# The influence of Biochar-Based Fertilizers on soil fertility for different pedo-climatic conditions in Karnataka

GEO 511 Master's Thesis

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## Summary

Soil degradation and vulnerability to climate change are major current agronomic issues. Tropical regions are particularly affected by these problems. Applying biochar (BC) to soil is thought to helping mitigate climate change, to managing waste and to conserving soil. Biochar-based fertilizers (BBFs) are additionally thought to keeping nutrients into the soil and to releasing them slowly and in a plant accessible way.

This study investigates the effect of BC and BBFs on C, N and P dynamics. BBFs were obtained impregnating BC with compost, organic fertilizers and mineral fertilizer. The aim of this study is to compare the effectiveness of untreated BC and BBFs for increasing soil fertility. Soils from four research sites along a pedo-climatic gradient in Karnataka (India) were adopted. Analysis were carried out through a laboratory characterization, an incubation experiment and a field trial.

BBFs showed generally more effectiveness in increasing soil fertility than BC.

The laboratory characterization demonstrated that all analysed soil types could profit from BC and BBFs, with soil from more arid locations profiting the most.

The incubation experiment demonstrated that C dynamics are influenced more by soil type than by treatment type applied. In average, all treatments increased soil respiration. Soils from humid locations profited the most. BC impregnated with compost leads to highest respiration with a raise of 21 % compared to BC.

Nutrient's dynamics were dominated by physical processes of flushing and absorption. Mineralization of N-$NH_4^+$, N-$NO_3^-$ and P-$PO_4^{3-}$ was also partly stimulated: the first is promoted more by BC in arid soils, the second by BBFs in humid soils and both BC and BBFs stimulated the latter in humid soils (especially BC with compost).

BBFs are in average 5 times more abundant in N and P than BC. Because of the high abundances, the relative N and P uptake and use efficiency measured from the field trial are greater for BC, but the relative N utilization efficiency is generally greater for BBFs. Most of the yields obtained from BBFs were higher, reaching up to 30 % when enhanced with half recommended doses of mineral fertilizer. Yields obtained from BBFs can be predicted by being inversely proportional to their C/N ratio and proportional to their functional surface reactivity.

Soil type and management practices have a greater impact on soil fertility than treatment type applied, indicating careful evaluation of the site before application.

Abbreviations

| | |
|---|---|
| BFF | biochar-based fertilizer |
| RH, RH450, RH700 | rice husk, rice husk pyrolyzed at 450°C, rice husk pyrolyzed at 700°C |
| SC, SC450, SC700 | sugarcane, sugarcane pyrolyzed at 450°C, sugarcane pyrolyzed at 700°C |
| BC | biochar (treatment) |
| BCC | biochar and compost |
| BCMF, MF | biochar and mineral fertilizer, mineral fertilizer |
| BCSJ, SJ | biochar and sugarcane juice, sugarcane juice |
| BCFL, FL | biochar and fenugreek leaves' solution, fenugreek leaves |
| BCMFSJ | biochar, mineral fertilizer and sugarcane juice |
| BCMFFL | biochar, mineral fertilizer and fenugreek leaves' solution |
| $BC_{\text{Kon-Tiki}}$, $BC_{\text{UAS}}$ | biochar produced through a Kon-Tiki-like open earth kiln, biochar produced through an oven elaborated by the UAS Bangalore |
| UAS | University of Agricultural Sciences Bangalore, GKVK (Karnataka, India) |
| UAS-method | Biochar production method elaborated by UAS |
| C, TC, TOC, SOC | Carbon, total carbon, total organic carbon, soil organic carbon |
| N, TN | Nitrogen, total nitrogen |
| OM, SOM | Organic matter, soil organic matter |
| GHGs | Greenhouse Gases |
| EC | Electrical conductivity |
| CEC | Cation Exchange Capacity |
| BD | Bulk Density |
| WHC | Water Holding Capacity |
| DRIFTS, IR | Diffuse Reflectance Infrared Fourier Transform Spectroscopy, infrared |
| XRF | X-ray Fluorescence |
| EA | Elemental Analyser |

Content

# 1. Introduction

## 1.1 Current challenges for agriculture

Among the serious global issues characterizing the 21st century are climate change and environmental pollution (Liu et al. 2015). Agriculture is directly linked to these challenges, both as contributing to them as facing their consequences (Tubiello et al. 2008).

The carbon (C) footprint of agriculture is going to increase since farming is set to expand to produce more food, timber and bioenergy for a growing world population (FAO 2017; Tubiello et al. 2008). This means more land-use change for increased crop production, more energy consumption for management practices, more greenhouse gases (GHGs) release during production, transportation and application of fertilizers and generally more demands for water and use of fossil fuels to manage the increased production (Abumhadi et al. 2012). As well as being a source of GHGs contributing to climate change, agriculture is itself affected by shifts in climate, which will affect the type and location of agricultural production worldwide (Huang et al. 2010). Table 1 resumes more in detail the challenges for agriculture in the 21st century that are urgent to address.

Table 1: Challenges for agriculture in the 21st century.

| Challenges for agriculture in the 21st century (adapted from Wèri 2010; FAO 2017) |
|---|
| – ensuring high quantity and quality crop production<br>– minimizing impacts of crops on biochemical cycles in order to reduce gas and solute emissions<br>– contributing to waste recycling while preserving soil<br>– controlling pest populations and optimizing pesticide treatments<br>– preserving water resources by developing farming systems that more efficiently utilize this resource while releasing less pollutants into groundwater and rivers<br>– developing and disseminating innovations in order to achieve a combination of these various functions, building upon indigenous and traditional knowledge |

As reported by the Food and Agriculture Organization (2017), agricultural technological improvements along with drastic cuts in fossil fuel use would help address climate change.

My thesis represents a contribution to the development of a technological innovation which could help counteracting climate change and increasing soil fertility while integrating traditional knowledge.

## 1.2 Soil fertility

The term soil fertility, often used as a synonym to soil quality or soil health, has only a general conceptual significance because it cannot be quantified exactly or defined in specific units (Abbott & Murphy 2007). For a particular site, the degree of soil fertility depends on the characteristics of the soil according to its origin and the land management practices implemented (Abbott & Murphy 2007). The definition suggested by Abbott & Murphy (2007: 4) is: The capacity of soil to provide physical, chemical and biological requirements for growth of plant for productivity, reproduction and quality (considered in terms of human and animal wellbeing for plants used as either food or fodder) relevant to plant type, soil type, land use and climatic conditions.

I will refer to soil fertility as an ensemble of physical, chemical and biological soil properties that allow to increase crop production and promote long-term soil sustainability taking environmental concerns into account.

### 1.3 Biochar

Due to their potential applications in energy storage, catalysis, adsorption and gas separation and storage, C materials are considered as ideal candidates for solving many of the practical issues encountered in the 21st century (Liu et al. 2015). Particularly, biochar is seen as one of the methods with highest potential for storing C in soils and for increasing soil fertility (Paustian et al. 2016).

Biochar is defined as a C-rich and porous solid produced by through pyrolysis, the thermal decomposition of biomass in a reactor with little or no available air and at moderate temperatures (e.g., 350−700 °C) (Lehmann & Joseph, cited in Liu et al. 2015). Biochar is primary composed of C (usually 45−60 wt %), hydrogen (H, 2−5 wt %) and oxygen (O, 10−20 wt %), with nitrogen (N) sometimes included (Liu et al. 2015). Biochar possesses specific properties, such as a porous structure, a relatively large surface area, a large number of functional groups and abundant mineral elements (Chen et al. 2018; Liu et al. 2015).

Recently interest in biochar rely particularly on the potential of C sequestration and climate mitigation as well as enhancing degraded agricultural lands (Ippolito et al. 2012). Biochar was cited for the first time in the Intergovernmental Panel on Climate Change (IPCC) report published on 8th October 2018, by being mentioned as a promising negative emission technology.

The idea of using charred organic matter (OM) to improve soil characteristics has already been used by Indians of the Amazonas over centuries. These soils are commonly known as Terra Preta and the application of char was used as a way of preventing infectious diseases, leading nonetheless to a highly productive and fertile soil in direct contrast to near soil without application (Gupta et al. 2016).

The effect of biochar on soil properties, crop growth and C recovery can nonetheless vary among crops, soils, climate and the applied biochar itself (Ippolito et al. 2012), which characteristics mainly depend on the initial OM and the conditions during pyrolysis (Kavitha et al. 2018).

#### 1.3.1 Biochar properties

During pyrolysis the initial biomass converts from lignin, cellulose and hemicellulose to some allotropes of C. Biochar is a mixture of organic and inorganic C, thus a mixture of disjointed graphite crystals based on hexagonally shaped C rings, with some leftover H and O attached, along with minerals (ash) that were in the initial feedstock (figure 1). These hexagonally shaped C compounds are fused C rings, called aromatic C, which are stable and thus difficult to degrade (Gupta et al. 2016). The more the biomass is heated, the more of these fused C rings are created while the more volatile elements are released, leading to a higher C recovery (Gupta et al. 2016).

Physically, pyrolysis increases the surface area and the pore structure of feedstock through introducing various pore sizes (nano- to macro-pores), which affect the water and air circulation, adsorption and transport processes and the soil microbial community (Atkinson et al. 2010). The physical structure of biochar, visible in figure 2, leads to a greater Water Holding Capacity (WHC), minor Bulk Density (BD) and major aggregate stability of the soils in which it is applied (Ding et al. 2016).

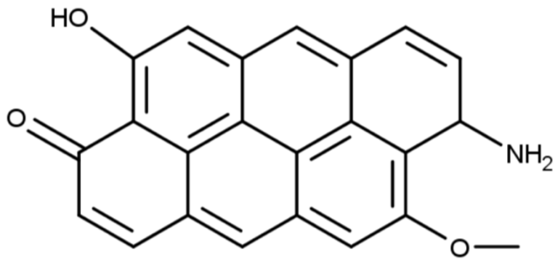


Figure 1: simplified, chemical structure of biochar. (adapted from Chen et al. 2018).

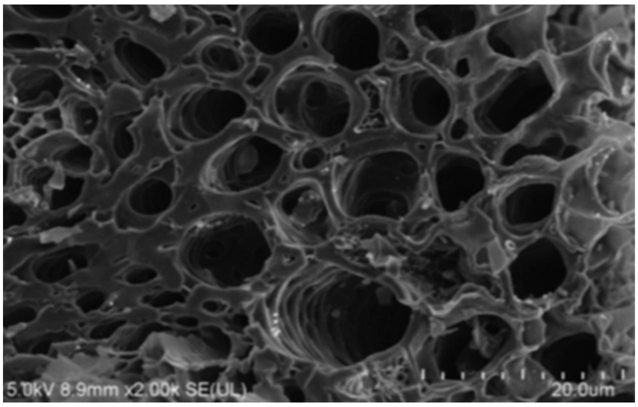


Figure 2: physical structure of biochar (adapted from Chen et al. 2018).

Together with C recovery and surface area and porosity, also pH and nutrient concentrations of the final product are controlled by pyrolysis temperature (Ippolito et al. 2012; Liu et al. 2010). High temperature pyrolysis has an important effect on feedstock pH by increasing the alkalinity of raw biomass (Kavitha et al. 2018) due to the detachment of functional groups and the formation of negative charges (as carboxyl ($COO-$) and hydroxyl groups ($OH-$)) that are capable of reacting with $H^+$ ions (Singh et al., cited in Kavitha et al. 2018). With an increased pyrolysis temperature, also the cation exchange capacity (CEC) of biochar increases, leading to an enhanced nutrient availability: through the adsorption of positive charged ions, other cations included several nutrients (e.g. $K^+$, $NH_4^+$, $Ca^{2+}$) are released into soil solution, becoming plant available (Brady & Weil 2014). Furthermore, enhanced CEC affects the remediation of metal-contaminated soils through adsorption (Zeng et al. 2015).

Thus, biochar's properties can be targeted to a range of different purposes by adjusting the pyrolysis temperature (Kavitha et al. 2018). For example, high-temperature biochar is more resistant to decomposition and is therefore a better candidate to fulfil the C sequestration function (Biederman & Harpole 2013).

### 1.3.2 Biochar decomposition

How biochar affects decomposition rates in soils in which it is applied is widely discussed in literature and the exact mechanisms are still uncertain. A literature overview about the persistence time of biochar found results spanning from a few years to over 5000 years (Lehmann et al., cited in Bellè 2017).

It is assumed that biochar C is environmentally more stable against decomposition than plant C (Ippolito et al. 2012). In fact, biochar stability constrains C mineralization rates and C and N uptake by microorganism (Wang et al. 2016). Nonetheless, also C sequestration through biochar only occurs above a certain level of C input, that can be higher than 10 metric t/ha and year for tropical soils (Mankasingh et al. 2011). Furthermore, biochar as substrate addition for microorganism can lead to an increased mineralization of SOC (Wang et al. 2016). In fact, the minerals comprise in the ash include several essential macro- and micro-nutrients for biological uptake and, therefore, represent valuable resources in the soil food web (Gupta et al. 2016).

For the success of any soil management, it is crucial to maintain an appropriate level of SOM and biological cycling of essential nutrients. Mulches and manure are for example used for microbial activation; however, the benefits are short-lived since decomposition rates are high (Bol, cited in Naeem et al. 2018). Due to its lower decomposition rates, biochar is increasingly studied as more resistant form of OM to increase soil fertility and crop productivity (Naeem et al. 2018).

### 1.3.3 Biochar and soil fertility

Biochar characteristics described in 1.3.1 and 1.3.2 indicate his potential to increase both soil fertility and soil C sequestration. Table 2 summarizes the benefits of biochar application for soil fertility found in literature.

Particularly valuable for soil fertility increase is the potential of biochar to reduce nutrient leaching and volatilization through adsorption of nutrient ions in his structure (Clough & Condron 2010; Kimetu & Lehmann 2010). Because of the same mechanism, nonetheless, in some cases of biochar application yields may decline because of the excessive adsorption of water, nutrients, pesticides and herbicides (Kavitha et al. 2018). Biochar could therefore reduce nutrient's availability and the effectiveness of management practices (Kavitha et al. 2018).

Furthermore, it has been reported that biochar itself does not contain enough nutrients for intensive crop growth (Asai et al. 2009). In fact, as argued by Lehmann et al. (2003), biochar application does little to contribute directly to the soil nutrient status, but it is combinations of biochar and applied fertilizer which cause yield enhancements via reduced nutrient leaching. Thus, fertilizers still play a vital role for nutrient supply (Chen et al. 2018). In addition, for an effective implementation, large quantities of biochar need to be applied on fields (Biederman & Harpole 2013).

Soil type is other influencing factor determining the efficacy of biochar for soil fertility increase. For example, the increase in CEC depends on the composition of the soil, with minimal enhancement in soils with high clay or OM content (Abiven et al. 2014). In addition, in alkaline soils an increase in soil pH through biochar application is not desirable as crops generally favour neutral pH (Brady & Weil 2014).

Table 2 describes a selection of constrains of biochar application for soil fertility found in literature.
Biochar is not as universally beneficial as often assumed and the outcomes of its application vary widely depending on the agricultural and climatic circumstances. Focus on developing designed biochar systems for individual applications that take into account soil type, climate, economic and social setting is required. Socio-economic factors influence e.o. the availability of biochar feedstocks, access to technology and investment capacity (Abiven et al. 2014). Even if not in the focus of my thesis, socio-economical aspects are key for a successful implementation of biochar as soil amendment (Abiven et al. 2014).

Table 2: Benefits and constrains of biochar application for soil fertility increase.

| Properties | Benefits | Constrains |
|---|---|---|
| Soil chemical properties | Increase in nutrient retention (Ding et al. 2016)<br>Decrease in leaching of nutrients (Ding et al. 2016)<br>Enhanced availability of nutrients for plants (Ding et al. 2016)<br>Increase in CEC (Ding et al. 2016)<br>Increase in pH-value (Kavitha et al. 2018)<br>Increase in EC (Gupta et al. 2016)<br>Stabilization of existing soil C (Ippolito et al. 2012) | Effect of biochar on soil chemical properties highly depends on specific ecological conditions (Abiven et al. 2014; Kavitha et al. 2018). |

| | | |
|---|---|---|
| | Decrease GHG fluxes (Kavitha et al. 2018)<br>Alleviation toxicity of heavy metals (Zeng et al. 2015) | |
| Soil physical properties | Increase in WHC (Ding et al. 2016)<br>Decrease in BD (Ding et al. 2016)<br>Increase in net soil surface area (Atkinson et al. 2010)<br>Increase in soil porosity (Atkinson et al. 2010)<br>Increase in aggregate stability (Ding et al. 2016) | Sorption and immobilization of nutrients, water, herbicide and pesticides (Kavitha et al. 2018)<br>Erosion/Leaching of biochar itself (Xu et al., cited in Bellè 2012) |
| Soil biological properties | Increase in microbial community and activity (Atkinson et al. 2010)<br>Favourable plant-fungi-microbe interactions (Gupta et al. 2016) | Immobilization of nutrients and competition for N between microbial and plants (Corning et al. 2016) |
| Growth and yield parameter | Increase in plant biomass (Lehmann et al. 2003)<br>Increase in yield (Chen et al. 2018)<br>Increase in fertilizer efficiency (Hagemann et al. 2017) | Inhibition of crop growth/yield (Ippolito et al. 2012; Kavitha et al. 2018)<br>Not enough nutrients contained in biochar itself (Asai et al. 2009)<br>High application rates required (Mankasingh et al. 2011) |

## 1.4 Biochar-based fertilizers

Due to the agricultural and environmental advantages, biochar-based fertilizer (BBF) has been receiving increasing attention (Chen et al. 2018). As BBF, biochar compound fertilizer or other, the combination of biochar with different types of fertilizers is intended. Impregnation is used to take advantage of biochar’s physical and chemical structure, which allows to adsorb and react with the amendment before field application.

As explained in chapter 1.3.3, biochar does not contain enough nutrients for plant growth (Asai et al. 2009) and thus supplementing biochar with nutrient-rich amendments seems reasonable. Many researchers have observed that BBFs delay the release of nutrients in soil because of the retention of dissolved nutrients in their porous structure and the subsequent slowly diffusion (Chen et al. 2018; Hagemann et al. 2017; Khan 2008). In addition, BBFs prevent C losses through biochar’s stability and thus increase OC contents in soils (Ippolito et al. 2012; Liu et al. 2012). Because of these properties, the combination of biochar with different amendments could be effective at low application rates. BBFs could reduce negative ecological impacts related to fertilizer loss and reduce therefore overall fertilization costs (Hagemann et al. 2017). Farmers could not only profit economically from lower fertilizer supply, but from increased yields (Zheng et al. 2017; Chen et al. 2018).

An increase in soil fertility due to BBFs application is expected. Nonetheless, little is known about how to produce BFFs and about the directly related effects of biochar on C dynamics as well as the implications of BBF inputs on other biochemical cycles relevant to agricultural productivity.

### 1.4.1 Amendments

The amendments whereby biochar can be enhanced can be of organic or/and inorganic character.
As organic amendments, research has focused mostly on compost. Both biochar and compost provide similar benefits in regard to improvement in soil fertility. The difference is that unlike biochar, compost is quickly broken down by microbial action in soil, process that is depending primary on climate (Gupta et al 2016). Biochar lasts at least ten times longer in most soils (Agegnehu 2015).
Biochar has important synergistic effects when added to compost. Researchers found that biochar makes faster, more nutrient rich, more biologically diverse and more humified, stable compost (Wilson, cited in Gupta et al. 2016). The synergetic effects of biochar when combined with compost are largely due to nutrient capture and delivery (Kammann et al. 2015; Gupta et al. 2016). Recent research suggests that the combination of biochar with organic amendments leads to an increase soil fertility, even when biochar is applied at low (0.5–2 t/ha) application rates (Schulz et al. 2014). Biochar combined with compost increases rate of plant growth as demonstrated by Schulz et al. (2012). Zeng et al. (2015) found an effective in situ remediation for heavy metal contained soils as well as changes in soil physic-chemical properties, such as total organic C (TOC), WHC and pH for biochar impregnated with compost. Liu et al. (2012) found a positive effect of soil water retention, while also plant-available nutrients and total SOC content increased. Nonetheless, the underlying mechanisms and the impact of combined application of OM and biochar remain unclear (Hagemann et al. 2017), Trupiano (2017) e.o. found no synergetic effect on a combined use of biochar and compost.

The impregnation of biochar with mineral fertilizers seems especially valuable for an increased nutrient supply. The benefits of mineral fertilizers have been widely demonstrated since the green revolution and are responsible for the increasing agricultural production in the last half century (Naeem et al. 2018). The application of fertilizer alone is nonetheless not a sustainable solution for improving soil fertility and maintaining yields; rather, it has been widely realized that application of excessive mineral fertilizers, especially N, may cause soil deterioration and other environmental problems (Palm et al.; Liu et al., cited in Naeem et al. 2018).
Impregnation of biochar with mineral fertilizer was recently and repetitively proven to increase C efficiency, immobilize of toxic metals, improve NUE and to decrease GHGs emission. Furthermore, less chemical fertilizer supply permits farmers to receive higher net income via increased yields (Chen et al. 2018; Zheng et al. 2017; Yao et al. 2015; Quian et al. 2014).

