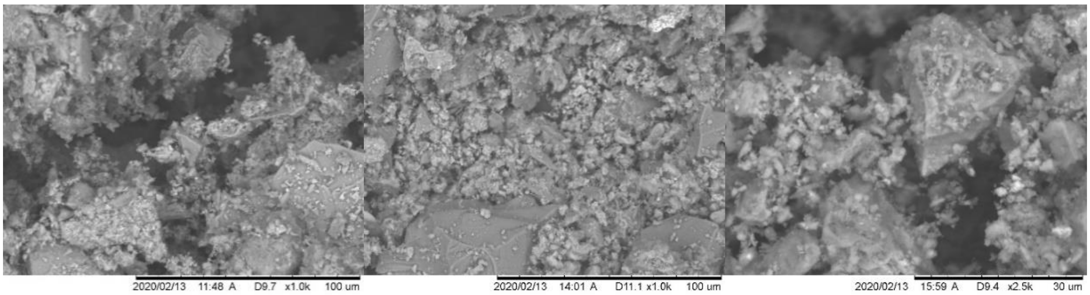
Element	Wt. %
C	70.55
O	21.00
Ca	3.24
S	1.62
Si	1.29
K	0.73
Al	0.63
Mg	0.50
P	0.27
Na	0.17

Supplementary Figure 4 *SEM-EDX map for all elements distribution across the area highlighted in image and associated energy dispersive X-ray (EDX) quantification of biochar* (H. L. Nicholas, Mabbett, et al., 2022b).

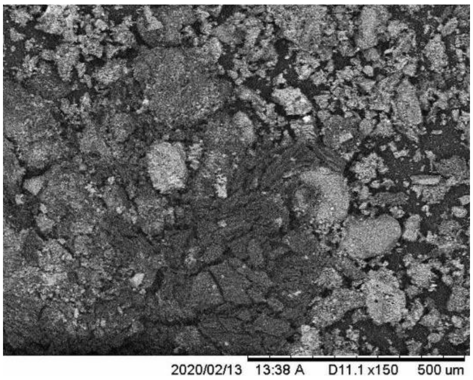
Ash particles were ground in a pestle and mortar to <125µm, acid washed particles of <2 mm were used "as is".



Supplementary Figure 5 *SEM micrograph and EDX micrograph of WAI ashed biochar showing possible quartz crystal*



Supplementary Figure 6 *SEM micrograph of (a) ashed WGL biochar, (b) ashed NSP biochar, and (c) ashed WAI biochar*

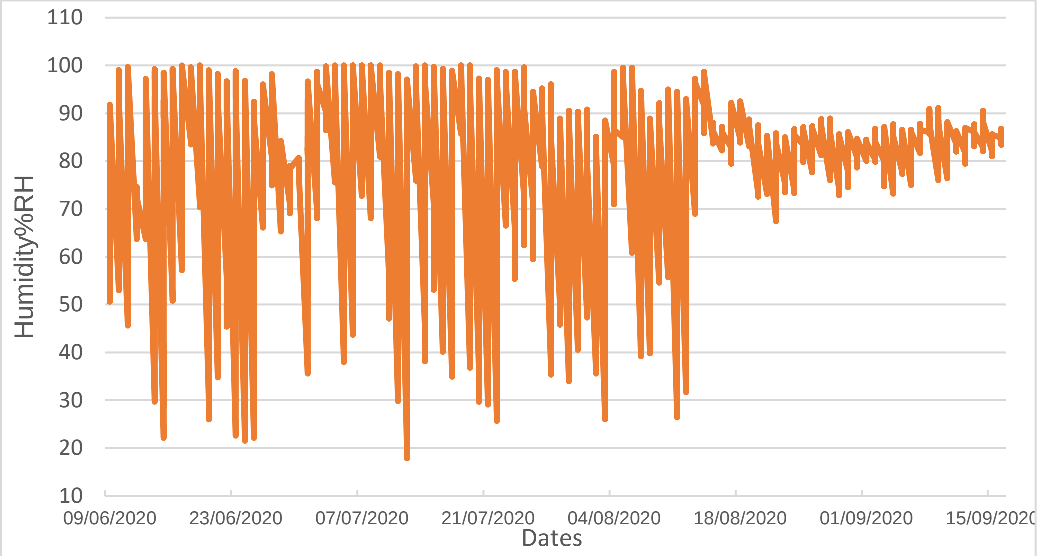


Supplementary Figure 7 *SEM micrograph of acid washed WGL biochar*

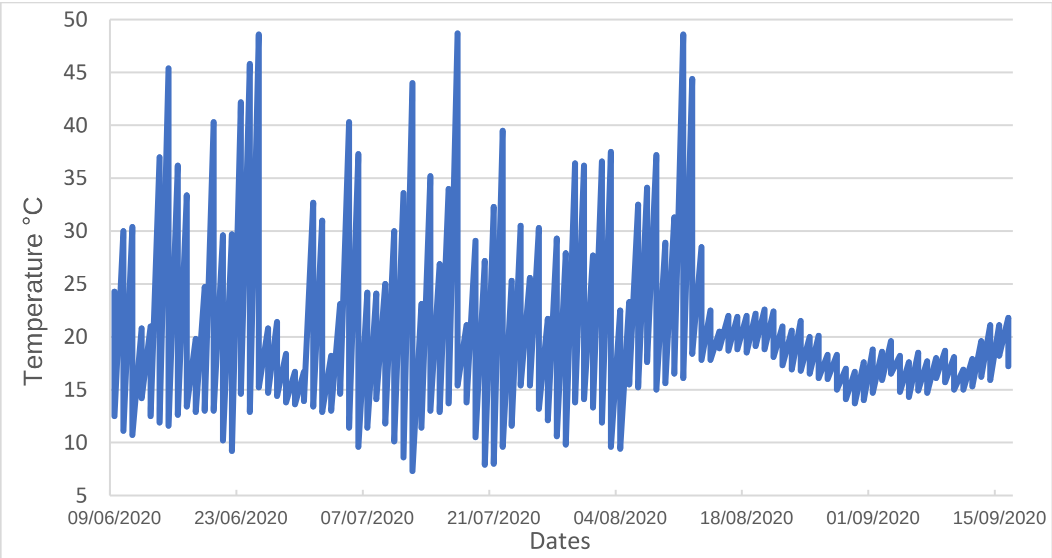
Supplementary Figure 8 *SEM micrograph of ashed WGL biochar, showing a possible alumino-silicate cenopshere.*

2 - Supplementary Information Chapter 5

Temperature and humidity graphs



Supplementary Figure 9 *Humidity (%) recorded by data logger for duration of outdoor greenhouse experiment.*



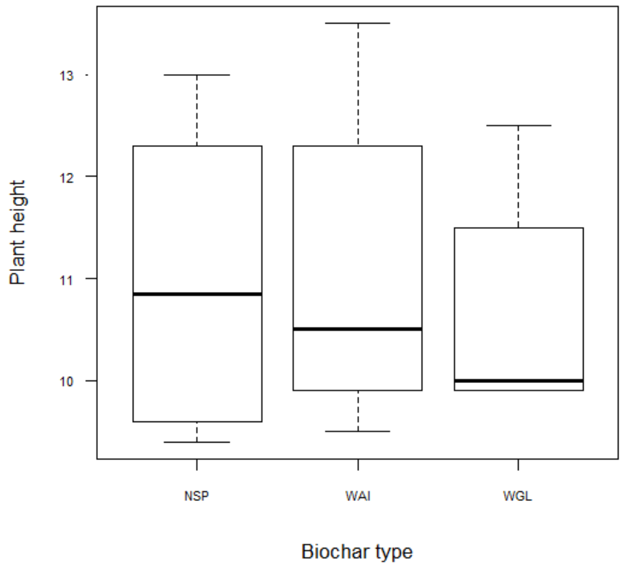
Supplementary Figure 10 *Temperature (°C) recorded by data logger for duration of outdoor greenhouse experiment*

Humidity and temperature were recorded every 2 hours using an Elitech RC-51H USB Temperature and Humidity Data Logger.