Naeem et al. (2018) studied the effect of biochar with both compost and mineral fertilizer addition to improve nutrient acquisition and productivity. Their findings show that the amendments are more effective in combination than alone. Highest leaf chlorophyll content, gas exchange attributes and nutrient concentrations were observed, and soil properties such as SOC, N, P, and K were significantly increased by the combined use of biochar, compost and mineral fertilizer. Nonetheless, as the study by Schulz et al. (2012) reports, a negative effect of combining biochar with organic and inorganic fertilizer is possible.

Finally, according to literature, combining biochar with organic and inorganic based fertilizer (alone or in combination) can be an option to achieve high productivity and low C intensity along with saving N fertilizer.

## 1.5 Biochar efficiency in tropical systems

Benefits of BBF are particularly valuable for tropical systems. Typical for the tropics are highly weathered soils which are low in fertility and where to maintain sustainable agricultural practices is a challenge (Glaser 2001).

Soil acidity is a major problem associated to tropical soils. Contributors to soil acidity are, despite the parent material composition, high rainfall rates and high degree of biological activity. In addition, human induced soil acidification is linked to chemical fertilizers and particularly the excessive amounts of N added to the fields. Once the soils are acid ($pH<5.2$), Al, Mn and Fe can become toxic and the availability of macronutrients like Ca, Mg, K, P, N and S is curtailed (Brady & Weil 2014).

One further major problem of tropical systems is the rapid decomposition of SOM (Zech et al., cited in Glaser 2001) due to the high temperatures, large amounts of precipitation and the lack of stabilizing minerals (Glaser 2001). Decline in SOM content results in decreased CEC (Agegnehu 2015); under such circumstances, the efficiency of applied mineral fertilizers is low (Glaser et al., Troeh and Thompson, cited in Agegnehu 2015). In addition, most small-scale farmers cannot afford to apply mineral fertilizers regularly because of high costs (Agegnehu 2015). Therefore, nutrient deficiencies are prevalent in many crop production systems of the tropics and this constrains productivity (Agegnehu 2015).

The productivity of some lands in the tropics has declined by 50%. In future, the long-term benefit of allocating more land to agriculture will not offset the negative environmental impacts of land degradation (Tilman et al., cited in Agegnehu 2015). A more promising approach to ensuring food security is to increase yield from currently cultivated land where productivity is low (Foley et al., cited in Agegnehu 2015). Sustainable agricultural intensification—increasing productivity per unit land area—is thus necessary to secure the food supply for the increasing world population (Tilman et al., cited in Agegnehu 2015).

Because of the rise in global population, an increasing need for freshwater will occur as well. Currently, it is estimated that approximately 75% of freshwater consumption is for the growth of agricultural crops and only 10% to 30% of this water is actually made available to plants. It is widely accepted that farming practices which rely heavily on chemical fertilizers and unsustainable land management practices have led in many regions not only to infertile soils with insufficient amounts of SOM, but also reduced WHC (Yu 2013).

As shown by recent studies, tropical systems could benefit from biochar as a sustainable agricultural intensification practice through an increase in soil water content, a stabilization of soil pH, an increase in CEC, nutrient availability and soil C content, what all leads to an increase in yields (Agegnehu et al. 2015; Bass et al. 2016; Chen et al. 2018; Yu 2013). Furthermore, biochar prevents erosion in highly weathered soils, as proven by Jien (2013).

Researchers have indicated that the combined application of biochar and compost in tropical regions leads to even enhanced benefits for soil fertility, for improved plant growth and for C sequestration (Fischer and Glaser, cited in Agegnehu 2015), even compared to the application of mineral fertilizer alone (Liu et al. 2012). Because of the liming effect of biochar, the application is most likely to be beneficial in acidic soils typical for tropics in respect to more alkaline soils (Van Zwieten 2010).

Information on BBFs on soil fertility and crop performance in tropical soils is nonetheless generally not adequate and not uniform: some negative impacts or biochar application were observed, especially when combined with fertilizer, suggesting careful evaluation of biochar type and soil properties before field scale biochar application (Van Zwieten 2010).

## 1.6 Research objectives, question and hypothesis

My master thesis addresses to a major environmental and agronomic issue in the context of degraded tropical regions particularly vulnerable to climate change and to agricultural land use, and it is a contribution to fill in the missing link between a large part of the literature describing the potential of biochar to mitigate sustainably global climate change while increasing soil fertility and its application.

My research question is, “are BBFs more effective in increasing soil fertility of different pedo-climatic regions in Karnataka as biochar alone?”. I hypothesize that (1) BBFs increase respiration rates relatively more on the short term then untreated biochar, that (2) BFFs lead to an increase in soil N and P concentration as well as N and P use efficiency as biochar alone, and that (3) biochar and BFFs increase relatively more soil fertility in arid zones in respect to more humid zones along the analysed pedo-climatic gradient.

Answering my research question requires the understanding of various systems and their interactions. I decided to reduce the complexity by proceeding by levels.

As first, I prepared and analysed biochar and BBFs in the laboratory. I did that considering two different feedstocks, two different charring temperatures, three different fertilizers and their combination. This analysis allowed me to have an insight into the mechanism underlaying the treatments I created, without any external factor or interaction with other systems.

A selection of the BBF were then adopted for a field experiment and an incubation experiment. The selection was carried out according to the availability of material at the research site in India and the possibility given by the University of Agricultural Sciences (UAS) of Bangalore. Same materials and amounts were used for both field and incubation experiment to be able to compare the results.

Through the incubation experiment, I was able to study the interaction between soil and treatments under controlled conditions. By controlling temperature and moisture content, I was able to control the drivers of mineralization and decomposition and thus provide insights into C, N and P dynamics. Soil from four research sites in Karnataka, south of India, were adopted for incubation experiment. This region is particularly interesting because of the very important gradients of pedo-climatic conditions within relatively short distances, resulting in different soil types. Thanks to the proximity of the research sites, other influencing factors are minimized.

Finally, I was able to test the products in real conditions through a field work. The field used for the trial is an agricultural field for rice cultivation. Rice plants were harvested after three months of growing season to look at yield and nutrient’s use, uptake and utilization efficiency.

Even if not the focus of this work, the field trial allowed a deeper understanding of the economic and social factors contributing to the success of biochar implementation. In Karnataka, there is an important variability of cropping systems and farmer socio-economical context in the region and the systems are fragile since the financial margins are small. How to implement an extension of the technology to farmers’ network will therefore be of primary relevance.

## 2. Material

### 2.1 Biochar and BBFs’ production under controlled conditions

Rice husk was bought already dry, whereas sugarcane was cut into 5 mm large pieces and dried in the oven at 50°C for a week to avoid too much water vapor during the process of pyrolysis. Compost was given available by the Forschungsinstitut Biologische Landwirtschaft (FiBL) in Frick. The compost can be characterized as immature and is composed of branch wood, foliage and hay with a ratio of 30:20:50. Mineral fertilizer was bought in an ordinary garden shop in Zürich. It's about a universal fertilizer for long-lasting lawns with NPK of 7:6:5. As organic fertilizers, sugarcane juice and fenugreek leaves' solution were chosen because of the different C:N ratios. Both are easily available in India since used for cooking and were bought in an Indian shop in Zürich.

### 2.1.1 Biochar preparation

Pyrolysis is the thermochemical decomposition of organic material in the absence of oxygen (Liu et al., 2015). The raw rice husk and sugarcane samples were inserted into a quartz-glass tube that holds two vents that was then located into a pyrolizer (figure 3). One vent is used to supply a constant N gas flow of 60 L/h, which prevents the material from being completely combusted. The second vent at the other extremity of the tube allows the outflow of gas and oil generated during pyrolysis. This gas and oil can be used as biofuels (Abiven et al. 2014).

The resulting biochar is characterized by a feedstock type (rice husk (RH) or sugarcane (SC)) and a charring temperature (450 °C (450) or 700 °C (700)). Pyrolysis duration was set up to 4 hours. Figure 4-5 show respectively RH biochar and SC biochar after pyrolysis process.

Figure 3: Pyrolizer. *Own picture.*

Figure 4: rice husk biochar charred at 450°C. *Own Picture.*

Figure 5: sugarcane biochar charred at 450°C. *Own Picture.*

### 2.1.2 BBFs preparation

BBFs are prepared by combining biochar (BC) with different amendments in liquid form (figure 6-7).

For the success of any soil management, it is crucial to maintain an appropriate level of soil organic matter and biological cycling of essential nutrients. Compost was chosen as amendment since it supports rapid cycling of soil nutrients through microbial biomass activity (Trujillo, cited in Naeem et al. 2018). Additionally, compost improves soil structure (Gupta et al. 2016). Compost was added to BC (BCC) with demineralized water for impregnation process.

Mineral and organic fertilizers are applied to soils for increasing essential nutrients' concentrations. Mineral fertilizer is the easiest way to add high concentrations of essential nutrients to the soils. Mineral fertilizer was mixed with BC (BCMF) and demineralized water while keeping a proportion of 100 mg/L of N.

Organic fertilizers with different C:N ratios where selected since fertilizers with relative lower C:N ratio contain higher N concentration, whereas fertilizers with relative higher C:N ratio stimulate decomposition more (Brady & Weil 2014). BC with sugarcane juice (BCSJ) has a relative higher C:N ratio than BC with fenugreek leaves' solution (BCFL). For BCSJ, raw sugar and demineralized water were mixed to simulate sugarcane juice, considering that sugarcane juice contains 20 % dry mass of sugar. For BCFL, fenugreek leaves were added to demineralized water, shaken for 1 hour and filtered to get the extraction.

For BCCMF, BC, compost and mineral fertilizers where mixed for impregnation process. Similarly, BCCMFSJ and BCCMFFL contain BC, mineral and organic fertilizer.

The BBFs were kept in covered ceramic vases for impregnation for about 1 week (figure 13 and 14). To proceed with the characterization, the impregnated samples were then oven dried at 40 °C for four days. Table 3 resumes components and composition of each BBF.

Figure 6 (left): rice husk biochar during impregnation with mineral fertilizer. *Own Picture*.
Figure 7 (right): sugarcane biochar during impregnation with sugarcane juice. *Own Picture*.

Table 3: BBFs' components and composition.

| Treatment | Component | Composition |
|---|---|---|
| BCC | Biochar+Compost | 50 g biochar<br>50 g compost<br>2 dL demineralized water |

| | | |
|---|---|---|
| BCMF | Biochar+Mineral Fertilizer | 50 g biochar<br>0.828 ml liquid mineral fertilizer<br>2 dL demineralized water |
| BCCMF | Biochar+Compost+Mineral Fertilizer | 50 g biochar<br>25 g compost<br>0.414 ml liquid mineral fertilizer<br>2 dL demineralized water |
| BCSJ | Biochar+Organic Fertilizer with high C:N ratio | 50 g biochar<br>2 dL demineralized water<br>40 g sugarcane sugar |
| BCMFSJ | Biochar+Mineral Fertilizer+Organic Fertilizer with high C:N ratio | 50 g biochar<br>0.414 ml liquid mineral fertilizer<br>2 dL demineralized water<br>20 g sugarcane sugar |
| BCFL | Biochar+Organic Fertilizer with low C:N ratio | 50 g biochar<br>2 dL fenugreek leaves' solution in demineralized water |
| BCMFFL | Biochar+Mineral Fertilizer+Organic Fertilizer with low C:N ratio | 50 g biochar<br>0.414 ml liquid mineral fertilizer<br>1 dL fenugreek leaves' solution in demineralized water |

### 2.2 Biochar and BBFs' production in the field

The BC and BBFs produced in the field represent a selection of the production under controlled conditions. The selection considers the availability of material at the site, the number of plots available for the trial and the reasonability considering that this technology is addressed to local and small-scale farmers.

One pyrolysis temperature was adopted since having a limited field available for the trial and since willing to use a simple biochar production method that can be applied directly on the fields. Furthermore, rice husk biochar was produced and applied on the field, since rice cultivation is usually practiced. Because of the availability of sugarcanes in the area, sugarcane juice was adopted as organic fertilizer.

Rice husk was bought in a rice mill in Mandya and sugarcane juice in the jaggery park VC Farm in Mandya. The recommended doses of mineral fertilizer for rice cultivation used commonly on the research site were adopted for the field trial: N was added through Urea, P (phosphate) through Single Super Phosphate (SSP) and K (potassium) through Muriate of Potash (MOP) with a ratio of 100:50:50. Compost (single superphosphate 16 % of $P_2O_5$) was given available by the UAS of Bangalore.

#### 2.2.1 Biochar preparation

BC was produced within the University areal of UAS Bangalore with an excavated earth kiln that works with the principles of Kon-Tiki. This method was elaborated by the *Ithaka Institute* and was explained to me by Hans Peter Schmidt, which I had the occasion to personally meet before my field trip.

Since commercially produced biochar will remain an expensive input for farmers to purchase, for small farmers it may come out in favour making their own biochar from accumulated farm, garden and household residues.

An open earth kiln is a simple and cost-efficient method for producing biochar at small farmer scale (Schmidt & Taylor 2014).

While burning, it’s actually the gas emitted by heating the wood and not the wood itself that burns. Once all the gas is consumed, oxygen can enter into the charred feedstock and glow the C to ash. A sign to recognize when the feedstock is pyrolyzing and not glowing to ash is a smokeless fire. To have a smokeless fire, the fire has to be lighted from above so that the fire in the uppermost layer heats the next lower layer, which consequently begins to outgas. In contrast, when you light a fire from below, much of the ascending gas will escape the flame and condense in the cooler air. This is what we see as smoke (Schmidt & Taylor 2014).
In the open earth kiln, gradually, layer by layer combustible material has to be added just before the layer below starts to become ash, while maintaining a smoke-consuming fire front. Charring temperature through the open kiln method reaches 650 to 700 °C. Biochar accumulates in the kiln and can be quenched by water or by a 5-10 cm thick layer of soil, sand or manure once the needed amount is reached or the kiln is full of material (Schmidt & Taylor 2014).

The open earth kiln had a diameter of 155 cm and a height of 60 cm. A wood pyramid was constructed and enlighten from above to start the process (Figure 8). Once ¾ of the pyramid was charred, the material was spread covering the bottom of the kiln and the biochar production could start. Layer by layer rice husk was spread over the fire (Figure 9). The fire was smokeless, but not always stable, especially in gusts of wind or when the wood was completely covered and therefore suffocated by the rice husk. In that case, we added a new wood layer to restart the fire and continuing the production. Once the kiln was full, water was used to quench the fire. Ideally the fire has to be quenched from below by letting water enter the kiln from the side (Figure 10). This was only possible when the smoke-consuming fire front was still working, avoiding that the upper layers of rice husk glowed to ash. The biochar was then left in the kiln to cool down over night before it was spread for drying under the sun. Charred wood pieces within the rice husk biochar were collected by hand and discarded. Four charring runs were performed with a total of about 200 kg biochar produced (Figure 11) Approximately, the weight recovery from rice husk to biochar was 50% (Figure 12). The biochar produced by the open earth kiln was used in Mandya for the field trial.



Figure 8: wood pyramid enlightened from above. *Own picture.* Figure 9: Smokeless fire front. *Own picture.*
Figure 10: Quenching fire through water. *Own picture.*

Figure 11: rice husk biochar. *Own picture*.

Figure 12: from rice husk to biochar. *Own picture*.

High quality wood, that takes fire fast and burns slowly, is necessary for biochar production in the open earth. Much more wood was needed as expected, factor that might be limiting considering that wood is a precious resource and use it e.o. for cooking. Once the kiln was quite full, the flame could reach impressive and dangerous heights. A good face musk, protection glasses and at least two to three people controlling constantly the fire are recommended. The wood pieces in the final biochar could alter the results if biochar is produced for research purpose.

Another technique tested to produce biochar is the UAS method. A small fire has to be enlightened into an oven with lateral holes and a chimney (Figure 13). The oven is then simply covered by rice husk (Figure 14). The biochar is ready once the outer layer of rice husk is turned black and the material can be extinguished with water (Figure 15).

Figure 13: oven of UAS method. *Own picture*.

Figure 14: covering oven with rice husk. *Own picture*.

Figure 15: rice husk converting to biochar. *Own picture*.

Compared to the open earth kiln, the UAS method does not require any wood and people controlling constantly the fire. A specific designed oven is nonetheless needed for this production method.

I will refer to the biochar produced through the two methods with $BC_{Kon\text{-}Tiki}$ and $BC_{UAS}$.

### 2.2.2 BBFs preparation

$BC_{Kon\text{-}Tiki}$ was mixed in closed containers with different amendments and left for impregnation for 6 days (Figure 16). Small amount of water was added to each container to allow a better impregnation. Especially with mineral fertilizer, nonetheless, not too much water should be added to avoid volatilization of ammonium

($NH_4^+$). Every day the BBFs were mixed by hand to avoid deposition of nutrients and to grant the final homogeneity of the product. Composition and amount of each treatment are described in the table 4. For BCMF, the recommended doses of mineral fertilizer (RDF) of 100:50:50 as NPK were adopted. N was added through Urea, P through Single Super Phosphate (SSP) and K through Muriate of Potash (MOP).

Figure 16: containers used for impregnation of BBFs. *Own picture*.

Table 4: Treatments composition and amount.

| Treatment name (number) | Composition and Amount |
|---|---|
| Control (T1) | - |
| RH (T2) | RH @ 4t/ha |
| $BC_{Kon\text{-}Tiki}$ (T3) | BC @ 4t/ha |
| BCC (T4) | BC @ 4t/ha + Compost @ 4t/ha |
| BCMF (T5) | BC @ 4t/ha + RDF |
| BCSJ (T6) | BC @ 4t/ha + Sugarcane Juice @ 4t/ha |
| BCMFSJ (T7) | BC @ 4t/ha + 1/2 RDF + Sugarcane Juice @ 2t/ha |

# 3. Methodology

## 3.1. Research area

### 3.1.1 The State of Karnataka, India

The State of Karnataka is situated between 110 31’ and 180 45’ north latitude and 740 12’ and 780 40’ east longitude and lies in the west-central part of south India (figure 17). It has a variety of topographical situations ranging from the coastal plains in the east, to gentle slopes and culminating in the heights in the west (figure 18). In addition, Karnataka has abundant water wealth with seven major rivers and a number of streams (Rajanna 2013).

The climate of Karnataka is basically tropical and determined largely by the physiographic and geographic location with respect to the sea and monsoon. The variability between the average annual rainfall and average annual temperature within Karnataka is unique for India, as visible in figure 19 and 20. The distribution of annual and seasonal rainfall over Karnataka state indicates that it is the highest on the west site with over 2500 mm/a and decreases down to the eastern parts with under 200 mm/a, creating a climatic gradient (Figure 19). Temperatures range from an annual mean below 20 °C to above 27.5 °C depending on the location along the gradient (figure 20) (Parthasarathy et al. 2008).

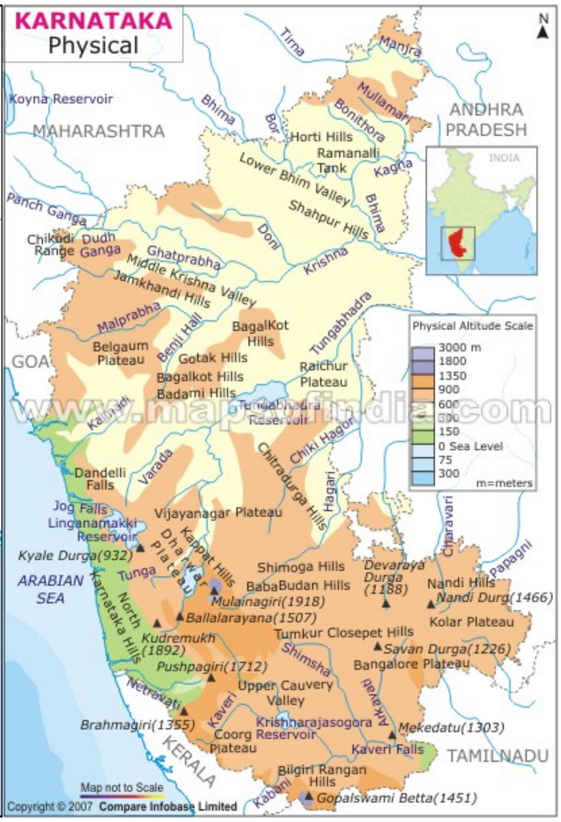


Figure 17 (left): Location of the State of Karnataka, India (www.mapsofindia.com [last access: 21.06.19]).
Figure 18 (right): Altitude [m a.s.l.] of Karnataka, India (www.mapsofindia.com [last access: 21.06.19]).

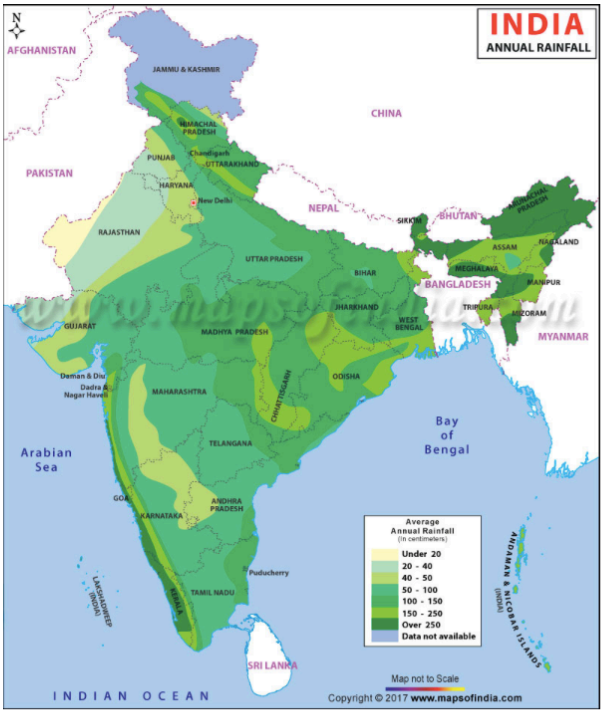
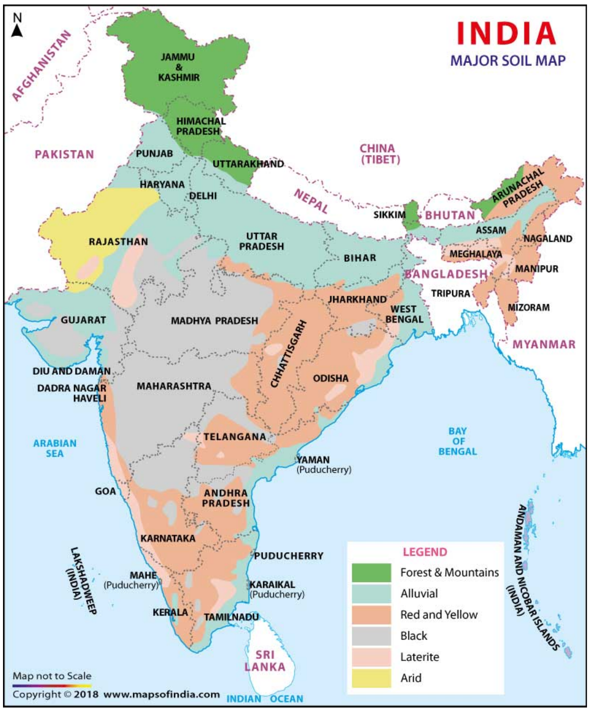


Figure 19 (left): Average annual rainfall [cm] of India (www.mapsofindia.com [last access: 21.06.19]).
Figure 20 (right): Average annual temperature [°C] of India (www.mapsofindia.com [last access: 21.06.19]).

The *All India Soil Survey Committee* in 1953 divided Indian soils into major groups (figure 21). In the State of Karnataka, the differences between the soil types are in accordance with the diverse climatic situations: on the coast lateritic soils predominates, in the northern half of Karnataka black soils developed whereas in the southern half the soil is classified as red (Rajanna, 2013). Main characteristics of the soil types of Karnataka are resumed in table 5.

Table 5: Soil types of Karnataka and main characteristics (adapted from www.indiagronet.com [last access: 21.06.19]).

| Lateritic soil | Black soil | Red soil |
|---|---|---|
| - Mainly in high temperature and high rainfall areas.<br>- Formed as a result of high leaching.<br>- Becomes soft when wet and hard when dry.<br>- Fast decomposition of OM by bacteria.<br>- Low humus content.<br>- Rich in: iron and aluminium.<br>- Deficient in: nitrogen, potash, potassium, lime.<br>- Colour: red colour due to iron oxide. | - Mature soil.<br>- High water retention capacity.<br>- Wide cracks in hot season. permit oxygenation and thus lead to high fertility.<br>- Rich in: iron, lime, calcium, potassium, aluminum and magnesium.<br>- Deficient in: nitrogen, phosphorous and OM.<br>- Colour: deep black to light black.<br>- Texture: clayey. | - Mainly low rainfall areas.<br>- Structure: Porous, friable.<br>- Deficient in: lime, phosphate, manganese, nitrogen, humus and potash.<br>- Colour: red because of Ferric oxide. The lower layer is reddish yellow or yellow.<br>- Texture: sandy to clay and loamy. |



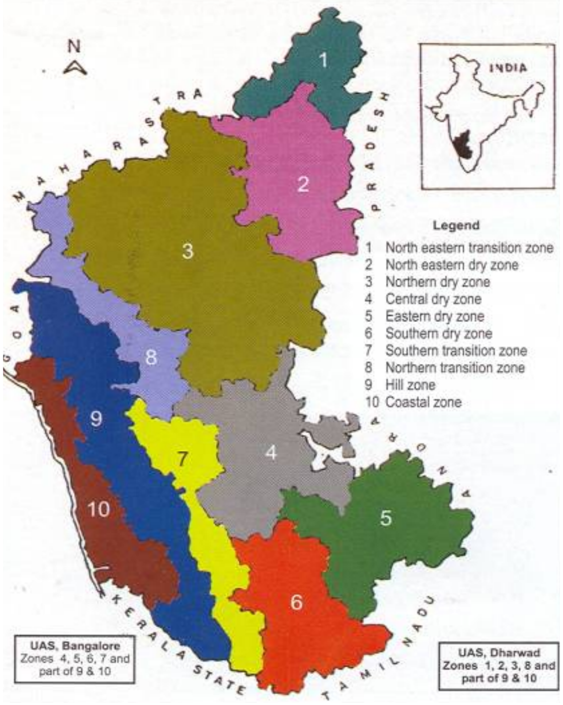


Figure 21 (left): Major soil types of India (www.mapsofindia.com [last access: 21.06.19]).
Figure 22 (right): Agro-climatic zones of Karnataka, India (KSDA n.d.).

Because of the variability of soils within relatively small areas, scientific knowledge of soils is a pre-requisite to understand the local ecology and to plan for agricultural development (Rajanna 2013). Based on the rainfall pattern, topography, soil characteristics, climate in general and cropping patterns, Karnataka state has been divided into ten distinct agro-climatic zones (Figure 22): North-eastern transition zone, North-eastern dry zone, Northern dry zone, Central dry zone, Eastern dry zone, Southern dry zone, Southern transition zone, Northern transition zone, Hilly zone and Coastal zone. Each zone is characterized by specific rice growing ecosystems with diversified rice cultivation practices (Rajanna 2013). Chapter 2.3.1 presents the cultivation practice I adopted for the field work in Mandya, region classified in the Sourthern dry zone.

### 3.1.2 Research sites

Four research sites along a pedo-climatic gradient in Karnataka were selected for this work (Figure 23). From west to east accordingly Mangalore, Hassan, Mandya and Bangalore. Mandya is the location that was chosen for the field work because of the proximity to the University of Agricultural Sciences (UAS) of Bangalore, the availability of fields in propriety of the University and the successful collaboration with the farmers on the site. Additionally, a long-term biochar project is monitored in Mandya. Sugarcane juice, which is needed for two of my treatments, is available locally: Mandya is called the sugarcane-city because of the extended sugarcane plantations.

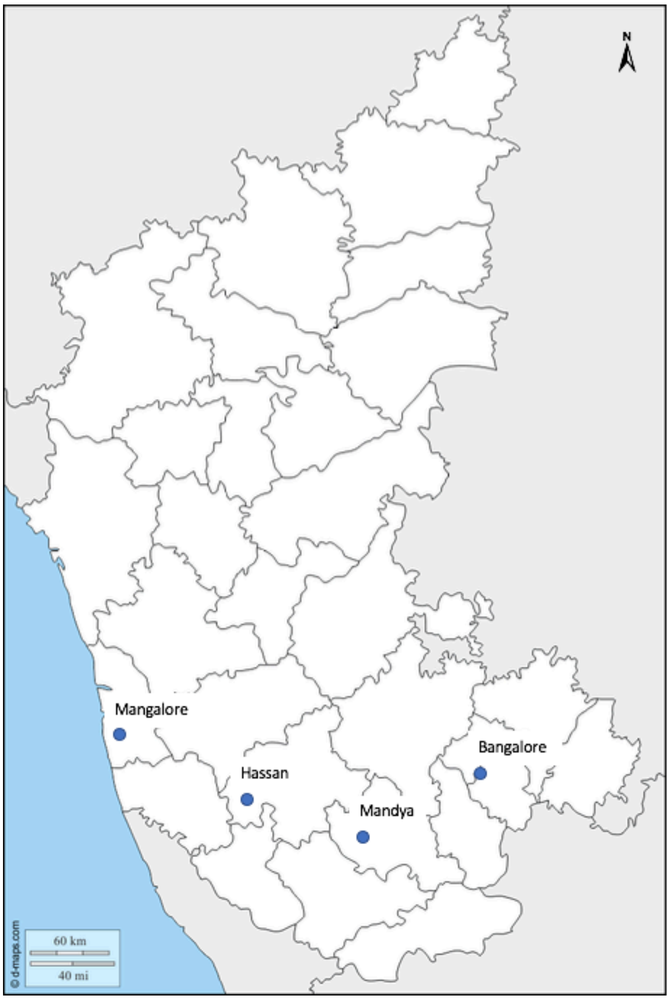


Figure 23: Location of the four experimental farms in Karnataka, India (adapted from www.d-maps.com [last access: 21.06.19]).

The four locations were selected in respect to the different pedo-climatic conditions that characterize them, and which are resumed in table 6.

Table 6: Main information about the research sites along the pedo-climatic gradient in Karnataka (www.climate-data.org, n.d.).

| Location | Bangalore | Mandya | Hassan | Mangalore |
|---|---|---|---|---|
| Average rainfall (mm/yr) | 831 | 782 | 1031 | 3783 |
| Average annual temperature (°C) | 23.6 | 25 | 23 | 27 |
| Indian Soil Survey classification | Red sandy loam | Red sandy loam | Red sandy loam | Lateritic soil |
| Agro-climatic zone | Eastern dry zone | Southern dry zone | Southern transition zone | Coastal zone |

### 3.1.3 Importance of rice for Karnataka

Rice is the most important staple food crop in the world, where it serves as a major source of calories for about 60% of the population. As population increases, global demand for rice in the next decade is expected to expand at around 1 %/yr (FAO, cited in Kollalu 2016). In India, rice represents the largest crop production with 104.32 Mt in 2016 (Directorate of Economics and Statistics 2016). It is expected that expansion will mostly stem from intensified production, with marginal increase in area (Calpe, cited in Kollalu 2016). 43.30 Mha of land are used for rice production in India, with a yield of 2.404 t/ha in 2016. In the state of Karnataka and for the same year, the land area for rice production and the yield account to 1.06 Mha and 2.982 t/ha (Directorate of Economics and Statistics 2016).

The rice production in India and especially in Karnataka is strongly influenced by amount and distribution of rainfall. In the State of Karnataka, only around 44 % of the total acreage is under irrigation while the rest is under regime of monsoon. Rice is cultivated in places where the rains are as heavy as much as 3000 mm/yr and in others where it is just 600 mm/yr. Major rice growing areas of the state can be broadly classified into two seasons, even if the unique feature of rice culture in the State is that it is either sown or transplanted during all seasons of the year (Rajanna 2013).

### 3.1.4 Current practices of rice cultivation

Current practices of rice cultivation in Karnataka are resumed by Patnayak et al. (2008) in their *rice seed production manual* and adapted by Anitha (2015). Same practices were adopted for the field experiment (chapter 3).

In most areas under assured irrigation or having plenty of water, transplanting is done using seedlings raised in nurseries. The seed bed of wet nursery should be prepared 35-40 days prior to the scheduled transplanting time. The seeds for sowing should be selected using salt solution and the floating one discarded. 50 to 60 kg of seeds per ha should be selected and soaked for 24 hours in water, then incubated for 48 hours beneath straw. Once germinated, the seeds should be broadcasted over the prepared seedbed. Three weeks before planting, the field should be dry ploughed and submerged by flooding 5-10 cm of standing water. The recommended dose of fertilizers for rice cultivation is of 100:50:50 as N (through Urea), P2O5 (through Single Super Phosphate) and K2O (through Muriate Of Potash). 50% of needed N should be applied together with P2O5 and K2O at the time of sowing basal (Anitha 2015). The second and third split of N are applied 25% each at 30 days and 60 days after sowing (Anitha 2015). The fields should be levelled up well to be ready for planting while maintaining a thin film of water. The seedlings (30-40 days old seedlings from wet nursery) should be transplanted at shallow depth of 3-4 cm with 2 seedlings per hill, at 10 cm (plant to plant) as well as 20 cm (row to row) spacing (Patnayak et al. 2008). Throughout the growing season, a 2-5 cm water film should be maintained. It should be taken into account that the water has to be drained out before topdressing with N fertilizer and water should be let in 24 hours later. The water should be drained out 15-20 days after 50% flowering; this ensures fast ripening of the grains. About three months after transplanting, when more than 95% plants are mature, it's time to harvest (Patnayak et al. 2008).

### 3.1.5 Current crop residue management practices in Karnataka

Since my research interest is to convert residues in BBFs, it's important to understand the traditional uses of residues in Karnataka. This allows to evaluate the feasibility of this technology in farmer's everyday life.

Annually 523 Mt crop residues are generated in India, out of which 127 Mt is surplus (Venkatesh et al. 2018). On a village level of about 500 inhabitants, an amount of 2000 t organic residues could be estimated for a year (Gowda et al. 1995). In contrast to the huge amounts of estimated agricultural residues, nonetheless, many farmers in rural Karnataka still lack in the necessary OM, either from crops or livestock, to fully perform sustainable agricultural practices (Purushothaman, Patil & Francis, cited in Bellè 2017).

Crop residues are either utilized or un-utilized due to various constrains (Venkatesh et al. 2018). Direct incorporation of crop residues in soils can conserve soil nutrients and organic C content but causes crop management problems related to a delayed decomposition (Grace, cited in Venkatesh et al. 2018). Surplus residues disrupt land preparation, crop establishment and early crop growth when left unattended. The residues are therefore either burnt or end up in landfill, degrading the environment, producing large amounts of GHGs and contributing to substantial nutrient losses (Yadav 2017; Venkatesh et al. 2018). Open field burning of crop residues is perceived as an age-old practice to boost soil fertility in terms of P and K, but often leads to a loss of other nutrients (e.g. N and S), organic matter and microbial activity required for maintain better soil health (IARI, cited in Venkatesh et al. 2018).

A village-based study in Karnataka found that 77% of the agricultural residues generated in the respective village were used as fuel for heating and cooking, for feeding livestock and for preparing traditional organic fertilizer. Only the remaining 23% of the residues have been left for decomposition or burning in agricultural fields itself, without any intended use (Gowda et al. 1995). Another study from Karnataka identifies different practices of managing agricultural wastes, ranging from compost production, fuel, construction material to cow dung manure production (Veeresh et al., cited in Bellè 2017).

Traditional practices of crop residue management could compete with the use of these wastes for soil fertility increase and thus hinder that biochar production is going to be applied. This entails that the identification of traditional farming practices as well as perceptions of residues as an agricultural resource by farmer communities is an essential topic before conceptualizing and introducing any alternative residue application for soil amendment from the side of science and technology (Gowda et al. 1995; Cardoen et al., Ghosh, Purushothaman et al., cited in Bellè 2017). Otherwise, biochar systems could put additional pressure on the fragile food supply in rainfed areas and could eventually trigger land-grabbing and promote deforestation (Venkatesh et al. 2018). Furthermore, residue amount estimation should be conducted at different scales to be able to predict the effective potential of residues transformation and an analysis that looks on priorities should grant that soil fertility is needed prior to other residue management practices.

The production of biochar from farm wastes and their application could offer multiple benefits if not in contrast to existing practices and allow the implementation of an efficient and sustainable residue management practice that is integrated in traditional agricultural practices (Gowda et al. 1995; Yadav 2017).

### 3.1.6 BBFs application in Karnataka– existing research and future potential

When looking at scientific literature, the application of biochar in India seems realistic.

In rural India women cook their food with biomass deriving mostly from wood and charcoal in highly polluting stoves, open earth pits or mounds. This causes deforestation, lots of time spent on wood collection and on cooking, back pains and other risks. Furthermore, charcoal is inefficiently produced releasing a considerable amount of methane emissions (Srinivasarao 2013; Bellѐ 2017).
The production of biochar in a small-scale system would be easily achievable by using already existing local techniques and only small adaptations would have to be made in order to increase the efficiency of C recovery in the biochar product (Lehmann & Rondon, cited in Bellѐ 2017).

Looking at a bigger scale, it has been estimated that about 309 Mt of biochar could be produced annually in India by using plant residues (Lal, cited in Yadav 2017). Beside to offset C emissions, both heat and gases can be captured during production of biochar and can be used as energy carriers (Yadav 2017). It is estimated, that if only 1 % of the Indian biomass would be converted to biochar, about 1300 and 900 t of biooil and biogas can be produced (Srinivasarao 2013).

The commercialization of biochar production devices and especially the diffusion of knowledge offer an opportunity to enhance the living conditions of rural families, counteract deforestation, protect biodiversity, increase crop production, improve agricultural waste management and remove C from the atmosphere as a C-negative strategy to fight global warming (Anon, cited in Srinivasarao 2013; Bellѐ 2017). Biochar as soil amendment has an additionally potential in India, since the intensive fertilizer use has brought to long term soil quality damages (Ghosh 2004). N is the most common nutrient that limits rice production since it is essential for plant growth and development, but, because of excessive application of nitrogenous fertilizers, rice yields are declining (Srinivasarao 2013). Specifically for India, there is to the need to revisit the traditional methods used in agriculture and to look for an alternative than combines chemical fertilizer-based technology with organic manure (Ghosh 2004).

Munda (2015) reports a positive influence of integrating biochar from rice husk together with chemical fertilizer on growth parameters, pH, OC, CEC, EC and available NPK compared to sole application of chemical fertilizers in India. This indicates that the combined application of biochar supplemented with chemical fertilizer could be recommended to improve soil fertility and crop productivity without affecting the soil quality, while decreasing the amounts of fertilizers needed.

Mohan (2018) investigated the application of rice husk biochar to improve Indian soil fertility, sequester C and increase crop production. Un-pyrolyzed husk was also used for soil amendments and compared to biochar. Fertilizers were not applied. An increase in WHC, TOC, CEC and a decrease in soil $CO_2$ emission were observed after biochar application to soil versus the application of the parent husk. Consequently, biochar improved soil fertility and enhanced crop growth. In addition, C mitigation was achieved because the biochar remained stable in the soil.

Little scientific literature can be found analysing the impact of BBF on Indian soils. Even if the existing literature shows promising results in regard to biochar application for soil fertility enhancement, any implementation of biochar application on the ground has to be foregone by an evaluation of the environmental and socio-economic context of farmer communities in which it shall be effectuated (Abiven et al. 2014; Joseph et al. 2015).

Even if not the focus of this work, on an environmental level, the successful implementation of biochar projects includes the availability of soils that benefits from the product (Abiven et al. 2014), but also the availability of agricultural residues for biochar production (Barrow 2012; Joseph et al. 2015). Additionally, socio-economic factors, including the capital and infrastructure to access and finance the biochar technology as well as the skill and knowledge to execute it, are essential for the introduction of a biochar system on farm level (Abiven et al. 2014). Additionally, any application has to be approached in a participatory way (Joseph et al. 2015).

## 3.2 Biochar and BBFs characterization

### 3.2.1 Biochar and BBFs

BC and BBFs were characterized in the laboratory looking at atomic elemental abundance, total C (TC), total N (TN) and chemical functional surface reactivity. BC was additionally characterized according to pH, electrical conductivity (EC), CEC and sorption properties.

A very small amount of each sample was sieved to <2mm with manual sieves to measure the pH and the EC. About 5 g of each sample were milled using a Mixer Mill for 2 minutes for RH samples and 8 minutes for SC samples at 25 1/s frequency to get the right texture. The milled samples are used for atomic elemental abundance analysis, TC and TN analysis and chemical functional surface reactivity analysis.

Different procedures are adopted in literature for **pH and EC** measurement of biochar. In this work, pH is measured both in $CaCl_2$ as in $H_2O$, EC only in $H_2O$.
To measure pH in $CaCl_2$, 5 g of BC are mixed in $CaCl_2$ solution for 30 minutes at 500 r/s, more specifically 25 ml of $CaCl_2$ for RH450 and RH700, 75 ml for SC450 and 37.5 ml for SC700. Different amounts of $CaCl_2$ were needed because of the different floating and absorbing properties.
The method recommended by Singh et al. (2017) was adopted to measure pH and EC of BC in $H_2O$. The procedure requires that 5 g of dry BC sample ground to <2mm are weighted in a 100 ml centrifuge bottle. Then, 50 ml of demineralized water have to be added and the closed bottle have to be shaken by hand before mechanically shaking them for 1 h at 25°C. pH in $H_2O$ and EC can be measured after allowing the suspension to stand for 30 min.
For both pH measurement methods and for the determination of the EC the 914 pH/Conductometer device was adopted, and two replicates were considered for each sample. The electrode had to be pressed through a layer of suspended BC to be able to carry out the measurements, thus the results could be altered.

The question of methodology is widely debated in case of pH of biochar. The use of pure water as suspension for measuring pH is sensitive to the soil:water ratio adopted and to small variation of the soluble salt content of soil (e.o. when containing fertilizer). These problems can be overcome by using an unbuffered salt solution like $CaCl_2$. Soil pH measured in $CaCl_2$ generally gives values that are 0.2 to 0.5 units lower than pH measured in pure water (Brady & Weil 2014). Additionally, the results are higher for a lower soil:solution ratio. Shaking time or position of the electrode in relation to the suspension also influence the results (Thomas, cited in Singh et al. 2017).