Biochar type

Plant growth responses

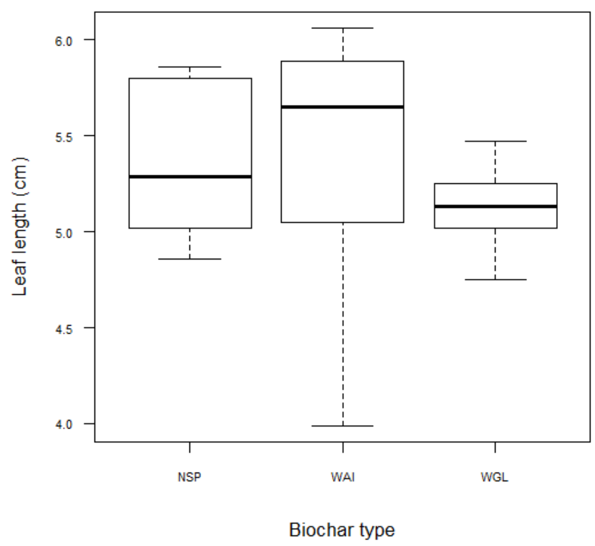
Plant height



Supplementary Figure 11 *Plant height (cm) measured at harvest for each biochar type, NSP (Narsapur biochar), WAI (Wai biochar), WGL (Warangal biochar) in both biochar containing treatments. Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum.*

A linear model showed there was no significant different between the biochar types in regard to plant height (Supplementary Table 1).

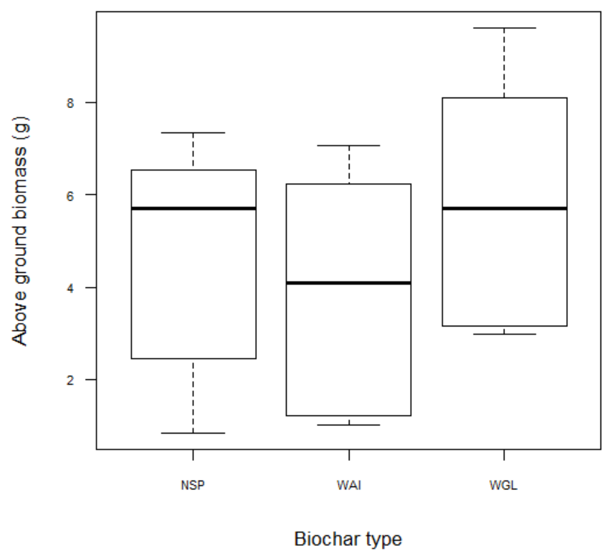
Leaf length



Supplementary Figure 12 *Leaf length (cm) for each biochar type, NSP (Narsapur biochar), WAI (Wai biochar), WGL (Warangal biochar) in both biochar containing treatments. Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum.*

A GLM showed there was no significant different between the biochar types in regard to leaf length.

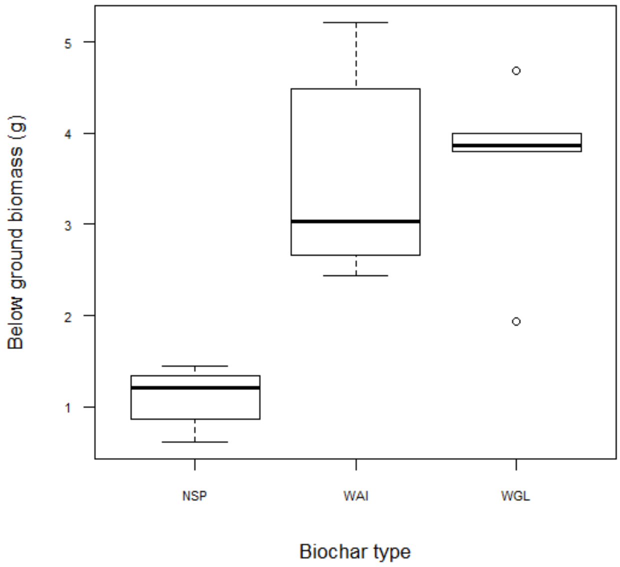
Above ground biomass



Supplementary Figure 13 *Above ground biomass measured at harvest for each biochar type, NSP (Narsapur biochar), WAI (Wai biochar), WGL (Warangal biochar) in both biochar containing treatments. Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum.*

For above ground biomass a linear model showed there was no significant differences between biochar types.

Below ground biomass

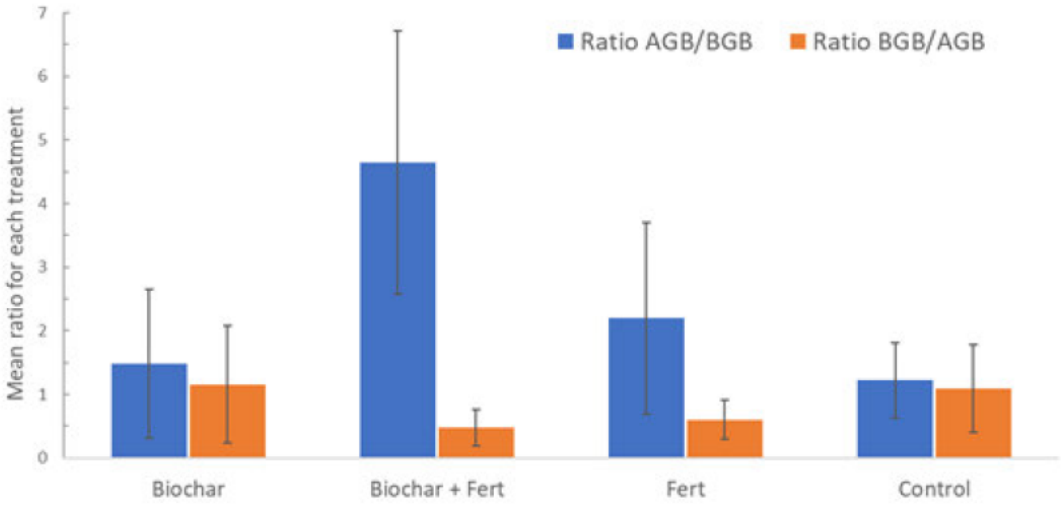


Supplementary Figure 14 *Below ground biomass measured at harvest for each biochar type, NSP (Narsapur biochar), WAI (Wai biochar), WGL (Warangal biochar) in both biochar containing treatments. Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum. Open circle symbols indicate outliers.*

For below ground biomass there were clearly significant differences between biochar types, with NSP biochar recording significantly lower below ground biomass than both the other biochars (WAI and WGL).

Supplementary Table 2 *The effects of biochar type on different plant growth responses using linear model and gamma generalised linear model with pairwise comparison for plant height, leaf length, and for both above and below ground biomass.*

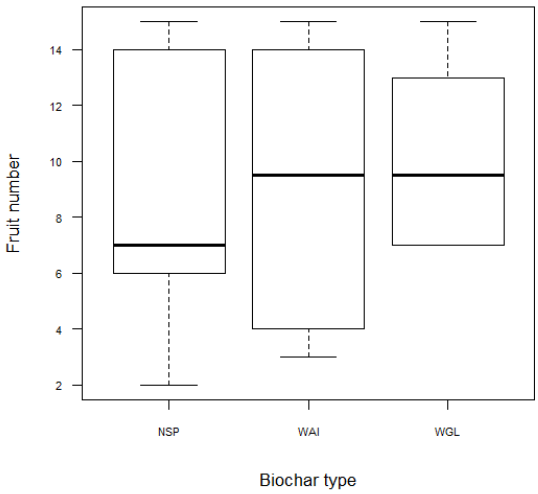
Plant growth response	**Biochar type pairwise comparison**	**Estimate**	**SE**	**t.ratio**	**p.value**
Plant height	NSP - WAI	-0.0333	0.8	-0.042	0.999
	NSP - WGL	0.3667	0.8	0.458	0.8915
	WAI - WGL	0.4	0.8	0.5	0.8724
Leaf length	NSP - WAI	-0.03	0.302	-0.099	0.9946
	NSP - WGL	0.227	0.302	0.75	0.7383
	WAI -WGL	0.257	0.302	0.849	0.6793
Above ground biomass	NSP - WAI	-0.0429	0.0744	-0.577	0.8342
	NSP - WGL	0.0397	0.0612	0.65	0.7954
	WAI - WGL	0.0827	0.069	1.198	0.4723
Below ground biomass	NSP - WAI	-2.360	0.494	-4.776	0.0007
	NSP - WGL	-2.573	0.494	-5.208	0.0003
	WAI - WGL	-0.213	0.494	-0.432	0.903



Supplementary Figure 15. *Ratios for below and above ground biomass comparison for each treatment at harvest, biochar and fertilizer (Biochar + Fert), biochar (Biochar), fertilizer (Fert), and Control.*

Fruit production

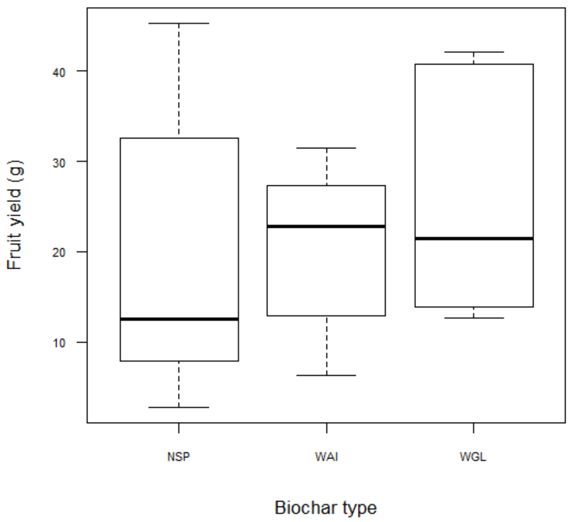
Fruit number



Supplementary Figure 16 *Fruit number measured at harvest for each biochar type, NSP (Narsapur biochar), WAI (Wai biochar), WGL (Warangal biochar) in both biochar containing treatments. Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum.*

A linear model showed that the differences in fruit number between biochar types was not significant.