Due to the difficulties of measuring **CEC** of biochar with conventional methods used for soil samples, I relied on the method elaborated for biochar by Munera-Echeverri et al. (2018). Nonetheless, some adaptations were needed. Table 7 summarizes the different procedure steps proposed by Munera-Echeverra et al. (2018) with the adaptations and expediencies that I followed for the analysis.

Table 7: Procedure steps for CEC characterization of biochar from Munera-Echeverri et al. (2018) and recommended adaptations.

| Step | Procedure | Adaptation |
|---|---|---|
| 1. | Pretreatment | |
| a. | Weight 1 gram of biochar in 50 ml plastic tubes. Record the weight of the tubes with the lids. | |
| b. | Add 20 ml of deionized water and shake horizontally at 200 rpm during 4 hours to ensure proper wetting of the sample. Once the tubes have been shaken for 4 hours, add 0.05M HCl gradually until pH 7. Record the volume of 0.05M HCl. Check pH at different intervals and if needed add more 0.05M HCl. | Add just 15 ml of deionized water. Use the remaining 5 ml to wash the pH-sensor from the sticking biochar. |
| c. | After 48 hours, centrifuge the tubes at 1700 g. Pipette out the supernatant avoiding the floating biochar particles, add 20ml of deionized water again and shake horizontally during 1 hour. | Centrifuge at 4000 rds. Pipette out the supernatant positioning the pipette between the layer of floating biochar and that of deposited biochar. |
| d. | Centrifuge the tubes at 1700 g and discard the supernatants. Repeat the washings with water until EC < 200µS/cm. | Centrifuge at 4000 rds. Use 5 ml of deionized water to wash the EC-sensor. Discard it together with the supernatants. |
| 2. | Saturation with 1M $NH_4OAc$ | |
| a. | Add 20 ml of 1M $NH_4OAc$ (pH7) and shake the tubes horizontally at 200 rpm during 24 hours. If you are interested in the exchangeable base cations, extract twice more with 20 ml 1M $NH_4OAc$ (pH7) and shaking during 2 hours each time. Centrifuge at 1700 g and collect the supernatants for analysis of base cations. Correct for the background levels of cations in the sequential extractions. | |
| 3. | Washing with 99% isopropanol | |
| a. | Add 20 ml of 99% isopropanol to the tubes and shake horizontally at 200 rpm during 2 hours. | |
| b. | Centrifuge the tubes at 1700 g and pipette out the supernatant. Repeat three times more. In total the samples are washed 4 times with alcohol. As quality control, $NH_4^+$ should be | Centrifuge at 4000 rds. |

| | | |
|---|---|---|
| | analysed in the supernatant after the last addition of isopropanol. | |
| 4.<br>a.<br><br>b. | Displacement of $NH_4^+$ with $K^+$<br>Add 20 ml of 2M KCl, shake the tubes horizontally at 200 rpm during 24 hours and centrifuge the tubes at 1700 g.<br><br>Collect the supernatants, store them in the fridge and analyse $NH_4^+$ as soon as possible. | |

$NH_4^+$ was analysed through colorimetric method using a VIS spectrophotometer of HACH LANGE with LCK 303 cuves. The $NH_4^+$ concentrations were needed to determine CEC through the equation (1) from Brady & Weil (2014: 340), considering 0.02 L of collected solution, 0.001 kg of biochar, the equivalent weight of $NH_4^+$ of 18 g, x as the measured $NH_4^+$ in mg/L and y as the resulting CEC in cmol $NH_4^+$/kg.

$$x\frac{mg\,NH_4^+}{kg}\,soil * 0.02\frac{L}{sample} * 0.001\frac{samples}{kg}\,soil * \frac{1\,mol\,NH_4^+}{18\,g} * \frac{1\,g}{1000\,mg} * 100\,\frac{cmol}{mol} = y\frac{cmol\,NH_4^+}{kg\,soil} \tag{1}$$

The **sorption properties** of BC were investigated through a batch sorption experiment for nitrate ($NO_3^-$) during five days of experiment. The experiment duration of five days was chosen after having carried out and evaluated different pre-tests, which showed a stabilization of the adsorption rate after approximately three days and a stabilization of the desorption rate after approximately two days.
Considering a concentration of 500 mg/L of $NO_3^-$, the reagent was added to 2 dl of water and 40 mg of BC. The solutions were shaken constantly at 1000 rs and $NO_3^-$ was repetitively measured using a LAQUAtrim measurement device until the stabilization of adsorption rates. Once the maximal sorption capacity of biochar was reached, the solution was filtered to collect the BC particles. These particles were then added to 2 dl of demineralized water and the desorption behaviour was recorded again measuring $NO_3^-$ concentration through LAQUAtrim device. Three replicated were considered for each sample.

**Atomic elemental abundance** was investigated using X-ray Fluorescence (XRF) through Spectro Xepos, AMETEK. Elements that have an atomic elemental abundance higher than <0.001 % are discussed in the results section.

**TC and TN** were analysed through an Elemental Analyser (EA). Because of the high concentration in C present in BC, only 0.5 mg of sample could be weighted in for measurement.

The **chemical functional surface reactivity** of the samples in the mid-infrared (IR) spectra were acquired by Diffuse Reflectance Infrared Fourier Transform Spectroscopy (DRIFTS). Spectra were recorded from 3996 to 461 $cm^{-1}$ on a powder containing 6 mg of milled sample and 194 mg of KBr. DRIFTS analyses shape, compactness, refractive index, reflectivity and adsorption of the particles. Higher values do not mean a higher amount of specific structures, but a higher reactivity of the surface structures of the material when irradiated by IR. Major IR adsorption bands and assignments used for my interpretation base on the literature compilation from Chatterjee et al. (2012) resumed in Table 8. To evaluate the results obtained by DRIFTS analysis, I did different manipulation. As first, the atmospheric manipulation allows to avoid $CO_2$ impacts, since $CO_2$ value are influenced by the breathing of people in laboratory. I smoothed then the values through a baseline correction of 17 to hide disturbances. Through a cluster analysis I grouped the results into common variables, what allows to see which factor has the highest influence.

Table 8: Major IR adsorption bands and assignments (Chatterjee et al. 2012).

| Band number | Wavelength (cm$^{-1}$) | Description (trend during charring) |
|---|---|---|
| 1 | 3050-3020 | C-H aromatic stretch (increase) |
| 2 | 3000-2800 | C-H aliphatic stretch (decrease) |
| 3 | 2850-2820 | Aliphatic C-H (difference between sample) |
| 4 | 1730-1680 | Aromatic carbonyl/carboxyl C=O stretch (increase) |
| 5 | 1610-1570 | C=C stretch (increase) |
| 6 | 1510-1500 | Lignin, Aromatic C=C stretch (decrease) |
| 7 | 1430-1380 | Aromatic C=C stretch (increase) |
| 8 | 1260-1210 | Cellulose (decrease) |
| 9 | 1060-1020 | Aliphatic C-O- and alcohol C-O stretch (decrease) |
| 10 | 880, 805, 745 | C-H aromatic bending deformation (increase) |

The MID-infrared index (2) described in Wiedemeier et al. (2014) allows to characterize char samples according to their heating temperature using the reactivity of the samples at specific wavelengths. The index was used to estimate the pyrolysis temperature reached by the two charring methods applied in the field.

$$Aromaticity\ ratio\ [\%] = \frac{1420 + 821}{1510 + 1320}\ cm^{-1} \qquad (2)$$

### 3.2.2 Soil samples

Soil samples from different research sites along a pedo-climatic gradient in Karnataka were considered during analysis. From east to west, Bangalore, Mandya, Hassan and Mangalore. For each sample 2 replicates were considered for laboratory analysis.

**Chemical functional surface**, **atomic elemental abundance**, **TC and TN** are analysed as described in section 3.2.1. For TC and TN, 2 mg of soil samples were weighted in for measurement.

To measure the **WHC**, soil samples were inserted into a fennel with a filter paper on its bottom. The samples were then wetted and the exceeding water was let drop out through the fennel overnight. The fennels were covered to avoid water evaporation. The difference between the weight of the sample once saturated with water and the dry weight represents the WHC.

For **pH and EC**, 10 g of soil with 25 ml of demineralized water were mixed, shaken and centrifugated to measure pH and EC through pH System 362 and respectively Conductivity Meter 306 both by Systronics.

**$NO_3^-$** [mg/L] was measured using LAQUAtrim measurement device considering soil:water ratio of 1:5.

For the soil organic C (**SOC**), the titrimetric method of Walkley and Black (1934) was adopted. Instead of Diphenylamine indicator and Orthophosphoric acid, only Ferroin indicator solution was added.

For the **CEC** measurement, the distillation or ammonium saturation method was adopted.

**Soil texture** was determined using the international pipette method, whereas **BD** was measured using sieved samples placed in keen's cups with a known volume. BD results from the weight of a dry sample divided by his volume.

## 3.3 Analysis under controlled conditions

### 3.3.1 Incubation preparation

Soils from four different research sites along a pedo-climatic gradient in Karnataka were adopted for this incubation experiment. From more arid to more humid climatic conditions, or better from east to west, the soils are from Bangalore, Mandya, Hassan and Mangalore. Each soil is sieved at <2mm and is enhanced through the BC and BBFs prepared in India and applied in Mandya for the field trial. To permit a comparison between field trial and laboratory incubation, the same treatment compositions and amounts are adopted during this research part (table 4). The experiment will be a short-term soil incubation considering a total of 87 samples: 4 soil types, 7 treatments + 1 blank and 3 replicates. Each sample is incubated individually in a glass jar. In each jar a suction glass was inserted and, from bottom to top, a layer of quartz gravel (40 g), filter paper and soil (40 g) with the respective amendment were added. The soil was then gently wettened by 35 ml of demineralized water. Through a suction pump water was extracted and the soil resulted saturated.
Apart from the suction glass, each jar contained 20 ml of distilled water to ensure the headspace was moist and 20 ml of 1M NaOH to capture the C-$CO_2$ product of the mineralization of SOC.
The jars were located inside incubators under controlled conditions of 25 °C for the incubation duration of 6 weeks.

### 3.3.2 Sampling

Measurements were carried out 5 times during incubation period, exactly after 2 days, 1 week, 2 weeks, 4 weeks and 6 weeks from start, due to the faster mineralization rate expected at the beginning of incubation.
During each sampling time, the NaOH bottles (brown bottles in figure 24) have to be taken out and replaced by new ones. The solution is then used for conductivity measurement to determine the $CO_2$ respired according to equation (3).

$$CO_2 + 2NaOH \rightarrow Na_2CO_3 + H_2O \tag{3}$$

The formula used to determine the g C-$CO_2$/kg soil respired is based on the change in conductivity of the NaOH solution that is dependent on temperature. The measured conductivity has to be corrected for a temperature of 25 °C as in equation (4). The $CO_2$ (mg/ml) must be calibrated using equation (5). The ratio from $CO_2$ to C of 0.2729, the volume of NaOH solution used and the quantity of soil adopted for incubation allow to calculate the respiration (g C-$CO_2$/kg soil) (6).

$$\begin{aligned} &corrected\ conductivity[\mu S] = \\ &\qquad measured\ conductivity[\mu S - (measured\ temperature\ [°C] - 25\ °[C]) * 2.4976 \end{aligned} \tag{4}$$

$$CO_2\ [\mu S] = -0.1695 * conductivity\ [\mu S] + 29.03 \tag{5}$$

$$respiration\ \left[\frac{g\ C - CO_2}{kg\ soil}\right] = \frac{total\ CO_2\ [mg\ in\ solution] *\ 0.2729}{dry\ mass\ soil[g]} \tag{6}$$

Additionally, at each measurement time the soil samples are flushed with 15 ml of demineralized water to produce soil extract, which is used for $NO_3^-$, $NH_4^+$ and $PO_4^{3-}$ measurement. Nutrients' concentration was determined through colorimetric method, using LCK cuves measured in a HACH LANGE VIS spectrometer device. The solution is extracted from the soil samples using a pressure pump at 160 mbar (figure 25).

Figure 24: glass jars. *Own Picture*.

Figure 25: suction pump. *Own Picture*.

## 3.4 Field trial

### 3.4.1 Land preparation

The experimental field (Figure 26) was ploughed (Figure 27), flooded and plots were delimitated constructing soil walls by hand (Figure 28). For my research, 21 plots of a size of 20 m$^2$ were built.

Figure 26: experimental field. *Own picture*. Figure 27: ploughing. *Own picture*. Figure 28: wall construction. *Own picture*.

The experimental design (Figure 29) includes three replicates for each treatment. Treatments T1- T7 were considered for my master thesis. The plots were aligned in three rows (here horizontal), each representing a replicate. For each replication row, treatment order is randomized. Distance from the sites prevents edge effect.

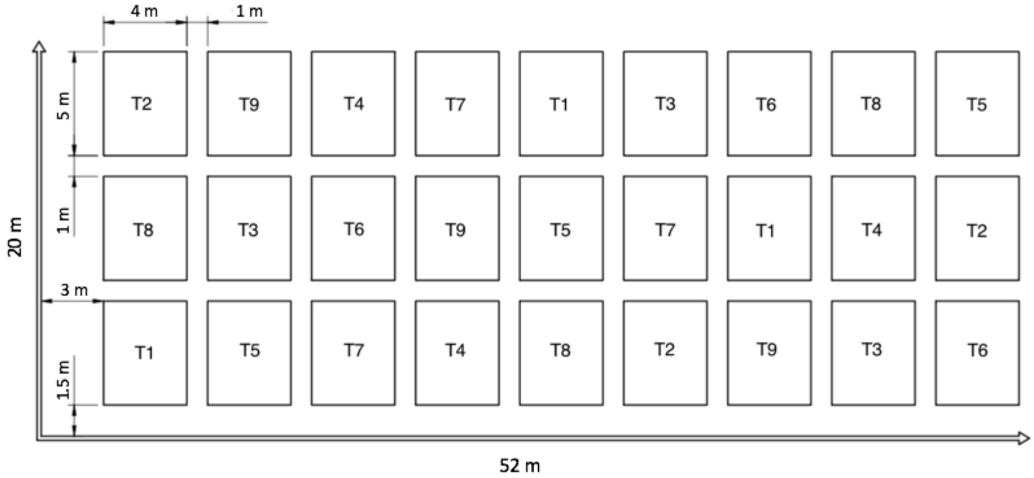


Figure 29: Experimental design.

### 3.4.2 Treatments’ application and planting

The plots were flooded just before treatments’ application. Treatments were applied on the field 7 days before planting and then uniformly incorporated by hand in the topsoil (Figure 30). Standing water was present during application. The rice type selected for the experiment is IET 723. After 21 days of nursery (Figure 31) the seedlings were transplanted on the 13th of January with a distance of 10 cm between plants and 20 cm between rows.

Figure 30: treatments’ application. *Own picture*.

Figure 31: nursery. *Own picture*.

Figure 32 gives a good overview of the research field once divided into plots and with the different treatments applied.

Figure 32: overview on experimental field after treatments' application. *Own picture*.

### 3.4.3 Sampling

A soil auger was adopted to obtain soil samples near the surface (0-15 cm). Soil and rice shoots were collected in 5 randomly chosen sites of 1 $m^2$ inside each plot and were mixed to obtain a sample. Outer parts of the plots located at the edge of the field were avoided because of the edge effect. Soil and plant samples were air dried before proceeding for analysis.

### 3.4.4 N and P efficiencies

N in shoot and in the treatments was measured in wt % through the EA. Relative N Uptake Efficiency (rNUpE), relative N Utilization Efficiency (rNUtE), and relative N Use Efficency (rNUE) were calculated according to equation (7) (Perchlik & Tegeder 2017). Only N supplied by the treatments is taken into account for analysis. rNUpE was defined as the ratio of total N in the aboveground shoot mass to total N supplied; rNUtE is the ratio of seed yield to total shoot N and rNUE is described as the combination of these two parameters, or the ratio of seed yield to the total N supplied.

$$\overset{\text{[rNUpE]}}{\frac{total\ shoot\ N}{N\ supplied}} * \overset{\text{[rNUtE]}}{\frac{seed\ yield}{total\ shoot\ N}} = \overset{\text{[rNUE]}}{\frac{seed\ yield}{N\ supplied}} \tag{7}$$

Same equation is used for rPUpe, rPutE and rPUE. Here, the abundance of P is related to the abundance measured from XRF. Only P amount supplied by the treatments was considered.

## 3.5 Statistical analysis

Datasets for all soil parameters for the four soil types were statistically analysed using the software R Studio 1.1.453 (2009-2018). Figures were carried out using R Studio or Excel 16.26.

Before running any statistical test, all datasets had been investigated looking at the descriptive statistics as means or standard errors of the mean. Correlation was tested using analysis of variance (ANOVA). Under the condition that the analysis of variance was significant ($p < 0.05$), post-hoc tests were conducted in order to identify which factors are significantly different ($p < 0.05$). Post-hoc tests were run with the Fisher's least significant difference (LSD), which compares the mean of individual groups with the mean of the other groups. Significances are indicated as follows: 0 '***' 0.001 '**' 0.01 '*'.

For the laboratory characterization, plant type (RH, SC), charring temperature (450, 700) or amendment type (RH, BC, BCC, BCCMF, BCMF, BCSJ, BCMFSJ, BCFL and BCMFFL) were tested for correlation with atomic elemental abundance, TC or TN. For the analysis under controlled conditions (incubation experiment), treatment and soil type are tested for correlation with respiration rate and nutrients' ($NH_4^+$, $PO_4^{3-}$ and $NO_3^-$) concentration at different sampling times. Sample sizes between analysed variable differ and are indicated with "n" in the results section (Chapter 4).

# 4. Results

## 4.1 Biochar and BBFs characterization

### 4.1.1 pH-value, EC and WHC

Table 9: pH-value and EC [mS/cm] of BC produced under controlled conditions.

| Sample | pH-value (in $CaCl_2$) | pH-value (in $H_2O$) | EC [mS/cm] |
|---|---|---|---|
| RH450 | 6.73 | 7.29 | 0.57 |
| RH700 | 5.45 | 7.78 | 0.56 |
| SC450 | 8.31 | 7.74 | 1.29 |
| SC700 | 9.29 | 7.64 | 1.34 |

Results of pH and EC analysis of the BC produced under controlled conditions are shown in table 9. pH-values measured in $CaCl_2$ range from 5.45 to 9.29. RH biochar results more acidic than SC biochar. pH-values measured in $H_2O$ show pH-values between 7.29 and 7.78. There is neither a trend looking at feedstock type than for charring temperature. EC [mS/cm] ranges between 0.56 and 1.34. RH shows lower EC [mS/cm] in respect to SC and no trend is visible looking at charring temperature.

Table 10: pH-value, EC [mS/cm] and WHC [%] of BC and BBFs produced in the field.

| Sample | pH-value | EC [mS/cm] | WHC [%] |
|---|---|---|---|
| RH | 6.74 | 1.12 | 162.4 |
| $BC_{Kon\text{-}Tiki}$ | 9.24 | 0.80 | 399.91 |
| BCC | 9.09 | 0.93 | 159.62 |
| BCMF | 8.02 | 7.41 | 262.80 |
| BCSJ | 7.64 | 1.89 | 234.61 |
| BCMFSJ | 7.64 | 4.55 | 255.45 |
| $BC_{UAS}$ | 8.29 | 0.73 | 609.43 |

Table 10 includes pH-values, EC [mS/cm] and WHC [%] of BC and BBFs produced in the field. pH-values were measured in $H_2O$ and range between 6.74 and 9.24. Lowest value was measured looking at RH, thus charring increases pH-values of the feedstock. All charred samples have an alkaline pH-value.

Looking at the production methods, $BC_{Kon\text{-}Tiki}$ has a pH-value of 9.245 and $BC_{UAS}$ of 8.29. pH-values of BBFs are relatively lower than untreated BC (9.24): BCC has a pH of 9.09, BCMF of 8.02, and both BCMFSJ and BCSJ of 7.64.

EC [mS/cm] ranges from 0.73 to 7.41 between analysed samples. The BC alone, both $BC_{Kon\text{-}Tiki}$ (0.8 mS/cm) and $BC_{UAS}$ (0.73 mS/cm), show the relative smallest values. BBFs have relative higher EC [mS/cm] than BC.

Especially BCMF (EC 7.41 mS/cm) and BCMFSJ (EC 4.55 mS/cm), both containing MF, show relatively highest EC values.

WHC [%] ranges from 159.62 to 609.43. Lowest WHC [%] resulted from RH, thus there is an increase in WHC through charring. The WHC [%] decreases significantly through the amendments: $BC_{Kon\text{-}Tiki}$ has a WHC of 399.91 % and $BC_{UAS}$ of 609.43 %, whereas all the BBFs range between WHC concentrations of 159.61 % (BCC) and 262.80 % (BCMF).

To resume, pH-values of BC produced under controlled conditions range between 5.45 and 9.29 if measured in $CaCl_2$ and between 7.29 and 7.78 if measured in $H_2O$. pH-values of BC produced in the field and measured in $H_2O$ range between 8.29 and 9.24. RH is more acidic and has lower EC [mS/cm] than SC. No trend is visible between pH-value and charring temperature. Charring increases pH-value of feedstock. Impregnation leads to lower pH-values but higher EC [mS/cm], especially for BC with MF. Charring increases the WHC [%] significantly, but all BBFs show lower WHC [%] than BC.

### 4.1.2 CEC

The CEC of the BC produced under controlled conditions and in the field are shown in table 11. The CEC of the BC produced under controlled conditions ranges from 2.27 to 7.18 cmol/kg. Both feedstock type and temperature influence CEC-values: higher CEC can be found using SC as feedstock and charring at 450°C . $BC_{Kon\text{-}Tik}$ resulted having a CEC of 3.17 cmol/kg and $BC_{UAS}$ of 4.03 cmol/kg.

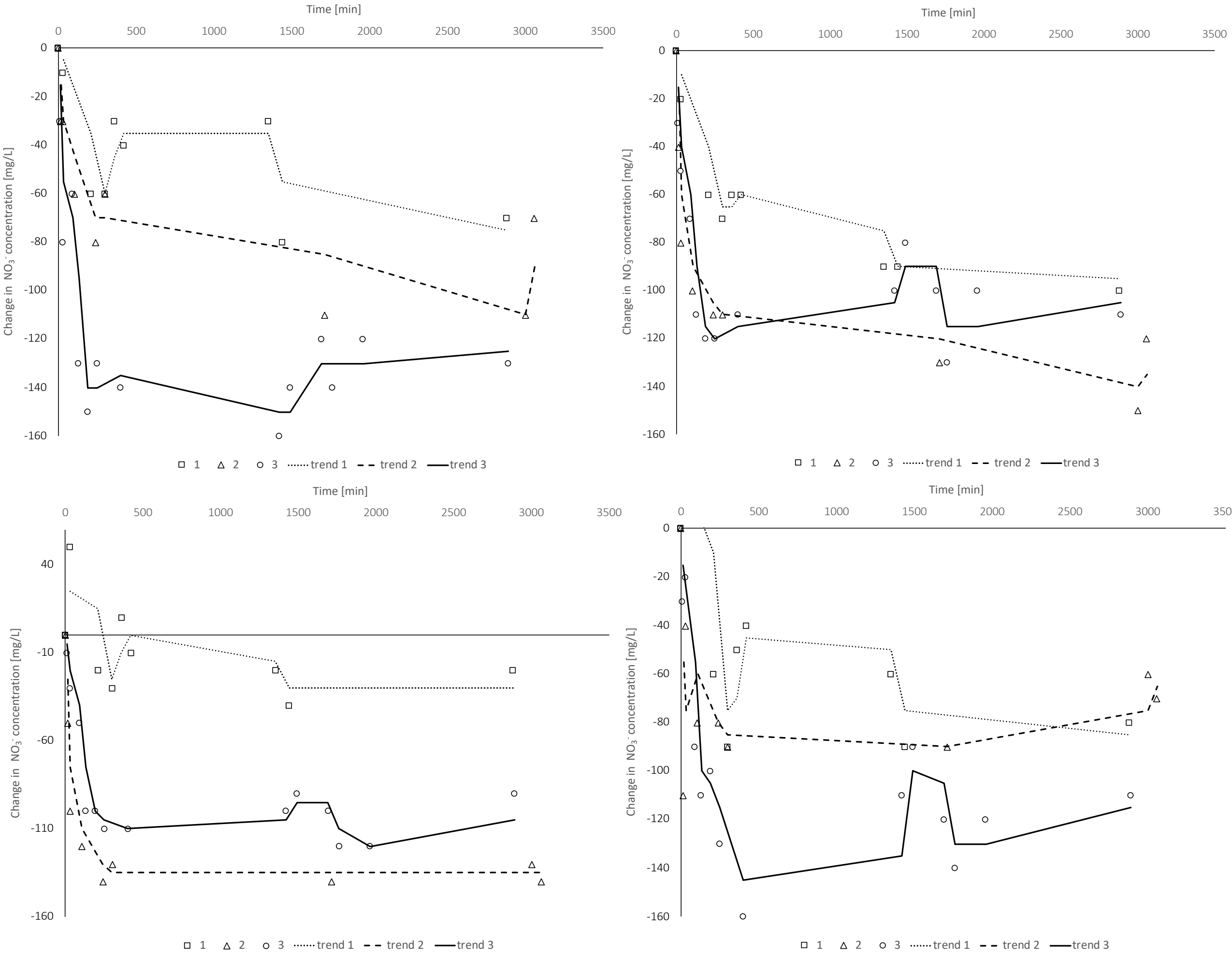
Table 11: CEC [cmol/kg] of BC.

| Sample | RH450 | RH700 | SC450 | SC700 | $BC_{Kon\text{-}Tiki}$ | $BC_{UAS}$ |
|---|---|---|---|---|---|---|
| CEC [cmol/kg] | 5.85 | 2.27 | 7.18 | 3.82 | 3.17 | 4.03 |

### 4.1.3 Sorption properties

Figures 33-36 show the concentration of nitrate ($NO_3^-$) during approximately three days of batch adsorption experiment for BC produced under controlled conditions between RH450, RH700, SC450 and SC700. Replicates show significance differences as visible in the figures below. Independently from the BC type, during the first measurement time (replicate 1) the results are of a smaller change in concentration of $NO_3^-$ with time in respect to the other two measurement times (replicate 2 and 3).

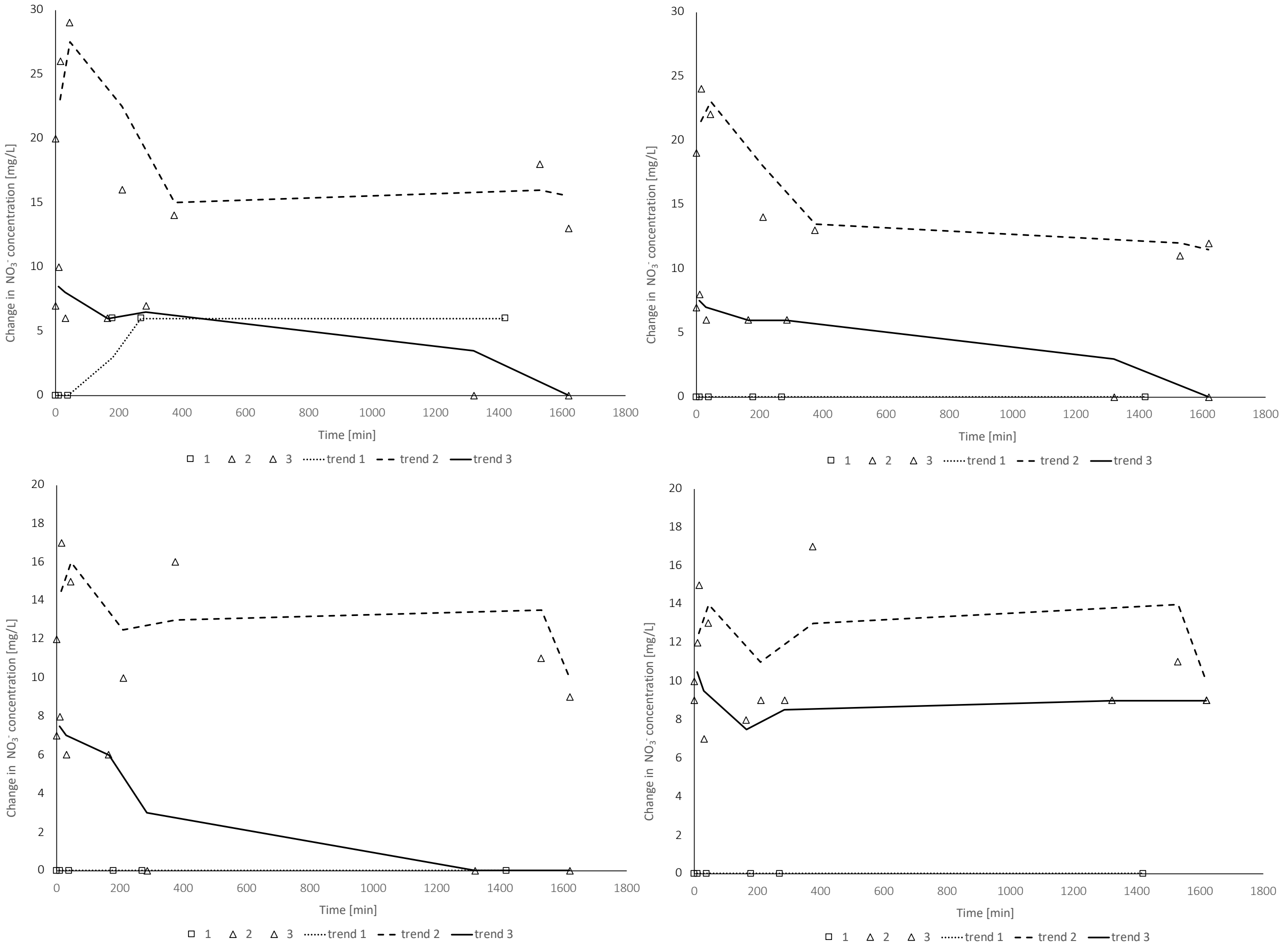
Common to the three replicates of RH450 is a strong adsorption until about 250 minutes from start of the experiment. Then, the behaviour between the replicates differs. At the end of the experiment, adsorption rates stabilize in average at -86.67 mg/L, whereas mean maximal change in concentration measured for RH450 is of -116.67 mg/L of $NO_3^-$. The same pattern described for RH450 is true for RH700. Replicate 3 shows a desorption period included in the general adsorption trend. The replicates of RH700 have a mean maximal change in $NO_3^-$ concentration of -133.34 mg/L and the final concentration of $NO_3^-$ in the water is of -116.67 mg/L.
SC450 shows a mean maximal change in concentration of -73.34 mg/L of $NO_3^-$. The trend is of strong adsorbance in the first 300 minutes of experiment, then the adsorption is quite stable until end of the experiment reaching an average of -86.67 mg/L. SC700 as well adsorbs $NO_3^-$ in the first 300 minutes, then the replicates desorbe some amount of $NO_3^-$ again stabilizing at about -86.67 mg/L. The mean of strongest change in concentration between the replicates of SC700 is of -120 mg/L.



Figures 33-36: results from batch adsorption experiment for SC450 (above right), SC700 (above left), SC450 (below right) and SC700 (below left). Change in concentration of $NO_3^-$ with time [min] of replicates (1,2 and 3).

Figure 37-40 show the desorption behaviour of the different BC types during approximately two days of experiment.

For RH450, the replicates show different trends at the beginning of the experiment, but all replicates stabilize after about 400 minutes and maintain a constant change in concentration of $NO_3^-$ in the water of about 7 mg/L until end of experiment. RH450 is the only BC type with data for replication 1. The water of RH700 concentrates in $NO_3^-$ in the first hour, but adsorbance dominates until end of experiment leading to a final concentration of about 7 mg/L. In both SC450 and SC700, there is a small increase in $NO_3^-$ concentration in the water after about 15 minutes, followed by a rapid decline in concentration of $NO_3^-$, before reaching an equilibrium at about 5 mg/L for SC450 and 9 mg/L for SC700.



Figures 37-40: results from batch desorption experiment for SC450 (above right), SC700 (above left), SC450 (below right) and SC700 (below left). Change in concentration of $NO_3^-$ with time [min] of replicates (1,2 and 3).

Looking at the sorption properties of the BC produced in the field, Results for sorption properties of BC produced in the field are similar between production method and between replicates (figure 39). The concentration of $NO_3^-$ in the water decreased exponentially during the first 400 minutes of the adsorption part of the experiment for both $BC_{Kon\text{-}Tiki}$ and $BC_{UAS}$, reaching a maximal change in concentration at respectively -150 mg/L and -125 mg/L. From then, both BC start to desorbe $NO_3^-$ again, reaching an equilibrium at around -90 mg/L for $BC_{Kon\text{-}Tiki}$ and at around -85 mg/L for $BC_{UAS}$.

Value obtained during the desorption part of the batch experiment are similar between replicates and between $BC_{Kon\text{-}Tiki}$ and $BC_{UAS}$ (figure 40). Both BC release about 15 mg/L of $NO_3^-$ once the samples are insert into the demineralized water with no initial $NO_3^-$ concentration. These amounts are then adsorbed again by the BC. After two days of experiment, the demineralized water contains 6 mg/L of $NO_3^-$ for both $BC_{Kon\text{-}Tiki}$ and $BC_{UAS}$.

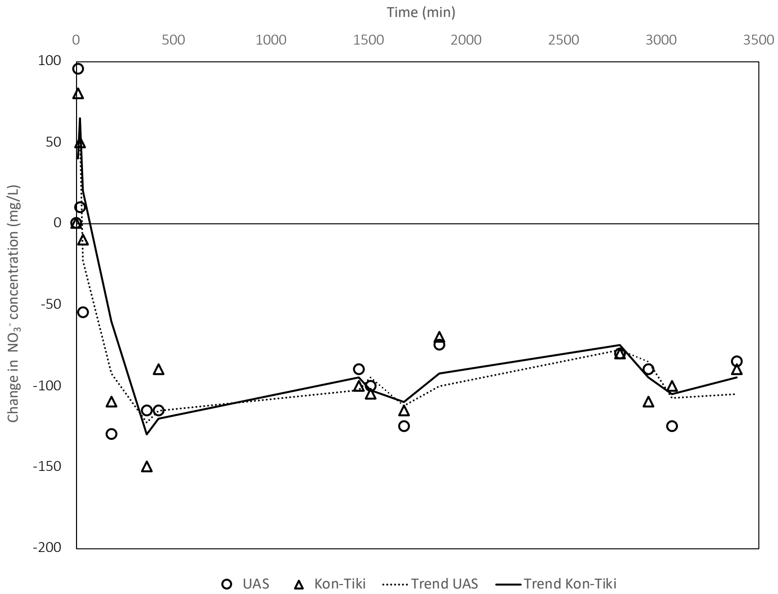


Figure 56: Results from batch adsorption experiment for biochar produced through UAS-method and Kon-Tiki-like open earth kiln. Mean change in concentration of $NO_3^-$ with time [min].

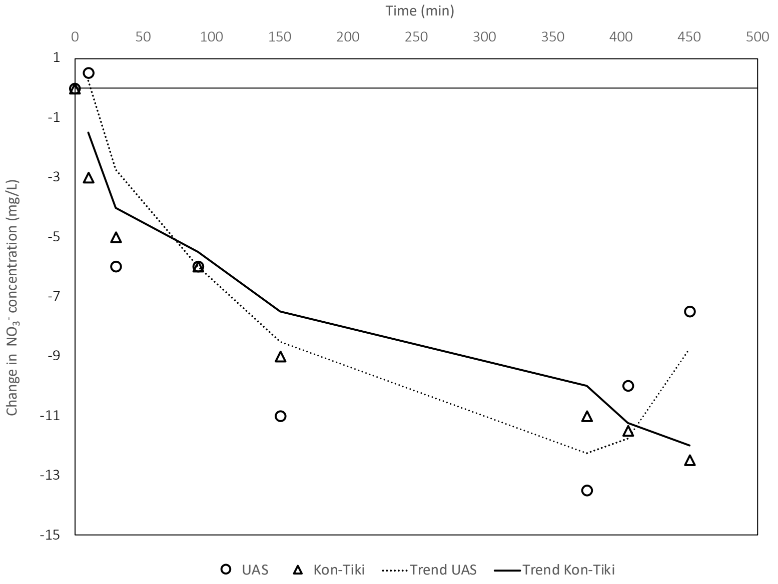


Figure 57: Results from batch desorption experiment for biochar produced through UAS-method and Kon-Tiki-like open earth kiln. Mean change in concentration of $NO_3^-$ with time [min].

To resume, the adsorption rate of BC when insert into water containing $NO_3^-$ is especially high at beginning of the experiment, then the rate decreases linearly and stabilizes. For the BC produced under controlled conditions, replicates show significance differences during the experiment and looking at total adsorption amounts at the end of experimental period. Higher charring temperature leads to more homogeneous replicates and higher maximal adsorption rates. During desorption experiment, change in concentration is relatively small and the adsorption dominates over the desorption. For the BC produced in the field, the adsorption behaviour is very similar between the two production methods and between the replicates. Main adsorption behaviour is same as described for the BC produced under controlled conditions, whereas the desorption is relatively weaker.

At the end of experimental period, for all BC types and production methods, about 100 mg/L of $NO_3^-$ present in the water is adsorbed, thus, about 20 % of initial concentration of 500 mg/L. From the approximately 100 mg/L of $NO_3^-$ present in the BC when starting the desorption part of the experiment, just about 6 mg/L are desorbed and measured in the demineralized water with no initial $NO_3^-$ concentration at the end of experimental period, thus about 6 %.

### 4.1.4 Atomic elemental abundance

Most abundant elements found for BC produced under controlled conditions differ between feedstock and temperature used for charring procedure: RH450 contains 1.17 % of Na and 0.82 % of P and RH700 contains 1.08 % of Na and 0.76 % of K; SC450 is formed by 2.5 % of K, 1.85 % of Na and 1.85 % of Si, whereas SC700 contains 3.70 % of K and 1.82 % of Si. Concentrations of all analysed elements can be found in the annexe in table 26. Correlations that resulted significant from statistical analysis are resumed in table 12.

Table 12: significant correlations between amendment and feedstock type of BC and BBFs produced under controlled conditions and atomic elemental abundance.

| | K [%] | Ca [%] | Na [%] | P [%] | Si [%] | Mg [%] | Al [%] | Fe [%] | Mn [%] |
|---|---|---|---|---|---|---|---|---|---|
| Feedstock type | 4.1e-05*** | 0.0155* | 0.000397*** | 4.42e-08*** | 0.00406** | | | | 0.0136* |
| Amendment type | | 4.78e-05*** | | | 0.000509 *** | 6.16e-07*** | 3.65e-07*** | 1.93e-08*** | 0.000236*** |

Between Bc and BBFs produced with RH (n=16) or SC (n=16) as feedstocks, significant correlations resulted analysing P, K, Ca, Mn, Na and Si abundance. SC contains significant higher abundances of Si (average of 2.97% in respect to 1.56%), K (average of 2.52% in respect to 0.93%), Ca (average of 0.95% in respect to 0.66%) and Mn (average of 0.013% in respect to 0.008%) whereas RH contain significant higher abundance of P (average of 0.74% in respect to 0.28%) (figures 41 and 42).

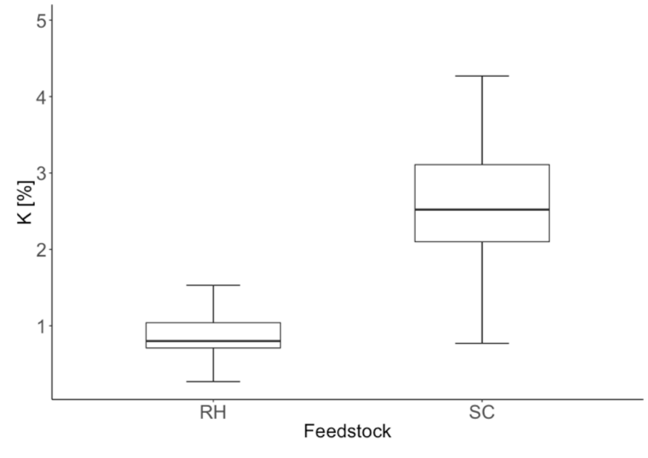


Figure 41: K [%] in respect to feedstock type.

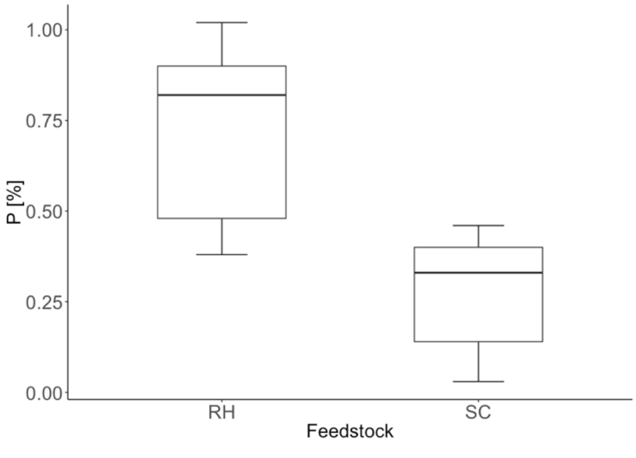


Figure 42: P [%] in respect to feedstock type.

From raw biomass to BC, an enrichment in Na, Mg, Al, Si, P, Cl, K, Ca, Mn and Fe is measurable in all samples produced under controlled conditions. For K, Cl, Mn, Na, Al and Fe a higher concentration is found in samples charred at higher temperature in respect to samples from a lower pyrolysis temperature. For Ca, P and Si the atomic abundance is higher for samples charred at 450°C in respect to 700°C instead. Nonetheless, none of the correlations between temperature and atomic elemental abundance resulted as significant from statistical analysis. Figures 43 and 44 show the Al [%] and Fe [%] concentration in respect to uncharred samples (n=2), samples pyrolyzed at 450°C (n=16) and samples pyrolyzed at 700°C (n=16).

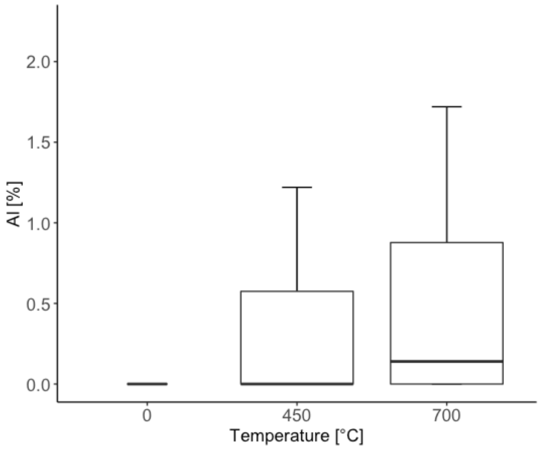


Figure 43: Al [%] in respect to charring temperature [°C].