Fruit yield



Supplementary Figure 17 *Fruit yield measured at harvest for each biochar type, NSP (Narsapur biochar), WAI (Wai biochar), WGL (Warangal biochar) in both biochar containing treatments. Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum.*

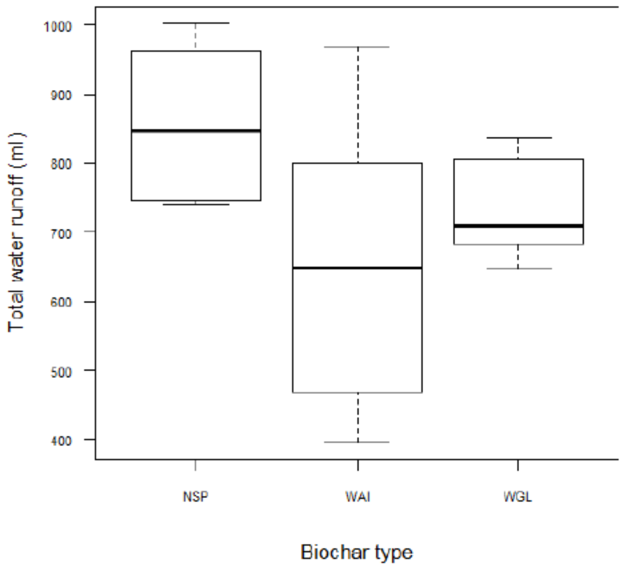
Again, there were no significant differences in fruit yield between biochar types.

Supplementary Table 3 *The effects of biochar type on fruit production using linear model and gamma generalised linear model with pairwise comparison for fruit number and fruit yield.*

Fruit production	**Biochar type pairwise comparison**	**Estimate**	**SE**	**t.ratio**	**p.value**
Fruit number	NSP - WAI	-0.667	2.62	-0.254	0.965
	NSP - WGL	-1.667	2.62	-0.636	0.803
	WAI - WGL	-1	2.62	-0.382	0.9233
Fruit yield	NSP - WAI	-1.72	7.67	-0.224	0.9729
	NSP - WGL	-6.45	7.67	-0.841	0.684
	WAI - WGL	-4.74	7.67	-0.618	0.8128

Soil Properties

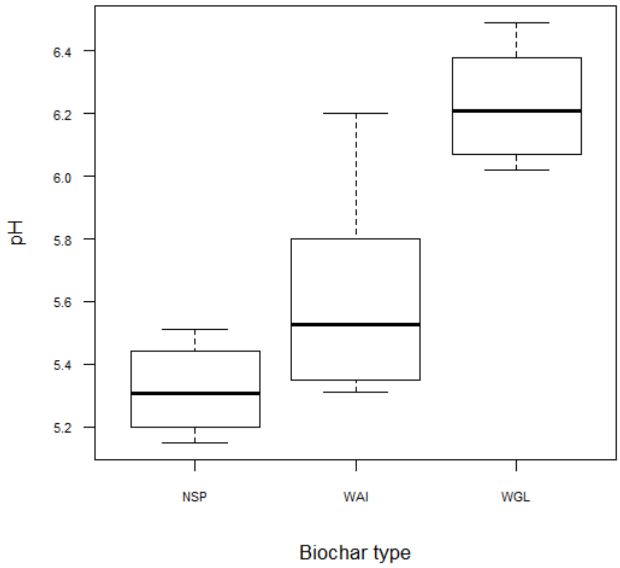
Water runoff



Supplementary Figure 18 *Total water runoff (ml) for each biochar type, NSP (Narsapur biochar), WAI (Wai biochar), WGL (Warangal biochar) in both biochar containing treatments. Box plots show minimum, first quartile, median (the solid horizontal line in the box), third quartile, and maximum.*

A linear model showed that the differences in total water runoff between biochar types was not significant.

pH



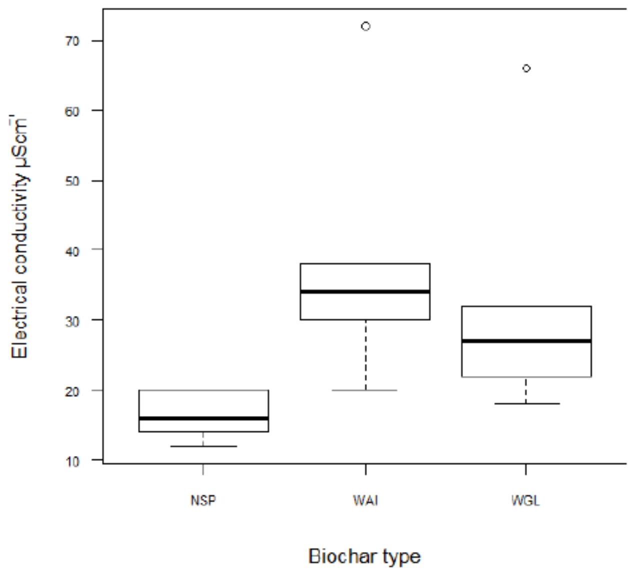
Supplementary Figure 19 *Soil pH values for each biochar type, NSP (Narsapur biochar), WAI (Wai biochar), WGL (Warangal biochar) in both biochar containing treatments. Box plots show minimum, first quartile, median (the solid horizontal line in the box), third quartile, and maximum.*

For soil pH values there were clearly significant differences between biochar types, with WGL biochar recording significantly higher soil pH values than both the other biochars (WAI and NSP). WGL biochar recorded the highest pH (12.25) out of the three biochars with WAI biochar and NSP biochar measuring 11.81 and 11.82, respectively.

Supplementary Table 4 *The effects of biochar type on total water runoff using linear model and soil pH using gamma generalised linear model with pairwise comparison for total water runoff and pH.*

Soil properties	Biochar type pairwise comparison	Estimate	SE	t.ratio	p.value
Water runoff	NSP - WAI	202.2	85.6	2.361	0.0776
	NSP - WGL	125.7	85.6	1.467	0.3337
	WAI - WGL	-76.5	85.6	-0.893	0.6526
pH	NSP - WAI	0.01	0.00452	2.222	0.0997
	NSP - WGL	0.0275	0.00432	6.376	<.0001
	WAI - WGL	0.0175	0.00418	4.177	0.0022

Electrical Conductivity



Supplementary Figure 20 *Soil electrical conductivity measured at harvest for each biochar type, NSP (Narsapur biochar), WAI (Wai biochar), WGL (Warangal biochar) in both biochar containing treatments. Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum. Open circle symbols indicate outliers.*

A Poisson form of a GLM was used to determine if there were any significant differences in electrical conductivity between biochar types. There were significant differences between biochar types with NSP biochar recording significantly lower EC values compared to the other two biochars. The electrical conductivity of NSP biochar alone was lower (1.79) than the other two biochars, WAI biochar (2.70) and WGL (9.00) biochar which would explain the significant differences.

Supplementary Table 5 *The effects of biochar type on soil electrical conductivity using gamma generalised linear model with pairwise comparison*

	Biochar type pairwise comparison	**Estimate**	**SE**	**z.ratio**	**p.value**
Electrical conductivity	NSP - WAI	-0.865	0.124	-6.981	<.0001
	NSP - WGL	-0.673	0.124	-5.417	<.0001
	WAI - WGL	0.193	0.102	1.893	0.1407

Soil analysis

Analysis	Result
Sand (%)	84.65
Silt (%)	13.66
Clay (%)	1.69
Texture Class	Loamy Sand
Very Coarse Sand (%)	3.91
Coarse Sand (%)	19.54
Medium Sand (%)	25.65
Fine Sand (%)	24.4
Very Fine Sand (%)	11.15
Stones >2 mm (%)	2.7

Supplementary Table 6 *Soil texture analysis and organic matter content carried out by Lancrop Laboratories*

Cation Exchange Capacity (Ca, Mg, Al, Na and K) Analysis

Method according to (Peech et al., 1947)

$ClNH_4$ 1M (25 ml) was added to soil sample (5 g) and shaken manually before being left to stand overnight (16 hrs). The following day, 75 ml of $ClNH_4$ 1M was added and then filtered using quantitative filter paper low ash.