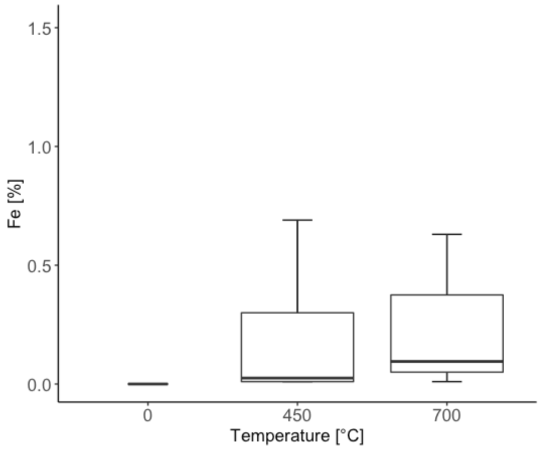


Figure 44: Fe [%] in respect to charring temperature [°C]

Looking at the distribution of my data in regard to amendments (n=4 for each amendment) and atomic elemental abundance, significant correlation resulted looking at Ca, Si, Fe, Al, Mg and Mn (figures 45-48). In all analysed elements, main pattern shows compost amendment having highest elemental abundance followed by BBFs containing FL, MF and finally SJ.

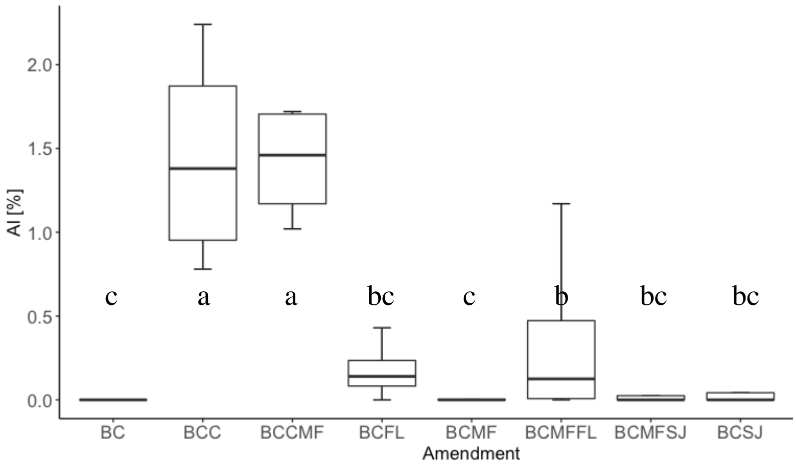


Figure 45: Al [%] in respect to amendment.

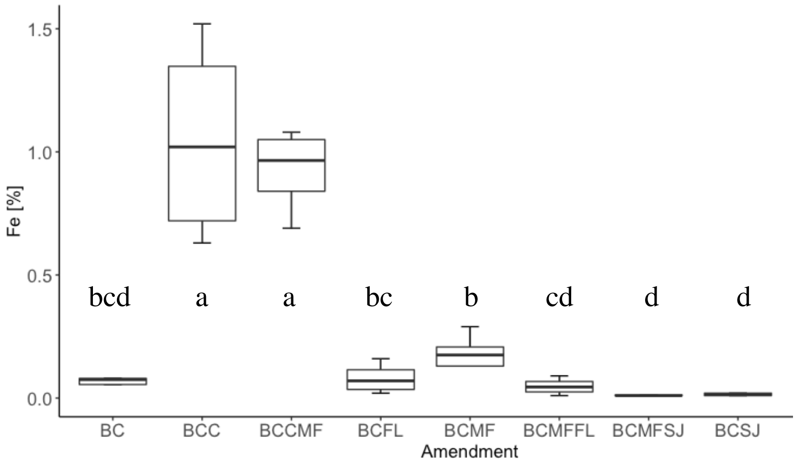


Figure 46: Fe [%] in respect to amendment.

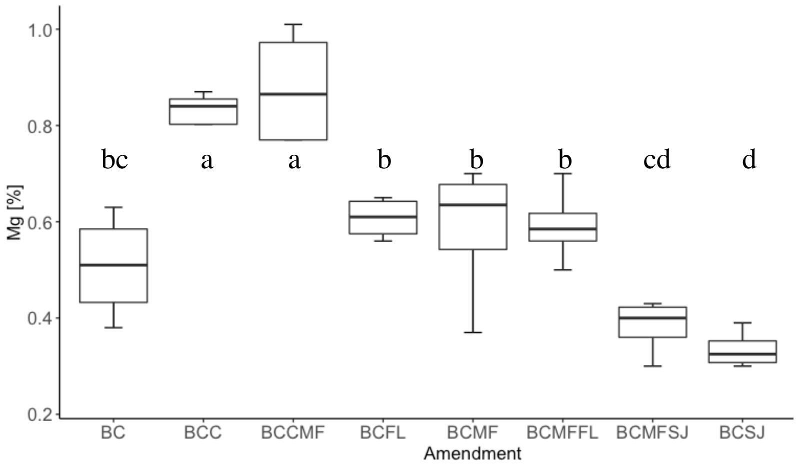


Figure 47: Mg [%] in respect to amendment.

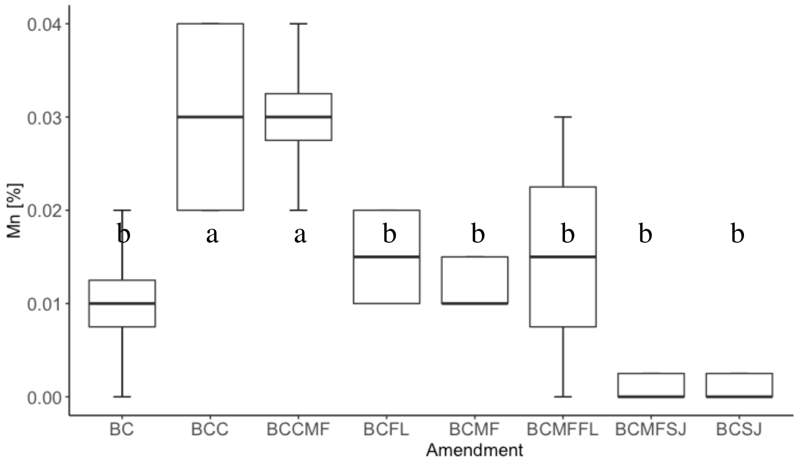


Figure 48: Mn [%] in respect to amendment.

Table 13: atomic elemental abundance of treatments produced in the field.

| Sample | Na (%) | Mg (%) | Al (%) | Si (%) | P (%) | K (%) | Ca (%) | Mn (%) | Fe (%) |
|---|---|---|---|---|---|---|---|---|---|
| RH | 0.72 | 0.18 | < 0.0020 | 8.09 | 0.07 | 0.55 | 0.07 | 0.72 | 0.18 |
| BC$_{\text{Kon-Tiki}}$ | 1.16 | 0.46 | 0.82 | 30.81 | 0.28 | 1.87 | 0.77 | 1.16 | 0.46 |
| BCC | 0.95 | 0.63 | 2.76 | 25.30 | 0.47 | 1.60 | 1.16 | 0.95 | 0.63 |
| BCMF | 1.52 | 0.43 | 0.79 | 21.66 | 1.10 | 2.89 | 2.59 | 1.52 | 0.43 |
| BCSJ | 1.26 | 0.55 | 0.76 | 28.73 | 0.38 | 2.05 | 0.92 | 1.26 | 0.55 |
| BCMFSJ | 1.46 | 0.42 | 0.75 | 24.11 | 0.76 | 2.54 | 1.82 | 1.46 | 0.42 |
| BC$_{\text{UAS}}$ | 1.20 | 0.34 | < 0.0020 | 33.88 | 0.33 | 2.38 | 0.35 | 1.20 | 0.34 |

Table 13 shows the atomic elemental abundance of BC and BBFs produced in the field.
Most abundant element in the treatments is Si (ranging from 8% to 33%), followed by K (about 2% in all samples) and Na (about 1 % in all samples). BC alone has highest Si abundance with 30.81 % in BC$_{\text{Kon-Tiki}}$ and 33.88% in BC$_{\text{UAS}}$. BCC has highest Al and Fe concentrations with respectively 2.76% and 0.63%. Samples containing MF (BCMF and BCMFSJ) contain Ca, Cl, P, K and Na more abundantly than the other treatments. RH is generally less concentrated in the analysed elements than the other treatments, thus there is an enrichment through charring. BC$_{\text{UAS}}$ shows higher Mg, Al, Si, P, Cl, K, and Mn concentrations in respect to BC$_{\text{Kon-Tiki}}$, which has respectively higher Na, Ca and Fe concentrations.

Considering all BC produced from rice husk, relevant differences can be found comparing Si [%] from field BC (more than 30 %) and production under controlled conditions (less than 1 %). Furthermore, BC from the field has higher relative higher K [%], Ca [%], Mn [%] and Fe [%] whereas relative lower P [%] than BC produced under controlled conditions. Table 14 resumes the different atomic elemental abundances of all BC produced from rice husk.

Table 14: atomic elemental abundance of BC produced with rice husk as feedstock.

| Sample | Na (%) | Mg (%) | Al (%) | Si (%) | P (%) | K (%) | Ca (%) | Mn (%) | Fe (%) |
|---|---|---|---|---|---|---|---|---|---|
| $BC_{\text{Kon-Tiki}}$ | 1.16 | 0.46 | 0.82 | 30.81 | 0.28 | 1.87 | 0.77 | 1.16 | 0.46 |
| $BC_{\text{UAS}}$ | 1.20 | 0.34 | < 0.002 | 33.88 | 0.33 | 2.38 | 0.35 | 1.20 | 0.34 |
| RH450 | 1.17 | 0.57 | < 0.002 | 0.06 | 0.82 | 0.77 | 0.03 | < 0.002 | 0.01 |
| RH700 | 1.08 | 0.38 | < 0.002 | 0.07 | 0.68 | 0.76 | 0.03 | < 0.002 | 0.08 |

To resume, charring leads to an enrichment in all analysed elements. For Ca, P and Si, nonetheless, the abundance is lower with higher charring temperature. Feedstock type resulted as significant when looking at P, K, Ca, Mn, Na and Si concentrations. Comparing only BC produced from rice husk, differences looking at the higher abundances of Si, K and Mn in BC produced in the field in respect to BC produced under controlled conditions were noticed. Between the treatments, BC alone has highest Si abundance, compost amendment has highest Al and Fe abundance in BBFs produced in the field and also highest Si, Ca, Mn and Mg in BBFs produced under controlled conditions.

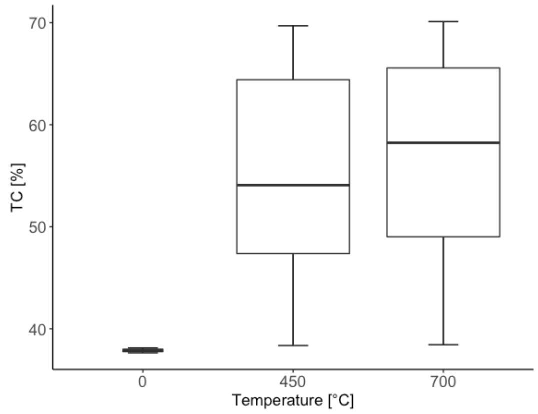
### 4.1.5 TC, TN and TC/TN

The TC [%] concentration of the BC and BBFs produced under controlled conditions are explained most importantly by temperature used for the charring procedure, secondly by the amendment type and thirdly by the feedstock type. For TN [%], concentrations are explained majorly by feedstock type, followed by temperature and the amendment type. Table 26 in the annexe includes results from TN and TC analysis for all analysed samples. Generally, TC ranges from 37.64 % to 70.11 % and TN from 0.20 % to 3.09 %.

Table 15: significant correlations between BC and BBFs produced under controlled conditions and TC [%] and TN [%].

| | TN [%] | TC [%] |
|---|---|---|
| feedstock type | 2.12e-08*** | |
| Charring temperature | | 0.0422* |
| Amendment type | | 3.74e-07*** |

As visible in table 15, only TC [%] is affected in a significant way by charring temperature (figure 49). Uncharred samples (n=2) contain an average of 37.87 % of TC, BC charred at 450 °C (n=16) an average of 54.95 % and biochar charred at 700 °C (n=16) an average of 56.98 %. C recovery is therefore of +17.08 % for biochar charred at 450°C and +19.11 % for BC charred at 700°C in respect to uncharred feedstock. An increase through charring is visible for TN [%] compared to uncharred feedstock but charring at 450 °C leads to higher abundances than charring at 700 °C (figure 50).



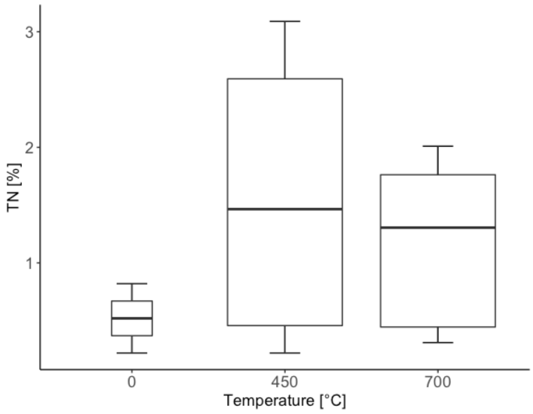


Figure 49: TC (%) in respect to charring temperature (°C). Figure 50: TN (%) in respect to charring temperature (°C).

Feedstock type affects TN concentrations but not TC concentration in a significant way (figure 51). The correlation between feedstock type and TN [%] demonstrated that samples deriving from RH (n=16) have higher concentrations (around 2.1%) of TN than samples based on SC (n=16) (around 0.6%) (figure 52).

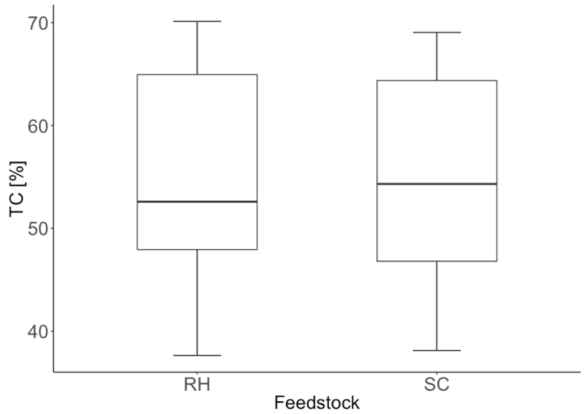


Figure 51: TC [%] in respect to feedstock type.

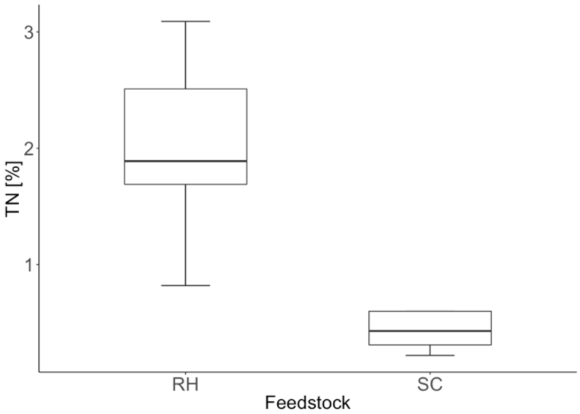


Figure 52: TN [%] in respect to feedstock type.

TC [%] correlates significantly with amendment type (n=4 for each amendment) (figure 53). In respect to BC with mean TC of 67.65 %, all amendments lower TC concentrations, especially samples enhanced through compost (BCC with an average of 43.56 % and BCCMF with an average of 45.87 %). The effect of MF is not overwriting BCC, BCSJ or BCFL.

TN [%] is not significantly correlated to amendment type (figure 54). Nonetheless, a trend is visible: MF (1.49 %) and compost (1.84 %) affect TN concentration by increasing the values relatively more in respect to BC alone (1.35 %) and to BBFs containing SJ (0.75 %) and FL (1.36 %). Large error bars indicate variability in TN [%] between same treatment.

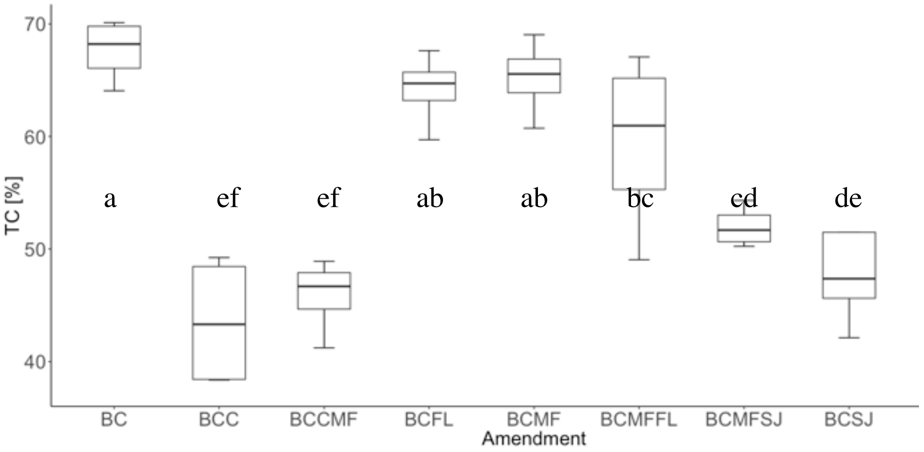


Figure 53: TC [%] in respect to amendment type.

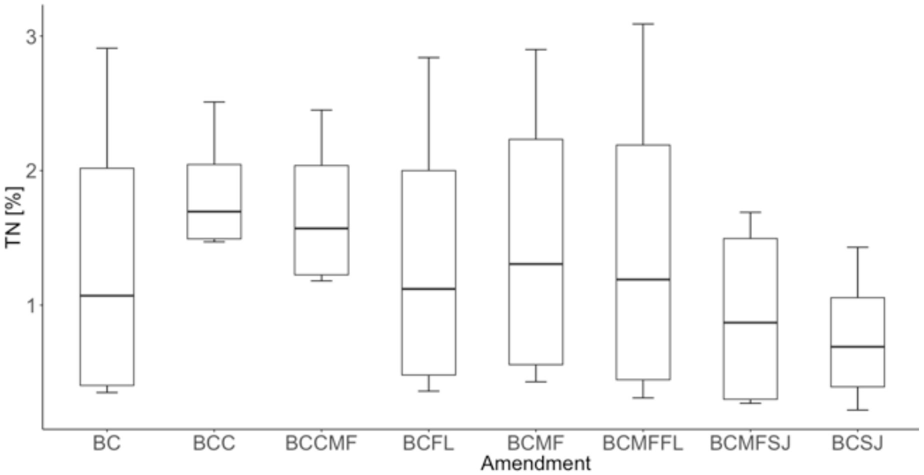


Figure 54: TN [%] in respect to amendment type.

TC/TN varies significantly between samples. Uncharred material has higher TC/TN than charred material and TC/TN increases with increased pyrolysis temperature. Between plant type, RH has a mean TC/TN of 30.25 whereas SC a mean TC/TN of 130.42. BC (102.68) has higher mean TC/TN than BBFs, except for BCSJ (108.66). BCC (24.28) and BCCMF (29.88) show relative lowest ratios, whereas MF increases the ratios when combined with organic fertilizers. BCSJ and BCMFSJ (107.72) have higher mean TC/TN than BCFL (91.28) and BCMFFL (82.83).

Table 16 shows the results from EA of BC and BBFs produced in the field. TC concentration ranges between 20.43 % (BCC) and 41.28 % ($BC_{UAS}$). Between production method, $BC_{Kon.Tiki}$ contains relatively less TC with 36.32 %. BBFs enhanced with MF have relative higher TC abundance than $BC_{Kon.Tiki}$, whereas the other BBFs show relatively lower concentrations.

TN concentration ranges between 0.34 % ($BC_{Kon.Tiki}$) and 1.62 % (BCMFSJ). Between production method, $BC_{UAS}$ has relative higher concentration with 0.56 %. All BBFs contain TN more abundantly than untreated BC, especially when enhanced with MF.

Considering TC/TN, $BC_{Kon.Tiki}$ has relative highest ratio (106.82) followed by RH (104.92), $BC_{UAS}$ (73.71), BCC (55.22), BCMF (43.78), BCSJ (43.08) and finally by BCMFSJ with a TC/TN ratio of 24.90.

Table 16: mean TC [%], TN [%] and TC/TN of BC and BBFs produced in the field.

| Sample | TC [%] | TN [%] | TC/TN |
|---|---|---|---|

| | | | |
|---|---|---|---|
| RH | 37.77 | 0.36 | 104.92 |
| $\mathrm{BC_{Kon\text{-}TIki}}$ | 36.32 | 0.34 | 106.82 |
| BCC | 20.43 | 0.37 | 55.22 |
| BCMF | 39.84 | 0.91 | 43.78 |
| BCSJ | 25.85 | 0.60 | 43.08 |
| BCMFSJ | 40.33 | 1.62 | 24.90 |
| $\mathrm{BC_{UAS}}$ | 41.28 | 0.56 | 73.71 |

### 4.1.6 Chemical functional surface

Temperature resulted to have the biggest impact on the chemical surface reactivity of BC and BBFs produced under controlled conditions in respect to wavelength, followed by feedstock type, compost, SJ and FL. MF has almost no impact on the analysed spectra when combined with other amendments.