Ca, Mg and Al were measured by PerkinElmer PinAAcle 500 Atomic Absorption Spectrometer

Na, K, were measured by Atomic Absorption Spectophotometer with Emission Flame.

Water soluble nutrients

Water soluble nutrients were measured by ionic chromatography: Dionex Aquion with High Capacity column AG9-HC.

Supplementary Table 7 All data from chapter 4 glasshouse experiment effect of biochar on micro-tom growth and yield

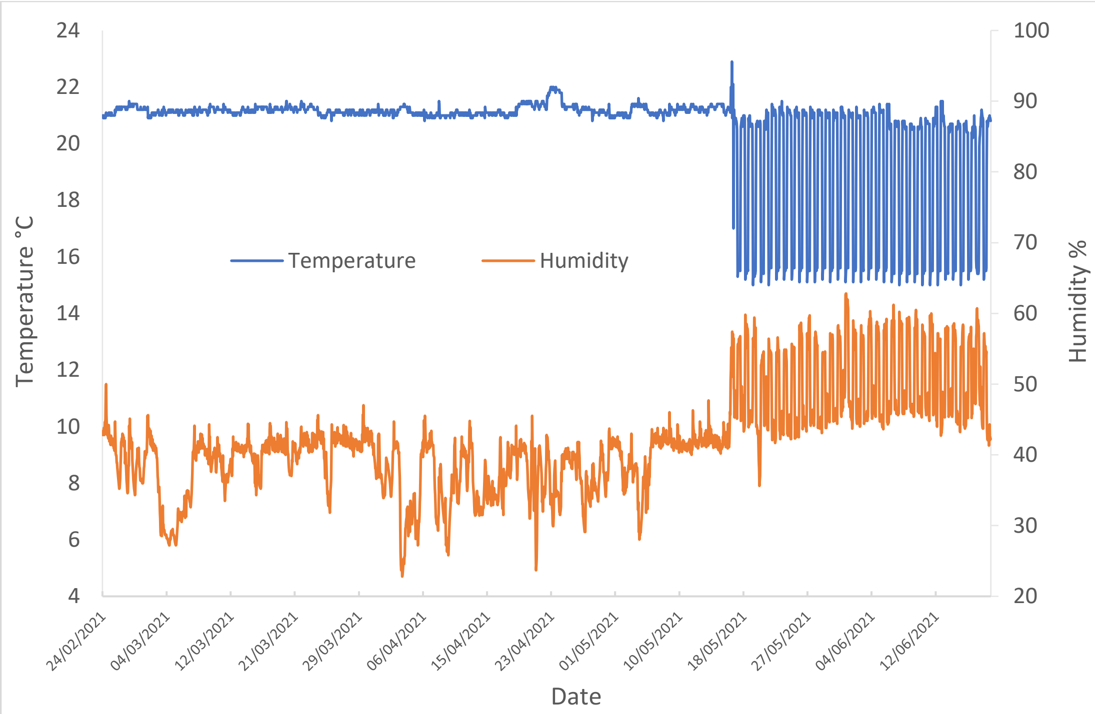
Block	Biochar type	Treatment	Plant height at end of experiment	Tomato number	Shoots weight (g)	Roots weight (g)	Leaf length (cm)	Fruit yield (g)	pH	EC (µS/cm)	Total water runoff (ml)
1	NSP	Biochar	10.7	2	5.3	1.26	5.8	2.82	5.15	14	868
2	NSP	Biochar	9.4	7	2.45	1.16	5.26	10.35	5.23	12	962
3	NSP	Biochar	11	7	0.85	0.62	5.02	7.88	5.38	16	1002
1	NSP	Biochar + Fert	13	14	6.54	1.34	5.86	45.26	5.2	20	740
2	NSP	Biochar + Fert	9.6	15	6.1	0.87	4.86	32.54	5.51	20	825
3	NSP	Biochar + Fert	12.3	6	7.33	1.45	5.31	14.7	5.44	16	746
1	-	Control	9	1	Missing Data	Missing Data	2.35	1.92	5.09	12	1261
2	-	Control	7.5	2	0.72	0.47	2.7	1.18	5.16	10	1274
3	-	Control	7	1	0.49	0.41	2.19	1.21	5.19	8	1272
1	-	Control + Fert	9.5	1	2.42	0.95	3.41	6.19	5.09	34	1131
2	-	Control + Fert	10	2	2.35	1.27	4.19	3.16	5.35	58	1111
3	-	Control + Fert	11.7	3	3.31	1.82	3.47	4.69	5.33	46	1165
4	WGL	Biochar	9.9	8	3.17	1.94	5.07	20.41	6.49	28	836
5	WGL	Biochar	9.9	7	4	3.8	5.19	13.86	6.2	66	733
6	WGL	Biochar	11.5	7	2.99	3.85	4.75	12.67	6.02	26	806
4	WGL	Biochar + Fert	12.5	11	8.08	4.68	5.47	40.78	6.38	22	647
5	WGL	Biochar + Fert	10	15	9.6	3.87	5.02	42.13	6.07	18	683

6	WGL	Biochar + Fert	10	13	7.4	4	5.25	22.42	6.22	32	684
4	-	Control	8.5	1	1.02	0.48	2.47	0.83	5.77	10	1213
5	-	Control	7.2	2	0.81	0.5	2.45	1.91	5.83	12	1202
6	-	Control	6	1	0.1	0.25	2.35	1.24	5.79	10	1210
4	-	Control + Fert	5.1	0	1.27	1.62	1.69	0	5.46	42	1201
5	-	Control + Fert	11.5	1	4.18	3.27	4.15	5.65	5.17	90	877
6	-	Control + Fert	11.2	2	2.47	1.15	4.54	2.89	5.48	38	989
7	WAI	Biochar	12.3	3	1.22	3.27	5.05	6.36	5.35	20	800
8	WAI	Biochar	10	4	3.56	2.44	3.99	20.18	6.2	72	969
9	WAI	Biochar	9.5	8	1.03	2.79	5.86	12.94	5.8	30	751
7	WAI	Biochar + Fert	11	14	7.06	2.66	5.44	25.46	5.35	34	545
8	WAI	Biochar + Fert	9.9	15	4.62	4.49	6.06	27.37	5.31	38	396
9	WAI	Biochar + Fert	13.5	11	6.23	5.21	5.89	31.53	5.7		469
7	-	Control	6	0	0.4	0.58	1.79	0	5.81	30	1191
8	-	Control	6.8	1	0.72	0.47	2.5	0.95	5.08	14	1156
9	-	Control	8	0	0.72	1.07	2.4	0	5.86	18	1214
7	-	Control + Fert	8.1	3	2.03	0.34	3.38	2.49	5.01	62	1149
8	-	Control + Fert	8	2	1.63	1.21	2.95	1.9	5.24	64	1122
9	-	Control + Fert	9	1	1.63	0.8	2.93	2.48	5.21	56	1149

3 - SUPPLEMENTARY INFORMATION CHAPTER 6

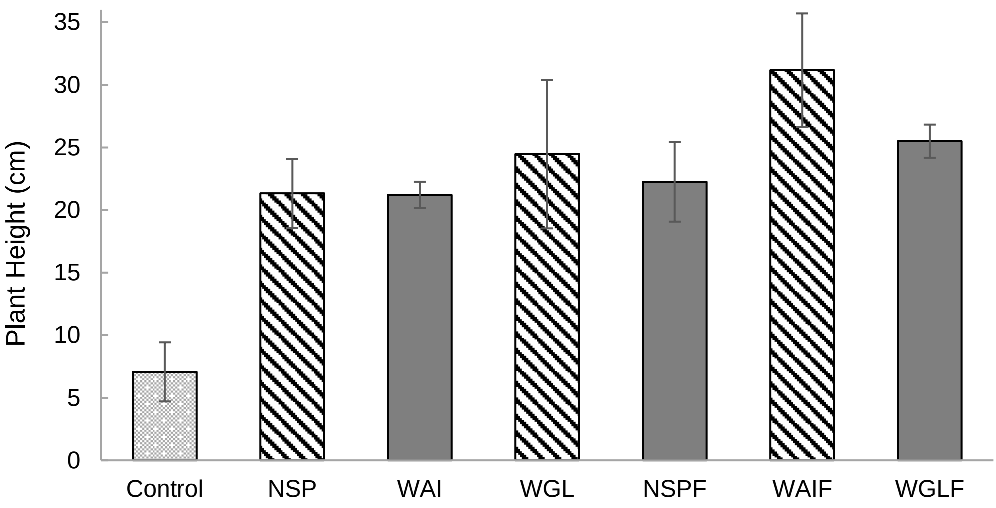
Biochar

Controlled Laboratory Conditions

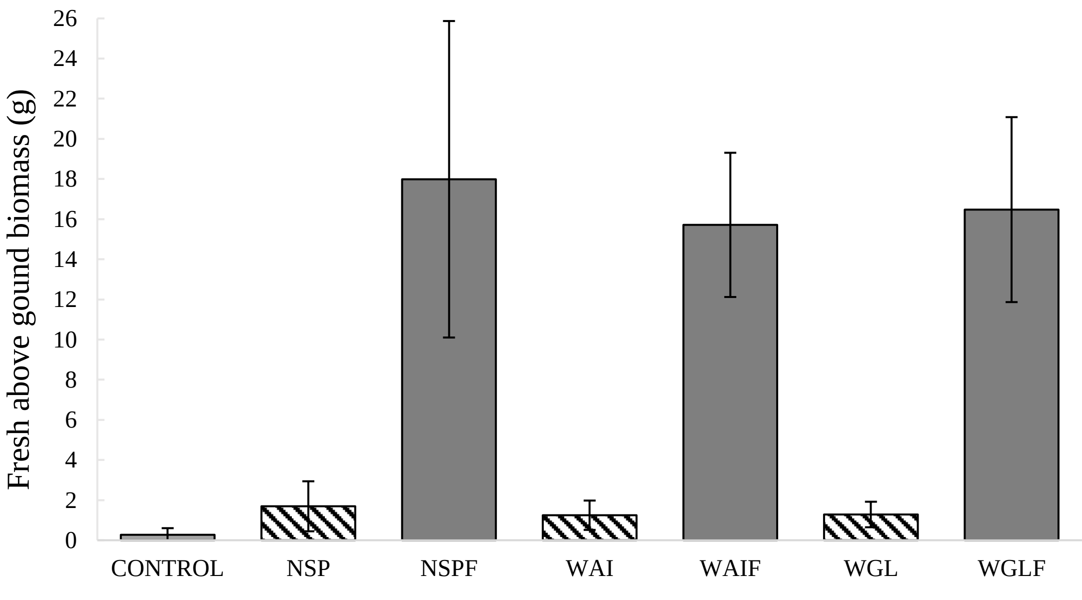


Supplementary Figure 21 *Humidity (%) and temperature (°C) in the controlled environment laboratory recorded via data logger for duration of continuous light experiment*

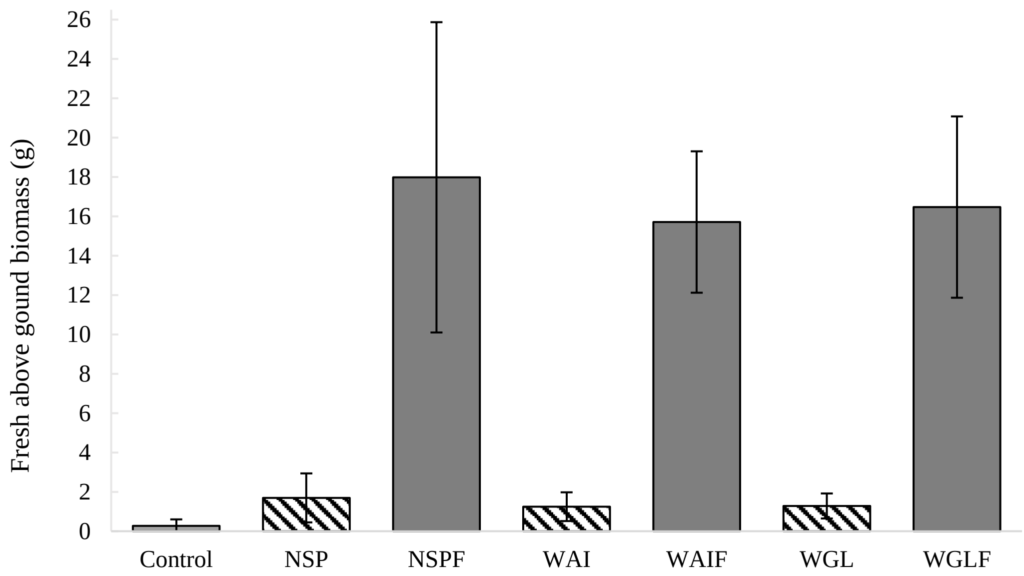
Plant growth responses



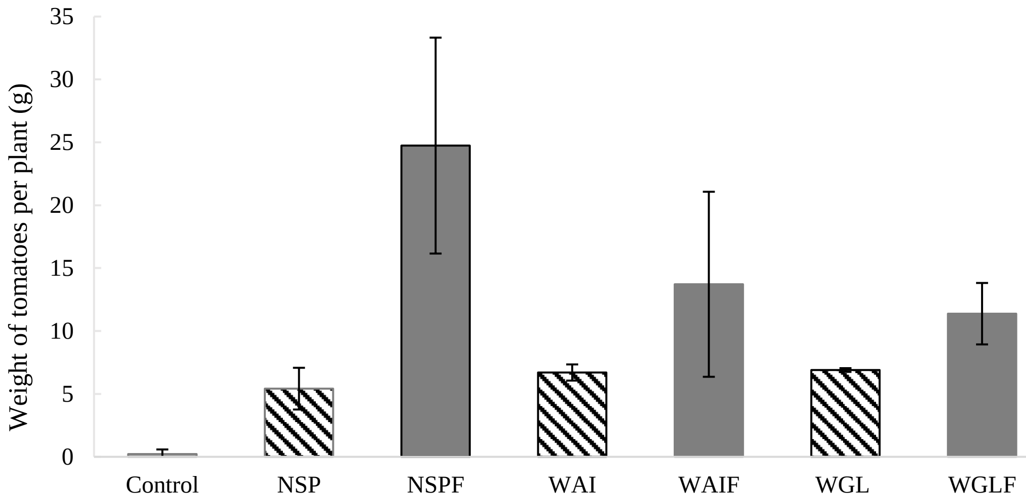
***Supplementary Figure 22** Mean plant heights (cm) for Micro-Tom plants in each sub – group including Control (Control), NSP biochar (NSP), NSP biochar and fertilizer (NSPF), WAI biochar, (WAI), WAI biochar and fertilizer, (WAIF), WGL biochar (WGL), and WGL biochar and fertilizer (WGLF) measured at harvest. Error bars represent the standard deviation in mean.*



***Supplementary Figure 23** Mean values of fresh above ground biomass for Micro-Tom plants in each sub – group including Control (control), NSP biochar (NSP), NSP biochar and fertilizer (NSPF), WAI biochar, (WAI), WAI biochar and fertilizer, (WAIF), WGL biochar (WGL), and WGL biochar and fertilizer (WGLF) measured at harvest. Error bars represent the standard deviation in mean.*



Supplementary Figure 24 *Mean values of fresh below ground biomass for Micro-Tom plants in each sub – group including Control (control), NSP biochar (NSP), NSP biochar and fertilizer (NSPF), WAI biochar, (WAI), WAI biochar and fertilizer, (WAIF), WGL biochar (WGL), and WGL biochar and fertilizer (WGLF) measured at harvest. Error bars represent the standard deviation in mean.*



Supplementary Figure 25 *Mean Micro-Tom tomato yield (g) biomass for Micro-Tom plants in each sub – group including control (Control), NSP biochar (NSP), NSP biochar and fertilizer (NSPF), WAI biochar, (WAI), WAI biochar and fertilizer, (WAIF), WGL biochar (WGL), and WGL biochar and fertilizer (WGLF) measured at harvest. Error bars represent the standard deviation in mean.*