Temperature resulted as the variable that affected most the value distribution and reactivity in respect to the analysed wavelengths (figure 55). The effect of charring is visible if comparing the BC samples (RH450, SC450, RH700 and SC700) to the uncharred feedstock (RH and SC): SC and RH show a relative higher reflectance for band 3, 5, 7 and SC also for 6. SC is generally more reactive along the analysed spectra than RH. Charred samples are reactive considering band 1, band 2, band 4, band 6 and for bands 11, 12 and 13. Nonetheless, higher charring temperature leads to significant less surface reactivity.

Chemical functional surface reactivity of BBFs in comparison to untreated BC produced under controlled conditions varies significantly between temperature and feedstock type (figure 77 in the annexe). Compost is the amendment whereby the surface reactivity increases more for all analysed BC types. The pattern along the spectra of BCCMF is almost the same in respect to BCC, thus MF is not taking over the effect of compost. For RH450, BCMFSJ is the BBFs which leads to lowest reactivity whereby for SC450 to relative high reactivity. For RH450 much higher values resulted from BCFL and BCMFFL. When charring at 700°C, for biochar based on RH only BCCMF increases reactivity respect to untreated BC, whereas for SC all treatments.

For the samples produced in the field, results differ. In general, the chemical surface reactivity of RH is lower than for the other treatments and, with BCMFSJ as exception, the reactivity of BC decreases if combined with amendments (figure 56). This is especially true for BCC. More in detail, RH is especially reactive at band 3, 5 and 8. All treatments containing BC are reactive for bands 9, 10, 11, 12 and 13. BC is additionally reactive for band 2, 4, 7 and 8. The other treatments, despite for BCMFSJ, are less reactive than BC and a peak is visible only for band 2, 4 and 6 (despite bands 9-13). BCMFSJ is significantly more reactive than all other treatments, and especially for band 1, 2, 4, 5, 6 and 8.
$\mathrm{BC_{Kon\text{-}Tiki}}$ and $\mathrm{BC_{UAS}}$ do not differ significantly looking at specific signatures along the analysed spectra (figure 57). Small differences can be seen from 3600 to 2800 cm-$^{1}$ were $\mathrm{BC_{Kon\text{-}Tiki}}$ is less reactive and between 1200 and 400 cm$^{-1}$, where $\mathrm{BC_{UAS}}$ is less reactive. Both BC are reactive for band 1, 2, 4, 5, 7, 8 and for the characteristic peaks for charcoal at bands 11, 12 and 13. A heating temperature of 650 °C can be estimated for both samples according to the MID-infrared index described in chapter 3.2.1.

To resume, low temperature pyrolysis increases the chemical functional surface reactivity of feedstock especially at wavelengths associated to aromatic structures, but not high temperature BC. SC is more reactive along all analysed spectra in respect to RH. Between the amendment types, BCC leads to greatest change in BC's chemical surface reactivity in respect to BC when produced under controlled conditions, but to least reactivity when produced in the field. BCMFSJ is especially reactive looking at field production. BC produced under controlled conditions is less reactive for band 1 and 5 respect to BC produced in the field.

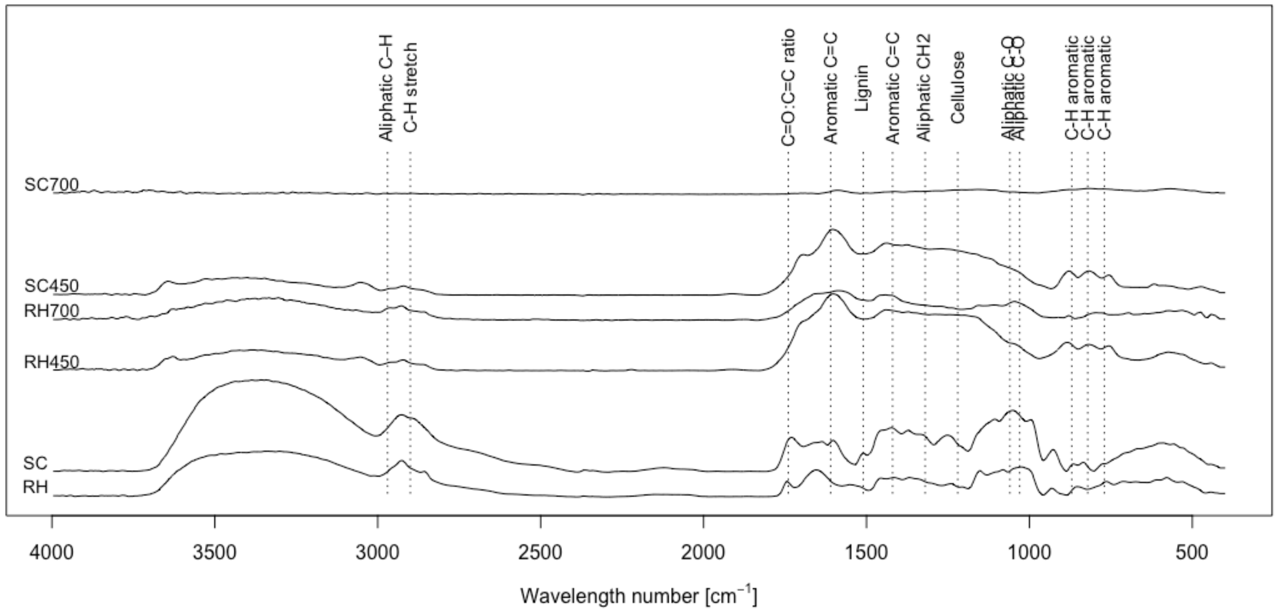


Figure 55: Chemical functional surface reactivity of uncharred and charred RH and SC. Pyrolysis was carried out with charring temperatures of 450°C and 700°C. Band 1-13 are indicated from left to right.

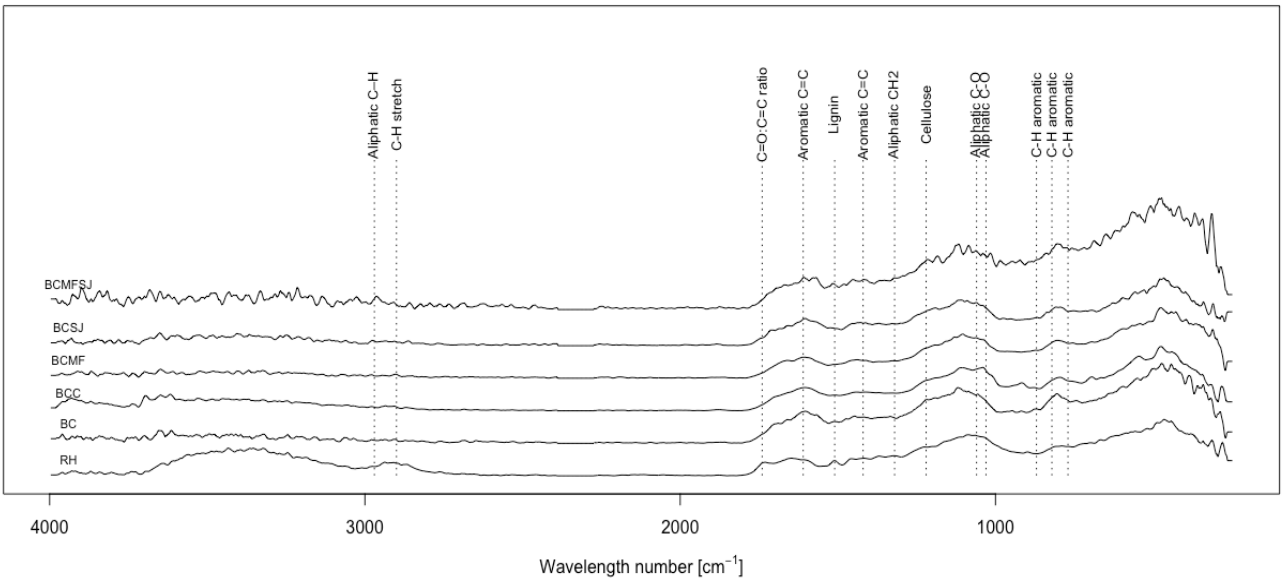


Figure 56: chemical functional surface reactivity of treatments applied for field work. Band 1-13 are indicated from left to right.

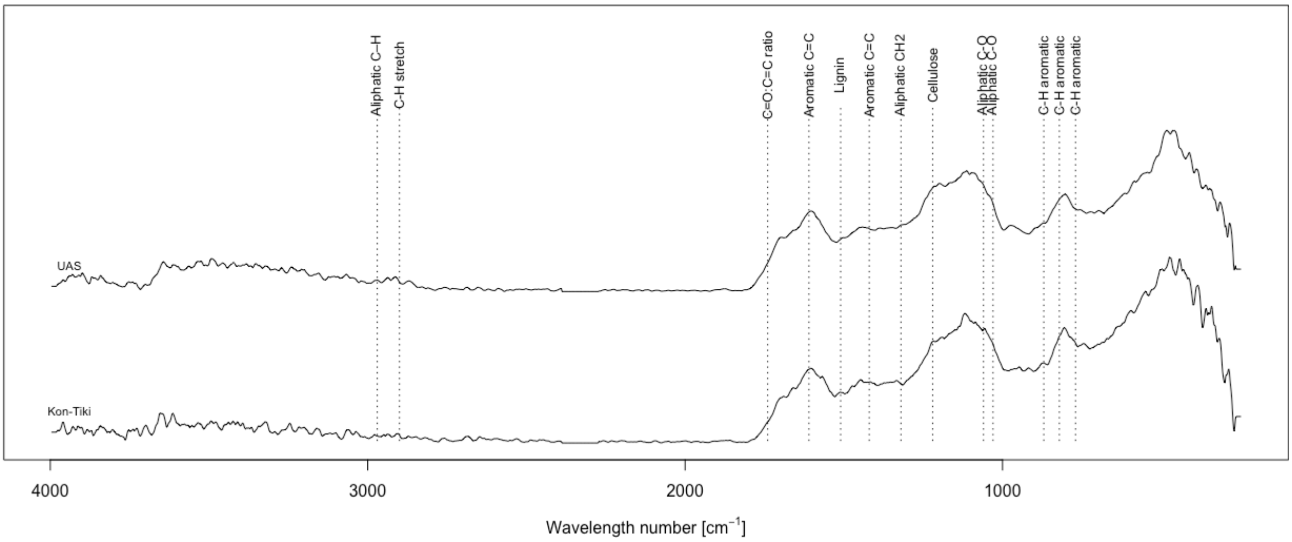


Figure 57: Chemical functional surface reactivity of BC produced through Kon-Tiki-like open earth kiln and oven designed by UAS. Band 1-13 are indicated from left to right.

## 4.2 Soil characterization

### 4.2.1 pH, EC, $NO_3^-$, OC, CEC, Texture, BD and WHC

Table 17: Soil properties of Bangalore, Mandya, Hassan and Mangalore.

| Sample | pH-value | EC [mS/cm] | $NO_3^-$ [mg/l] | OC [%] | CEC [cmol/kg] | Sand [%] | Silt [%] | Clay [%] | Soil Texture | BD [g/cm$^3$] | WHC [%] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bangalore | 4.60 | 0.04 | 50 | 0.73 | 3 | 82.32 | 17.63 | 0.05 | Loamy fine sand | 1.27 | 37.03 |
| Mandya | 8.06 | 0.31 | 555 | 1.21 | 0.5 | 89.64 | 8.08 | 2.29 | Fine sand | 1.37 | 39.91 |
| Hassan | 4.98 | 0.08 | 54 | 2.97 | 1 | 92.28 | 6.90 | 0.82 | Fine sand | 1.24 | 36.33 |
| Mangalore | 5.67 | 0.06 | 47 | 3.78 | 2 | 76.18 | 22.35 | 1.47 | Loamy fine sand | 1.47 | 32.27 |

Table 17 resumes the general soil characteristics found for Bangalore, Mandya, Hassan and Mangalore. Mandya differs from the other research sites by having an alkaline soil with pH-value of 8.06, highest EC value with 0.31 mS/m and highest $NO_3^-$ concentrations with 555 mg/L. Bangalore, Hassan and Mangalore show pH-values ranging from 4.6 to 5.67, EC values ranging from 0.04 to 0.08 mS/m and $NO_3^-$ concentrations around 50 mg/l. An increase in OC abundance is visible following the pedo-climatic gradient, with Bangalore having lowest concentration of 0.73 % and Mangalore highest with 3.78 %. No significant differences between research sites are visible between CEC (0.5-3 cmol/kg), BD (1.24-147 g/cm$^3$) and WHC (32.37-39.91 %). Between soil particle sizes, sand predominates followed by silt and clay. Clay abundance is <3% in all samples.

### 4.2.2 Atomic elemental abundance

The results from the atomic elemental abundance analysis of the soil samples are described in this section and are resumed in table 18.

Table 18: atomic elemental abundance of soil samples from Bangalore, Mandya, Hassan and Mangalore.

| Sample | Na (%) | Mg (%) | Al (%) | Si (%) | P (%) | S (%) | Cl (%) | K (%) | Ca (%) | Ti (%) | V (%) | Cr (%) | Mn (%) | Fe (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bangalore | 0.55 | 0.46 | 12.97 | 22.58 | 0.07 | 0.03 | 0.00 | 0.53 | 0.14 | 0.61 | 0.01 | 0.02 | 0.05 | 4.03 |
| Mandya | 0.85 | 0.82 | 10.74 | 24.54 | 0.10 | 0.05 | 0.01 | 1.37 | 0.75 | 0.37 | 0.01 | 0.01 | 0.04 | 2.63 |
| Hassan | 0.61 | 0.61 | 11.04 | 23.96 | 0.04 | 0.04 | 0.01 | 0.85 | 0.13 | 0.43 | 0.01 | 0.03 | 0.04 | 3.26 |
| Mangalore | 0.50 | 0.26 | 7.99 | 30.04 | 0.07 | 0.07 | 0.01 | 0.33 | 0.18 | 0.33 | 0.01 | 0.02 | 0.00 | 2.27 |

The most abundant element found in all soils is Si, with 22.58% for Bangalore, 24.54 % for Mandya, 23.96 % for Hassan and 30.04 % for Mangalore. Al and Fe represent the second and third element which is most concentrated in the soils: for Bangalore, Mandya, Hassan and Mangalore respectively, 12.965 %, 10.735 %, 11.04 % and 7.994 % of Al and 4.028 %, 2.631 %, 3.264 % and 2.268 % of Fe. Mandya contains significant amount of K as well, with 1.37 %.

Two main trends are detectable by looking at the results. As first, Mandya differs significantly from the other soils looking at Na, Mg, P, Cl, K and Ca concentrations that are relatively higher. As second, Bangalore and Mangalore show opposite positions: Bangalore is the research sites with highest relative Al, Mn and Fe concentration and Mangalore the research site with lowest values for same elements; on the contrary, Mangalore show highest Si concentration, element for which Bangalore shows lowest value.

### 4.2.3 TC, TN and TC/TN

Table 19: mean TC [%], TN [%] and TC/TN of soil samples from Bangalore, Mandya, Hassan and Mangalore.

| Research site | TC [%] | TN [%] | TC/TN |
|---|---|---|---|
| Bangalore | 0.58 | 0.05 | 11.60 |
| Mandya | 0.73 | 0.06 | 12.17 |
| Hassan | 0.59 | 0.04 | 14.75 |
| Mangalore | 0.71 | 0.06 | 11.83 |

The TC concentration of the analysed soil samples ranges between 0.58 % (Bangalore) and 0.73 % (Mandya) For TN [%], soil from Hassan contains relative lowest concentration (0.04 %), whereas soils from Mandya and Mangalore contain relative highest concentration (0.06 %). The TC/TN ratio ranges between 11.6 (Bangalore) and 14.75 (Hassan) (table 19).

### 4.2.4 Chemical functional surface

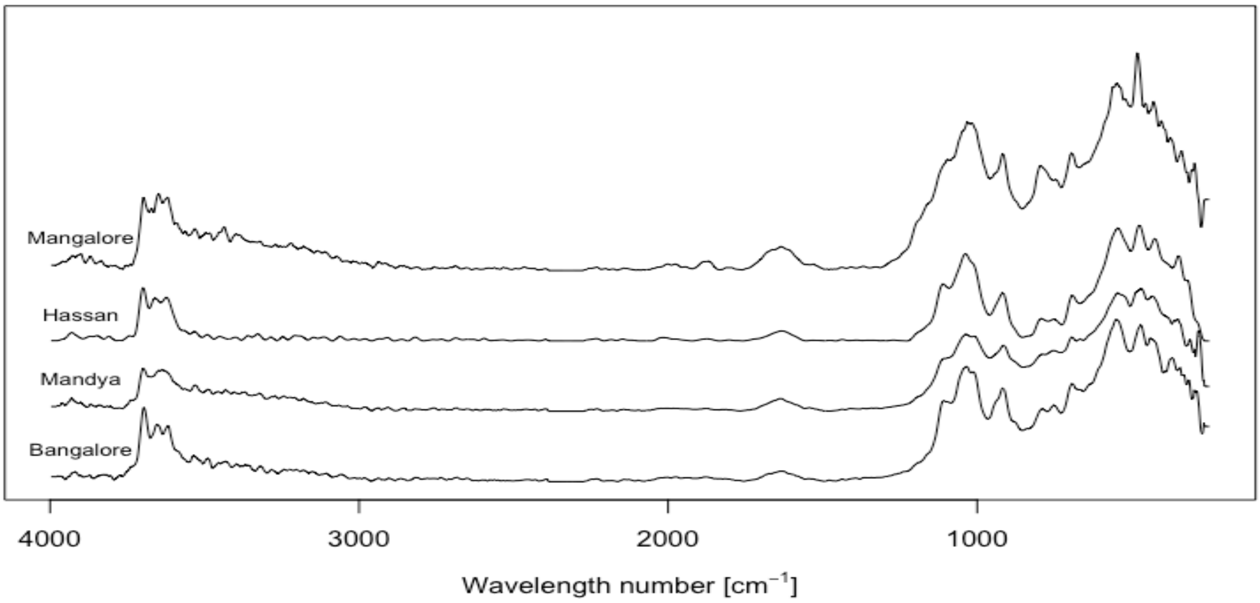


Figure 58: Chemical functional surface reactivity of soil from Bangalore, Mandya, Hassan and Mangalore.

Soil from Mangalore has highest chemical functional reactivity along the analysed spectra, followed by Bangalore, Mandya and Hassan (figure 58).

Reactivity is visible near 3690-3620 cm$^{-1}$, near 1600 cm$^{-1}$, near 1100-1000 cm$^{-1}$ and different peaks are visible at lower wavelengths (912, 787, 689, 542 and 482 cm$^{-1}$). Compared to the other samples, soil from Mandya is not reactive at 3657 cm$^{-1}$, soil from Hassan is especially reactive at 1100 cm$^{-1}$ and soil from Mangalore is especially reactive at 1600 cm $^{-1}$, 787 cm$^{-1}$ and 482 cm$^{-1}$.

## 4.3 Analysis under controlled conditions

### 4.3.1 C dynamics

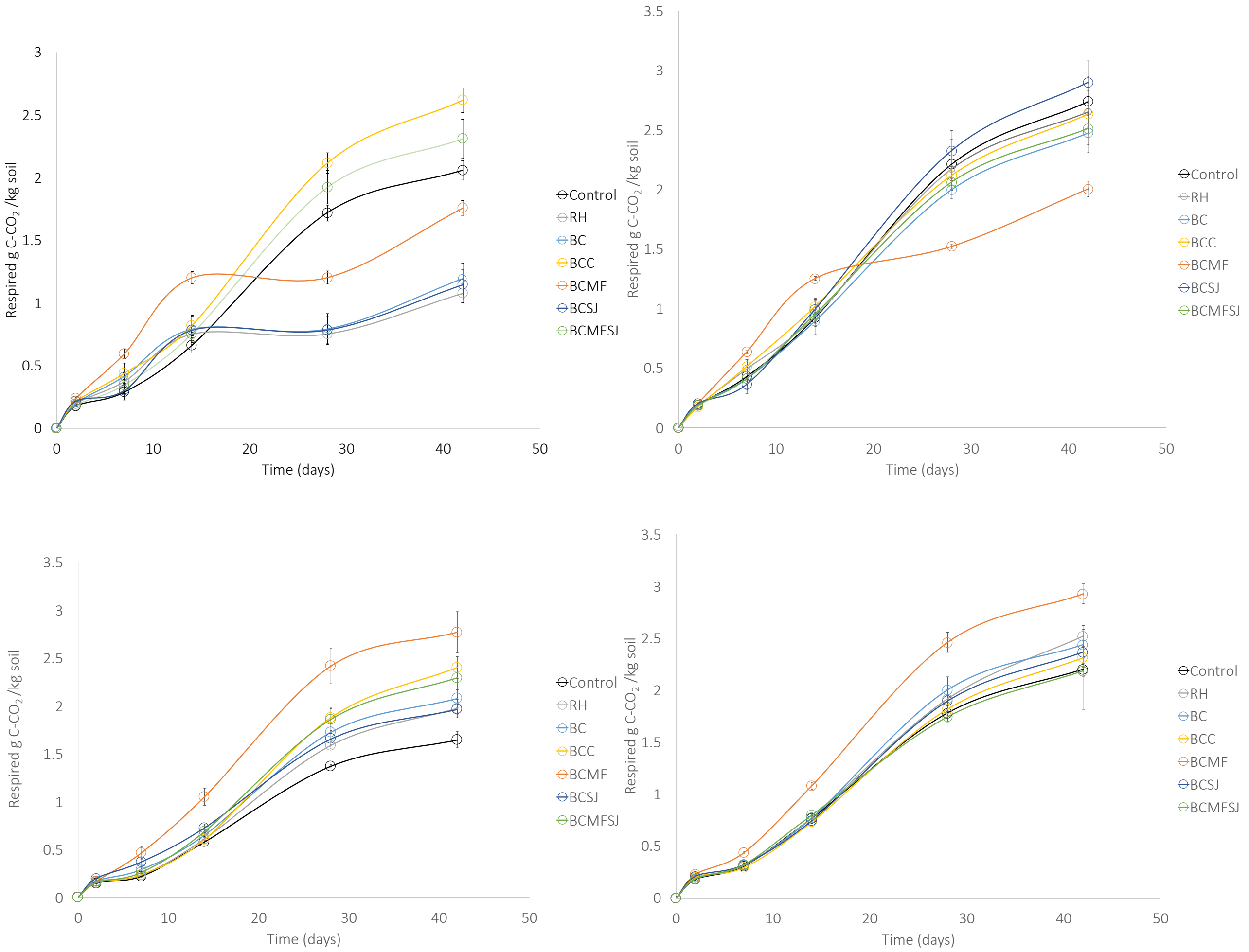
Soil respiration rates measured during incubation experiment are most importantly explained by soil in which treatments were applied than by the treatments themselves (table 21).