SEQ Supplementary_Figure * ARABIC

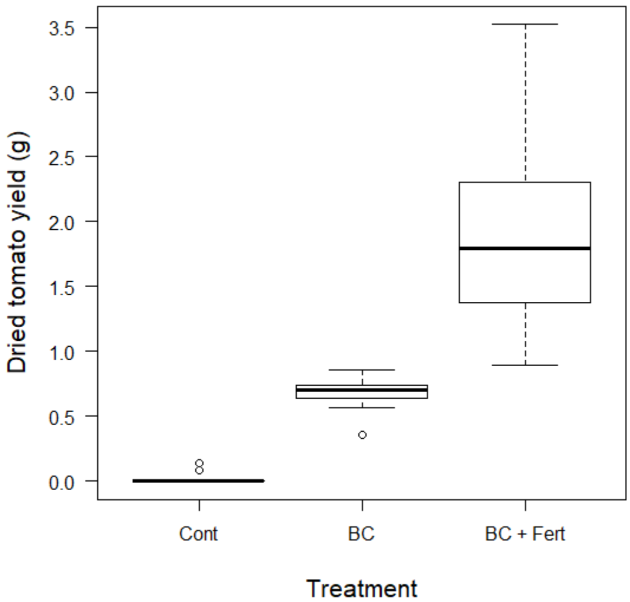
Visual evidence of CL-induced chlorosis

Supplementary Figure 26 *Plants after 45 days of continuous light (left- the control treatment, middle- the biochar treatment, right - the combined biochar and fertilizer treatment.*

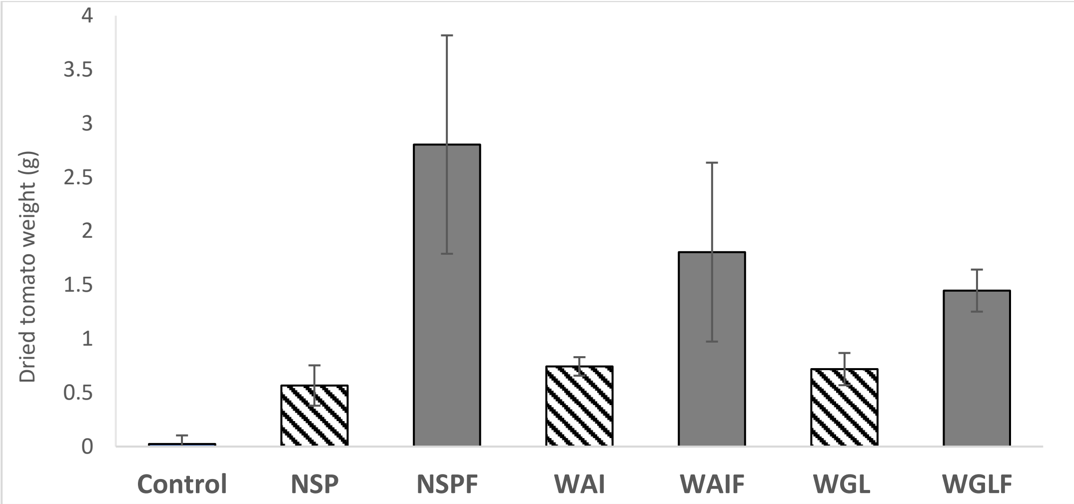
Supplementary Figure 27 *NSP biochar treatment subgroup (left) compared with NSP biochar and fertilizer treatment (right) after 98 days of continuous light*

Supplementary Figure 28 *WGL biochar treatment subgroup compared with WGL biochar and fertilizer treatment after 98 days of continuous light*

Dried Tomato Yield



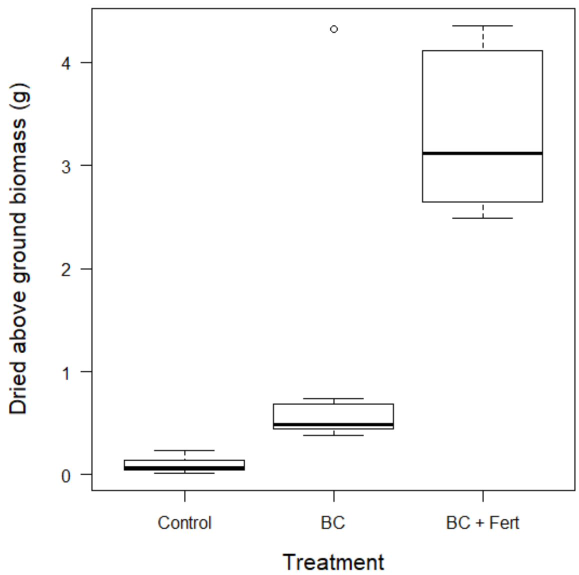
Supplementary Figure 29 *Dried tomato yield measured at harvest for each treatment, Cont (control), BC (biochar), BC+Fert (biochar and fertilizer). Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum. Open circle symbols indicate outliers.*



Supplementary Figure 30 *Bar chart of dried tomato yields for each treatment subgroup*

There are significant differences in means between all three main treatments. Similar to fresh yields there were significant differences between the control and biochar treatments, and between the control and combined biochar + fert treatments, however the dry yield produced significant difference between the biochar treatment and biochar + fert treatment.

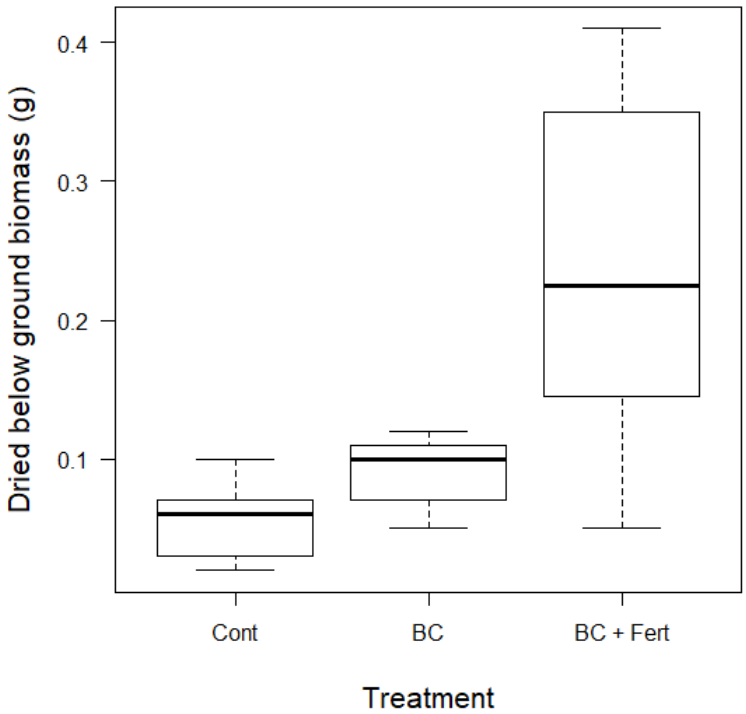
Dried above ground biomass



Supplementary Figure 31 *Dried above ground biomass measured at harvest for each treatment, Control (control), BC (biochar), BC+Fert (biochar and fertilizer). Box* *plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum. Open circle symbol indicates outlier.*

Dried aboveground biomass median for control treatment (0.07 g) was significantly smaller than biochar and fertilizer median values (3.12 g) whereas biochar recorded median value of 0.49 g.

Dried below ground biomass



Supplementary Figure 32 *Dried below ground biomass measured at harvest for each treatment, Cont (control), BC (biochar), BC+Fert (biochar and fertilizer). Box plots show minimum, first quartile, median (the solid line in the box), third quartile, and maximum.*

Control median values for dried below ground biomass (0.06 g) were not significantly less than biochar (0.10 g) but biochar and fertilizer treated plants produced significantly greater dried below ground biomass (0.225 g) than all other treatments.

4 - Supplementary Information Chapter 7

Below are all the statements from the survey to the question:

"What are the reasons (if any) that you would be wary of eating fruit and vegetables that had been grown in faecal sludge biochar?"

If there were QA issues at the drier facility, reducing the efficacy of the removal / denaturing of pathogens

Just doesn't sound very nice but having now read that it contains no harmful bacteria I'd be more happy to buy fruits and veg grown using it.

None at all.

The term "Faecal sludge" does not have positive connotations with things I want to put in my mouth.

Just doesn't feel right

I guess just producers not being responsible but that is the same risk as anything you don't know the whole production chain for.

Just the initial thought of this is alarming but with information and proof thats its safe I would not have a problem with it

Possible transmission of diseases, high concentration of hormones, heavy metals, toxins? I clarification in these would help to make a more conscious assessment.

None

None

No logical reason to be wary really- it's the 'ick' factor. E.g. much like being told that eating insects is good to combat climate change. I think if I (and others) were to be educated better on how safe faecal biochar is, the ick factor might be reduced.

Would wish to see short trial of this feed to show behind doubt that the various plants being fed on it can absorb all nutrients and deal with any unexpected bi products.

None

N/a

I would need to see evidence that it is completely safe

None

Pharmaceuticals and heavy metals

My lack of knowledge

As a farmers wife, I am aware of the benefits of spreading faecal sludge on our fields.

No more wary than eating veg grown in chemical fertilizers, in fact probably less wary

None - seems like a natural way to nourish plants to me

Lack of knowledge/information about the process/what it is. I guess the wording isn't very appealing either.

Sewage from human waste would put me off.

The word faecal is off putting

Not wary at all. Would certainly give it a go.

Just to ensure that it was clean

The thought of eating faeces

none

N/A

N/A

I think I need to do some more research on this subject

None

N/A

I don't know enough about it and would like to have an informed opion.

No reasons

I think it's one of those things you would rather not know about.

N/A

Logically, now explained, it's fine, but the words "faecal sludge" just put me off, I think you'd have to word it differently to make me feel as happy as I should be about it!

Not all pathogens and metasolids are safely neutralised within the UK, more strictly controlled in the EU. Times are just not desperate enough yet to justify and publicise faecal sludge biochar and until fully safe, no point in even considering this option.

I would only be wary if there would be any residual fecal bacteria left in the biochar

To be honest it's something I haven't much knowledge of, I need to do more research.

I think it's psychological. Assuming the process of producing the biochar as well as the processes within the growing plants themselves nullifies any bacteria or taste effects from the sludge, why would it be any different from drinking milk from cows which ate pasture fertilised with cow slurry?

Despite reassurances, many years of having information regarding cleaning and the affects of bacteria drummed into me, makes me still sceptical.

Unknown.

Nope

No problem. Gimme that biochar sludge goodness

Xx

Faecal

Control of the processes required to produce safe biosolid or biochar to ensure zero risk in the food chain

Getting ill

As long as it has been properly tested it would be fine by me!

None

-

My worry would be that its not treated properly

None

Quality standards in the processing and distribution. Harm to wildlife and humans if viruses and bacteria are still present. Also, the environmental impact of processing it all.

Safety

None- perhaps a better name for marketing and image purposes?

None

None

I grow all my own fruit and veg using my own compost and biochar made from bramble pruning. I use no manure and am almost vegan. I therefore know that we overfeed our soil and there in a consequent nitrogen run off. However I do consider the use of faecal sludge biochar a sensible use of waste. I buy very little fruit and veg but would be happy to buy the little that I do buy grown in faecal sludge biochar. Especially considering that by turning it into biochar it sequesters carbon in a more permanent way than just using the sludge.

It sounds unpleasant. I would prefer to think of my fruit and vegetable being full of natural nutrients from the soil.

I don’t know enough about it and what chemicals are used to create it. Wary that it doesn’t smell. I use horse manure and chicken shit as a fertiliser though. I suppose there’s a lot of inorganic crap in those too?

Didn't know enough about it

Mainly the description- faecal sludge! - perhaps there's a lesson to be learned from the people at processed fungus ("mushroom based") Quorn

The look of the product would ultimately decide if I purchased and ate it.

Nonsense brain squirminess but I know it’s silly!

Any diseases that the faecal sludge my still carry

The medicinal chemicals that are still present in sludge.

Just psychology of veg grown from poo!

Just doesn't seem very clean

The word faecal is off putting

I am not wary of it as I am aware of what an outstandingly useful substance humanure is!

It doesn’t really bother me, things are grown in all sorts already

I think I'd just prefer not to know about it! It feels uncomfortable and something I'd prefer not to think about while I'm eating, even knowing it's safe.

The word "sludge"!

Cannot think of any particular reason.

Just the thought makes me wary.

I’m not wary

Just the knee jerk reaction to the unfamiliar idea of linking faeces to safe consumption

Just the idea of it, nothing that couldn't be overcome if it tasted good.

Not necessarily wary, just the psychological element of eating things grown in human poo.

Ensuring that it has had harmful bacteria fully removed.

Currently that COVID traces can be found in faecal sludge

None

Potentially Starting a process where more animals are kept inhumanely to provide a product

None

I'm ok with all this

None

n/a

not a great fruit & veg eater but have no problem with organic rather than manufactured fertilizer

Presence of chemicals and impact on the environment.

None

I don't have any

I'm cool with it

The connotation from the name

It's probably profoundly illogical, but it just sounds unpleasant. Perhaps the disgust reaction is too ingrained - I think there's a linguistic aspect here, as "sludge" is such an unpleasant word. Nonetheless, I'm sure that with adequate reassurances and if it benefitted the environment (or at least wasn't as harmful as aggressive farming techniques using pesticides that deplete the bees, etc) it could be overcome!

Potential disease

n/a

As long as regulatory framework and inspection arrangements were transparent and robust, I would be comfortable eating products.

\-

I think I need to find out more about biochar. At the moment I have no knowledge of it, it's usefulness or efficacy. If I am told that there is no danger to my/my family's health, the environment is helped and the food produced is good food, and not an exorbitant price then I would buy it. As I was doing the survey I found it hard to answer because I don't know the answer to the questions above. I'd be interested in reading your research when you have completed it.

I have no objections

Just need to know bit more about it

I just imagine them making it expensive. Cheap stuff is always bad for the environment

It just sounds eww but if it saved the environment I would change my ways

Just difficulty to shake the associations with "faecal sludge", even while trying to think about it rationally - a very visceral recoil away from associating "faecal" with food. I'd rather just not know!

If there are any related health hazards

Poo is not an appealing thing to think about eating.

All food is grown with help of manure of some kind so no difference really.

All food is grown with help of manure of some kind so no difference really.

I wasn't aware that fruit and vegetables are already grown using sewage sludge so i suppose I don't mind! It's the idea of it that doesn't sound nice, but realistically if I already am eating them then what difference does it make!

Lack of knowledge and understanding about how it is treated and made safe. But if I didn't know then I probably wouldn't mind and unlikely to make the effort to find out!

Potential health risks

None

Just does not sound nice. Not really a rational answer

NA

We used to buy it to use on our allotment..great stuff

none

I would say that as long as there are no diseases than can be transmitted there would be no reason. I don't know the science involved, although I do know that you're not supposed to put animal faeces into your compost bin if you have a pet.

None

I don't know enough about it. If I saw studies showing that it was safe I'd be more interested. However there is a general 'yuck' factor that I'd need to push past.

N/a

Risk of infection but none if shown to be safe

n/a

None

None safer than using pesticides

Worry about cleanliness and potential diseases e.g. E coli. Especially for uncooked salads.

N/a

No reason

If it was shown to be dangerous

Emotional distaste

Not knowing what regulation(s) is(/are) the treatment process covered by (i.e. are there health and safety standards in place)?

Possible contamination of crop during harvesting.

Just don't know anything about it, and it sounds rather off-putting.

N/A

Ebola and if converting faeces to biochar is actually carbon neutral / positive

Safety

No reason, would be good to hear more about it!

Simply the word faecal rather than anything real

I come from farming background it’s very common they use animal and human faecal in fields

Just the thought

None, its simply nutriment for the plants.

The possibility of unwanted, currently unknown effects.

No issue at all.

I don’t trust large companies as they don’t have human consumption at the heart if what us produced. They are for profit companies who take short cuts. They also have interests in food addiction and pharmaceutical industries. If this was just about smaller farms and not multinationals I would have more trust.

Understanding the process and the treatment temperature is helpful in dispelling concern, in my opinion.

none

Horse and cow manure is not too different is it

Correct procedures followed at all levels of the process.

I do not want to eat poop

None

Could there be a risk of virus or bacteria spreading this way would be a question I would need very clear proof on or statistical risk analysis

psychological

I’m happy with it

Eventually, all farming methods change.

Health risk

Eve

Eventually, farming methods change.

Not knowing the process

No reason

None

Environmentally friendly

I have an allotment

So grow most things

No problem as long as government intervention doesn't reduce the high safety standards.

Contamination from heavy metals

None

I think it's more the thought of it, in your mind rather than the reality!

Nada!

Only wary if it affected taste in any way.

I have no faith that the big growers properly adhere to the guidelines or that it is tested to the nth degree

Wouldn’t be wary

None

My grandfather had the largest and most beautiful vegetables grown through the proceeds of his organic, compostable toilets before it became a fashionable concept

When you think about it, lots of plants are grown with the help of manure but I guess it's not a pleasant thought when you think of the diseases spread by faecal matter, especially in these Covid days where we've all become far more hygiene conscious, especially when told that it can be spread by using the same bathroom etc.

None- I'd do the same things in terms of washing veg and fruit as I currently do anyway

I have an eating disorder and the thought freaks me out.

idk but i’m poor lol

N/A

None

I’ve got Crohn’s disease so am generally more worried about what I put inside myself and I’m also immune compromised because of meds.

I would have no problem eating such fruit and veg.

The word faecal is off putting, but overall something I can get past if it has a positive environmental impact

Sounds toxic

Not wary

More just the idea of 'faecal sludge' but in reality, this knowledge would not stop me eating the fruit or veg grown in this way

I would need to know that it had been approved for agricultural purposes to produce food for human consumption

Neautral answers due to not knowing enough information about this topic but something I’m now intrigued to find out more.

Initial concern about bacteria but if reliably informed about safety with evidence then I wouldn’t be wary.

Simply psychological- the thought is revolting

The downside is that sewage can also contain heavy metals and other chemical contaminants.... basically a good idea but but the contaminant s should be monitored.

Even though I know farmers use slurry for years, that is something in the back of my mind and I don’t think about it. If An item wasn’t labelled with the faecal sludge biochar then I’d just go ahead and eat it. If I knew it was that then I’d be likely to not eat it. It’s all down to the thought, the knowing of what it is. If that makes sense.

Religious reasons

N/a

N/A

I would like to be assured of the treatment process .

Just old fashioned and don’t fancy eating stuff grown faecal matter. Probably be fine as long as I didn’t know.

nn

none if they would taste the same as usual

Not heat treated to kills of harmful bacteria / viruses

None

I think it sounds unappealing but otherwise there’s nothing wrong

Lack of knowledge

None

N

As long as it isn't raw sewage - like it used to be, according to my rural grandparents, during the war - I'm fine with it.

The idea of it coming from humans scares me

none

fear pf contamination of some sort

Is the faecal sludge you are referring to from sewage treatment plants? Or animal slurry? I’d be interested to see if people had a preference. Initially I feel wary, but as you point out farmers have used faecal matter on soil for over 80 years, therefore it shouldn’t be an issue for me. I prefer the the thought of biofertiliser from AD plants nourishing the fruit and veg I eat :) good luck with you phd.

Not sure

Literally just the word faecal!

None

I'm not wary of eating them.

NA

N/a

Does it affect taste?

None

Not in the least wary

Not at all wary

It could do with some branding work. Maybe de-emphasis faecal?

n/a

Covid can be found in sewage, so that would now put me off

I do not have any

Lack of information regarding it

I wouldn't be any more wary eating fruit and vegetables growing in biochar than I am eating them now not knowing what they are growing in.

I have never heard of it before so don’t know enough about it

None

I think it's the thought of it more than anything else

I think it is simply a mental, rather than physical, issue...

I'm not wary as I am aware of how plants work

Logically I know it's safe but the thought of it has a bit of an ick factor

I would have no worries about eating food grown using gaecal sludge.

None

I know that heavy metal contamination in sewage sludge has been a problem. I'd be happy about its use if I'm reassured, with details, that this contamination is guarded against.

I guess its just the idea of faecal sludge that is slightly off putting. Not knowing may be better :)

Concerned that it had been properly tested and was not affecting nutrients of fruit and veg.

None.

Difficult to combat or neutralise a lifetime's negative imprint

None

No particular reasons.

No real reason to not eat it but slightly uncomfortable at the thought

I’m ok with biochar

None

Need to know more about it

None

The bacterial side of things, however you have mentioned above that no harmful bacteria is present.

I have no worries. Manure is better for the environment than chemicals and there is always a plentiful source.

Na

None

Not worried. Comfortable with the regulations re use of bio char.

Contamination

No reason that I could really back up, I think it's just a concept that isn't yet mainstream and not something that we're used to seeing day to day in the supermarket. I think people generally associate sewage with something that's unclean and unsafe so it will take education and attitude change for people to see it's safe and has other eco benefits.

Organic earth with animal fertilizer but human faecal waste disturbs me. I'll research more but this is my initial reaction..

None

Ignorance! Sounds great, just needs a rebranding exercise, and people would love it!

I personally feel I don't know enough about it to be wary of it.

None

Transfer of hormones/microplastics/viruses/bacteria from human excrement into the plants can't always be avoided, as it's difficult to remove these when treating the waste. It also requires a lot of energy to treat the waste which is obviously a downside for the environment. I believe there are also concerns about eutrophication the same as any fertiliser.

I wouldn't be wary!

N/A

Because of the chemical treatment process faecal matter has to go through to become "safe"

I don't have faith in the treatment process

The presence of unwanted chemicals in waste sludge.

Initially off-putting, when ypu consider food you don't want to be thinking about faecal sludge, however the plant will take what nutrients it needs from the biochar, its notnthensame as covering your food with faecal sludge!

None once I knew it was safe

None really if the sludge is heated treated or similar to destroy harmful bacteria

None as did work on biochar and understand it

It's just the thought of poo, innit?

I don't want to eat poo

Lack of trust that it is safe

I would like more info

Contamination

Define 'treated'. Transmission of potential hazards contained in the biomass

It’s just the word faecal. Makes me think of dangerous bacteria

More than anything the wording has the most negstive connotations. However, if it is completely safe for the production of food for humans then I see no issue using it. Perhaps it more of a branding problem than anything?

None

It's the thought of where it has come from and that it may not be 100% safe from disease etc

No rational reason, it just makes me feel very uncomfortable. I am happy with the idea of using animal manure, but I couldn't bring myself to eat something grown with human sewage.

That they’d be unpleasant

One has to trust optimum levels of biochar will be used. Too much biochar is harmful to plants and soil. You can't correct this problem without removing the soil. If hat hapens

I am concerned about how much antibiotics transmit in faeces

I am ok to eat food grown in faecal sludge biochar.

Just an irrational visceral response that I could overcome

None

N/a

Not sure I am wary of eating fruit and veg grown like this.

Just the safety issue, that there was no room for error in removing any unsafe bacteria that could cause harm.

Lol! Just knowing it is sewage! But as you point out I have been eating shit for years! Joking aside we need to be savvy and recycle our waste to maximise our resources. I do draw the line at Soylent Green! Good luck!

Trust of the process, we are always told half truths in the UK.

None

N

None

Would like to read more before deciding

None

Am a country girl by origin and know how farmers fertilise fields!! However price is generally the issue when buying organic produce. Would food produced neccesarily be strictly organic ie could still use pesticide

As long as there was a low Ecoli count on the fruit and veg. I would be OK with purchasing food grown in faecal sludge biochar.

Poor regulation and process control

none

Just a basic human response to not being comfortable with the thought of it but after reading and being told of the safe use of this material i would be more willing .

Unclean

I think it’s mostly the wording. Faecal sludge sounds obviously disgusting and off putting and like no one would want to eat anything that had been in it. Maybe if people were better informed about it and it was better worded and marketed it could have an impact

None

Just don’t like the sound of it. I would need proof it’s 100% healthy

Concern over bacteria

Wouldn't feel comfortable that all bacteria etc. Was removed.

none

No reason

Simply because of the faecal connection.

I wouldn't be wary. I'm aware that farmers already use sewage as fertiliser.

Perception and visualisation of “faecal sludge” very off-putting.

Need to be 100% confident that all potential harmful matter eliminated

My Dad grew vegetables fertilised by horse manure

If I was given scientific proof that the treatment eliminateted such things as antibiotic material, heavy metals, irradiated products and such like harmful materials I would have no problems in using such fertilizers for growing my veg and fruits as I see the benefits of using such abundent material for increse of soil richness. Good luck a worthwile research project.

I am not wary

I am not wary

Biological contamination

N/A

None

Think there should be transparency with traceability.

.

Just sounds awful, which is ridiculous but is probably the main reason

It would seem I’ve already been eating fruit and vegetables grown in some form of treated faecal matter. I have no issue with buying and eating food grown in biochar, if biochar can help mitigate climate change then I’m all for it.

Worried that there would still be harmful bacteria on the fruit and vegetables

I'm wary about the origin and production of everything I eat

None

Residual chemical treatments somehow being stored in the fruit/veg as it grows? Not sure how this would happen? Also as farmers have been doing this for years I assume all tests have been performed and it must be one of if not the safest method of recycling this waste.

I have answered that I would not be wary

It just sounds gross

The thought if where it came from

I don't eat my poop so why would I eat something grown in someone else's poop?

None

The actual thought of it.

Sounds unattractive.

That the process doesn't work correctly, and mistakes can happen.

Illness is carried in urine and feaces

None

No reason

N/A

I wouldn’t be wary as you explained the process well. Good luck

Some people would be worried about germs, if I trusted the tteatment process Ithen i would not be worried. I think we should all be using compost toilets rather than flushing all the nutrients away

None

Because of the mental association.

Ignorance of the facts.

During procesding If it had not either reached a certain temperature or not been processed over a long period of time.

Lack of knowledge

It sounds gross! But seriously, I would only be concerned about parasites, bacteria or viruses surviving the treatment process and being used to grow vegetables that I then eat it give to my kids, exposing us to potential infection.

chemicals in soil antibiotic use in animals - farming inorganically

I don't know enough about it and the name "faecal sludge" makes me feel queasy!