Table 21: significant ($p<0.05$) correlations between respiration rates at different sampling days, soil type and treatment whereby soil was enhanced.

| Respiration rate at sampling day | 2 days | 1 week | 2 weeks | 4 weeks | 6 weeks |
|---|---|---|---|---|---|
| Treatment | | 0.0408 * | 0.00363 ** | | |
| Soil | 0.000802 *** | 0.00524 ** | 0.00852 ** | 0.00753 ** | 0.00468 ** |

Figures 59-62 show the cumulative respiration of the analysed soil samples according to treatment applied. Generally, the respiration increases exponentially in the first week of experiment. With time, the increase in reparation decelerates in rate. Between week 2 and 4, some treatments show no or really small increase in respiration: for Bangalore, treatments RH, BC, BCMF and BCSJ; for Mandya BCMF.

In contrast with the other treatments, BCMFSJ and BCC lead to higher respiration than the control when applied in Bangalore’s soil. For soil from Mandya, only BC has higher respiration than the control. All treatments have higher respiration than the control when applied in Hassan's soil. In case of Mangalore, the control shows lowest values together with BCMFSJ.



Figures 59-62: cumulative respiration [g C-$CO_2$/kg soil] in soil from Bangalore (above left), Mandya (above right), Hassan (below left) and Mangalore (below right) according to treatment applied.

The respiration amount of the four soils is similar during the first 2 days of experiment and differs then gradually with time (figure 63). The control treatments of Mandya and Mangalore show largest error bars but relative highest respiration during all experimental period. Final cumulative respiration is highest for Mandya with 2.6 g C-$CO_2$/kg soil, followed by Mangalore (2.2 g C-$CO_2$/kg soil), Bangalore (2.06 g C-$CO_2$/kg soil) and Hassan (1.64 g C-$CO_2$/kg soil). The gradient of highest to lowest respiration does not reflect the pedo-climatic gradient of the locations.

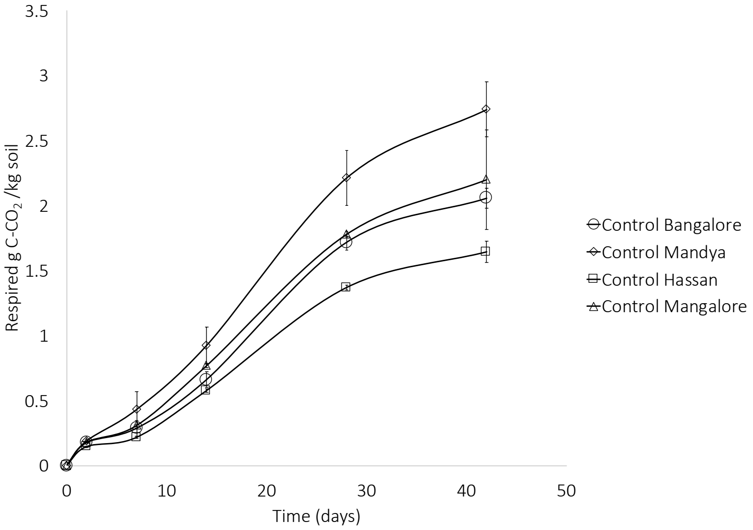


Figure 63: cumulative respiration [g C-$CO_2$/kg soil] of control treatments.

After 2 days from start of incubation experiment, control shows lowest cumulative respiration followed by, BCMFSJ, BCC, BC, RH, BCSJ and with BCMF showing highest amounts. After 1 week and 2 weeks, control is still the treatment with lowest values (0.3 g C-$CO_2$/kg soil after 1 week and 0.7 g C-$CO_2$/kg soil after 2 weeks) and BCMF with highest values (0.52 g C-$CO_2$/kg soil after 1 week and 1.12 g C-$CO_2$/kg soil after 2 weeks). The other samples equalize their respiration amounts: around 0.35 C-$CO_2$/kg soil after 1 week and around 0.75 g C-$CO_2$/kg soil after 2 weeks. Large error bars indicate higher influence of soil type on respiration rate. BCC and BCMFSJ have significantly smaller error bars in respect to other treatments. At day 4, all treatments have mean respiration amounts ranging from about 1.7 to 2 g C-$CO_2$/kg soil.

Finally, control had lowest respiration amount during all experimental period. Final cumulative respiration is thus lowest for control, followed by BCSJ, RH, BC, BCMFSJ, BCMF and with BCC having relative highest final cumulative respiration with about 2.5 g C-$CO_2$/kg soil. Figure 64 shows the final cumulative respiration [g C-$CO_2$/kg soil] for the different treatments, independently from soil type in which they were applied.

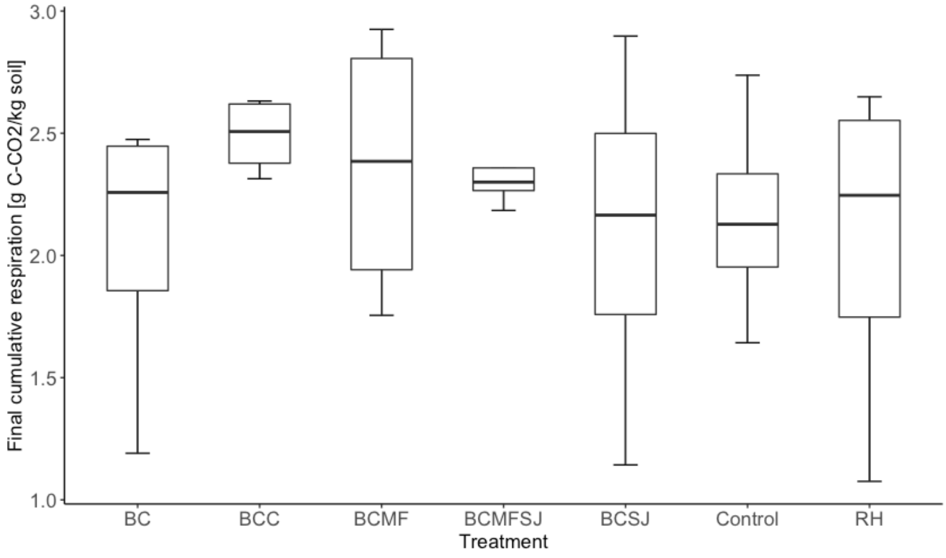


Figure 64: final cumulative respiration [g C-$CO_2$/kg soil] after 6 weeks of incubation experiment in respect to treatment applied and independently from soil type.

Generally, soil type affects respiration more importantly than treatment application. The gradient of soil respiration amounts does not follow the climatic gradient of the soils' location. Nonetheless, treatment's application lead to highest raise in respiration compared to the control for soils of more humid locations (Mangalore and Hassan). Independently from soil type and in average, at the end of the experiment, all amendments show highest cumulative respiration than the control. Nonetheless, this is not true if considering

Bangalore or Mandya singularly. BCC is the BBFs where more $CO_2$ was respired (+21 % compared to BC). Additionally, BCC and BCMFSJ show similar respiration amounts independently from soil type.

### 4.3.2 N and P dynamics

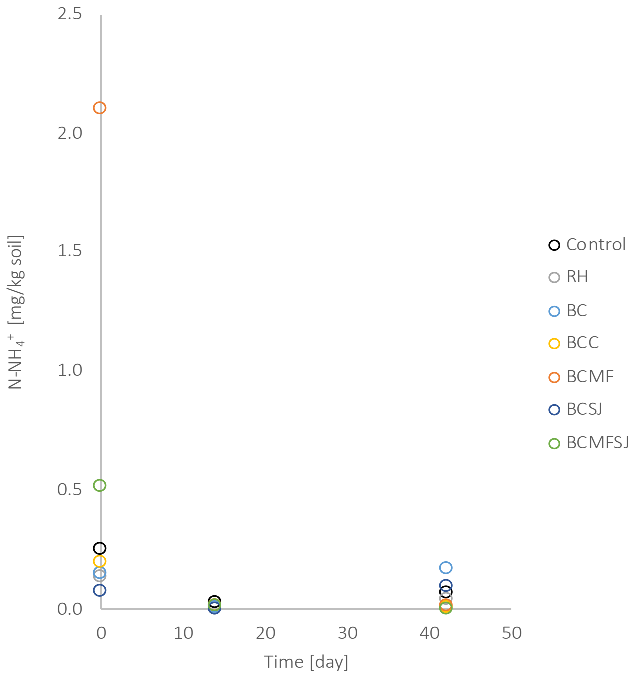
The concentration of N-$NH_4^+$ decreases from day 1 to day 24: mean 0.379 mg/kg soil at day 1 and mean 0.034 mg/kg soil at day 14. At day 42 the abundance is higher than at day 14, with mean 0.050 mg/kg soil.

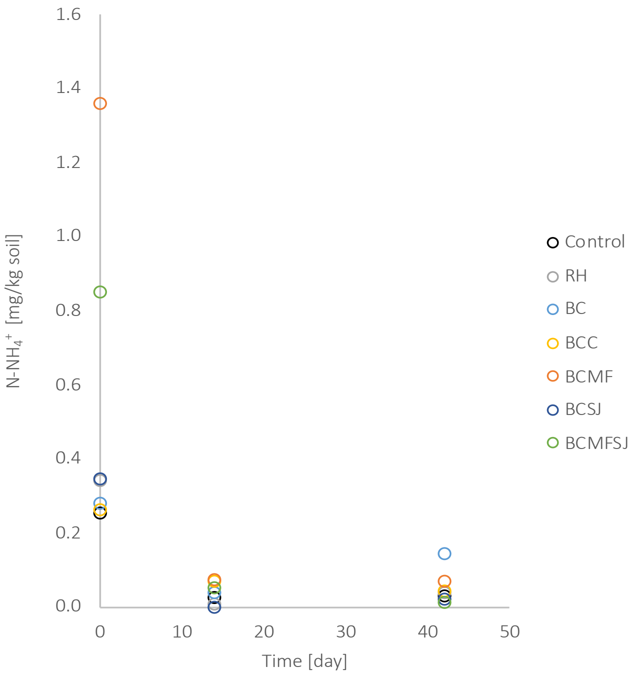
In soil of Bangalore value range from 0 to 2.11 N-$NH_4^+$ mg/kg soil (figure 65). At day 1 BCMF has relative highest abundance and differs significantly from other samples. All treatments have lower values compared to the control at day 14. BC has relative highest abundance of N-$NH_4^+$ at day 42.

In soil of Mandya value range from 0 to 1.36 N-$NH_4^+$ mg/kg soil (figure 66). Again, BCMF has highest abundance at day 1 and BC has highest abundance at day 42. The treatments lead generally to higher respiration amounts than the control during all experimental period.

In soil from Hassan value range from 0 to 0.38 N-$NH_4^+$ mg/kg soil (figure 67). Again, BCMF is the treatment with highest initial concentration. The control treatment is relative stable during experimental period. The other treatments have lower concentrations than the control, but BC still is the treatment with highest abundance of N-$NH_4^+$ mg/kg soil at day 42.

In soil from Mangalore, the pattern is quite different. Value range from 0.01 to 0.54 N-$NH_4^+$ mg/kg soil (figure 68). Highest abundances were measured for BCSJ at day 1 and 14 and for RH at day 42. At day 42 only RH and BC have higher concentrations of N-$NH_4^+$ in respect to the control.





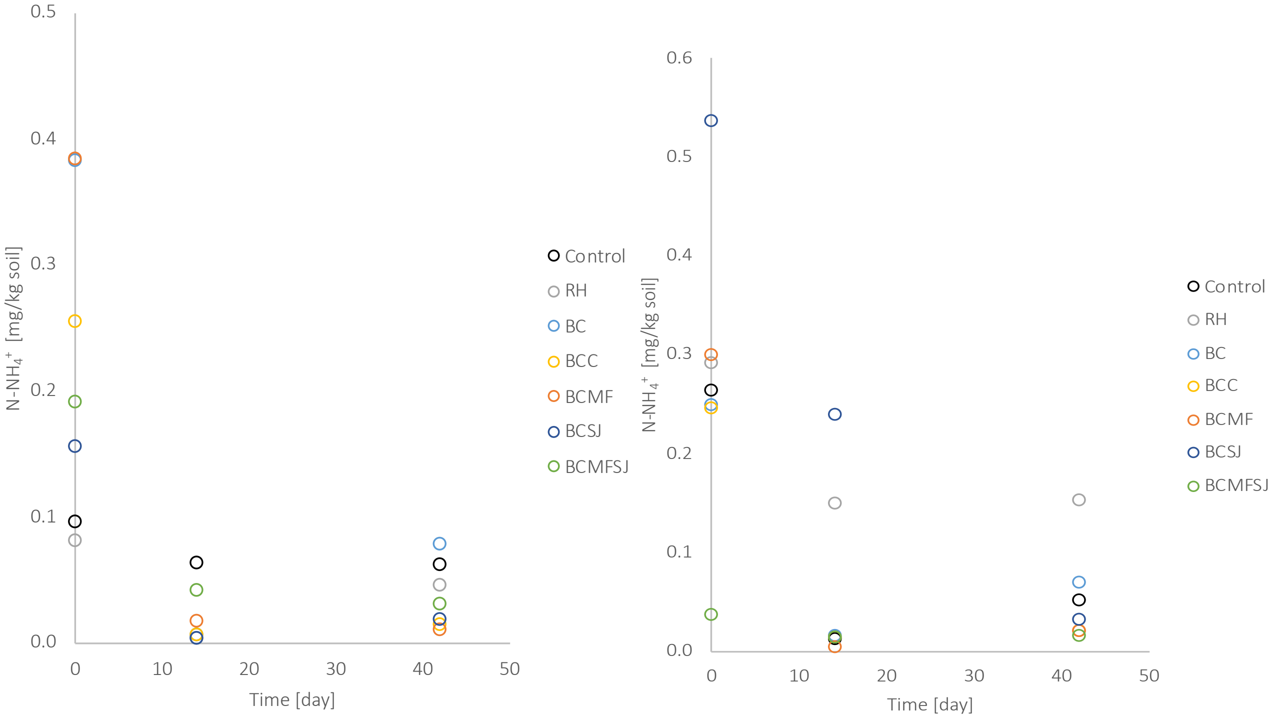


Figure 65-68: N-NH$_4^+$ [mg/kg soil] in soil from Bangalore (above left), Mandya (above right), Hassan (below left) and Mangalore (below right) according to treatment applied.

Considering N-NO$_3^-$, a decrease in concentration was measured during incubation experiment: mean 1.250 N-NO$_3^-$ mg/kg soil at day 1, mean 0.266 mg/kg soil at day 14 and mean 0.194 mg/kg soil at day 42.
For Bangalore, value range from 0 to 1.754 mg/kg soil (figure 69). BC has lowest initial concentration (0.825 mg/kg soil) and is the only treatment with lower values than the control (0.88 mg/kg soil). The control is the second most abundant treatment at day 14 (after BCSJ) and at day 42 (after BCMF).
In Mandya, the control has relative low concentrations in respect to the other treatments. The range of values for Mandya goes from 0 to 0.992 N-NO$_3^-$ mg/kg soil (figure 70). Values for BCMF at day 14 and BC at day 42 are significantly higher than the other treatment. Despite these irregularities, BCC leads to relative high values during all experimental period.
In case of soil from Hassan, no clear trend can be described. Value range from 0 to 6.18 N-NO$_3^-$ mg/kg soil (figure 71). The control is the treatment with lowest N-NO$_3^-$ [mg/kg soil] at the beginning of the experiment and maintains relative low values during experimental period. BCMF is the sample with highest concentration at day 14.
In soil from Mangalore value range from 0 to 1.533 N-NO$_3^-$ mg/kg soil (figure 72). RH has relative highest concentration during all sampling days. No clear trend is visible comparing the control to the other treatments.

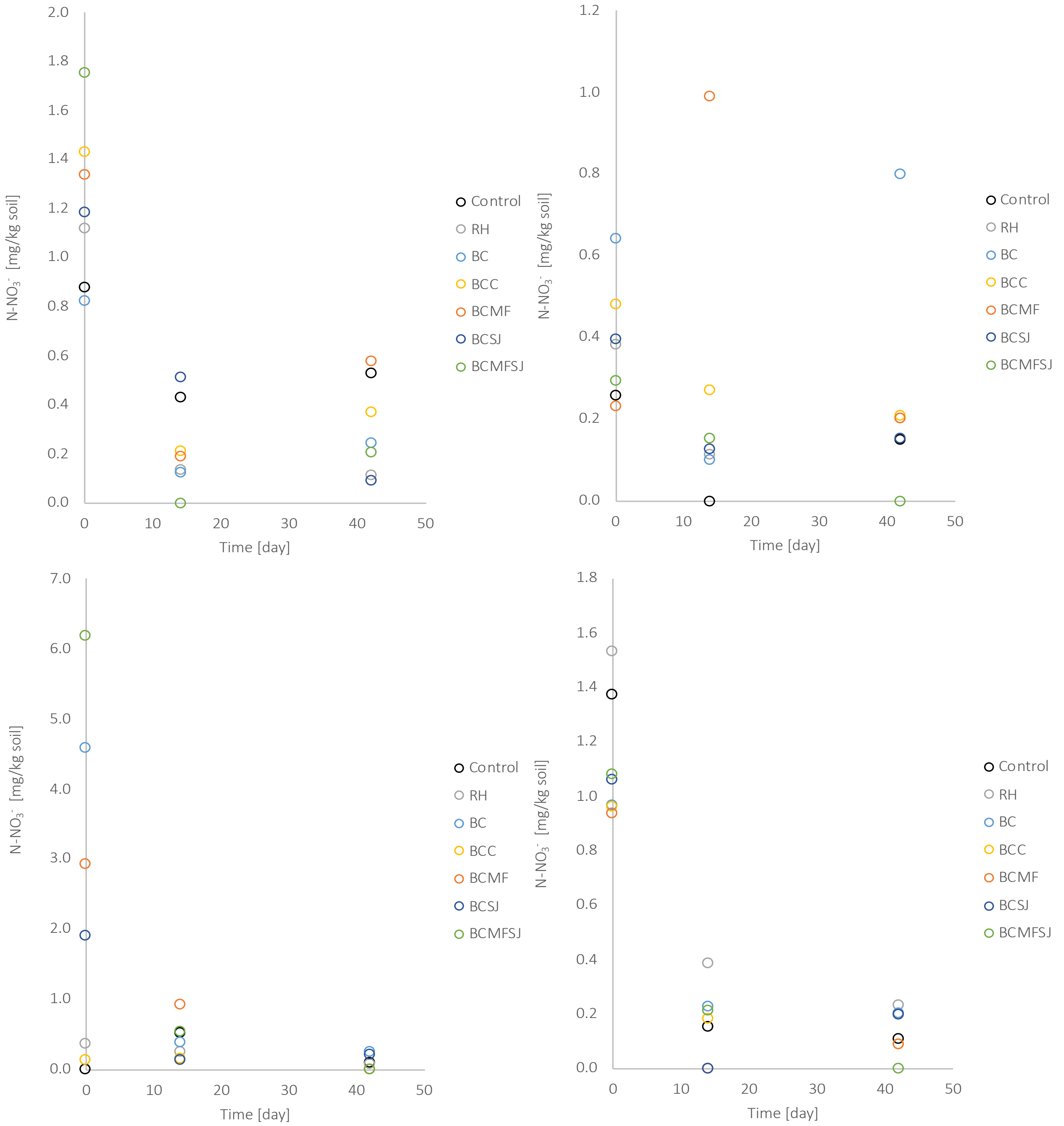


Figure 69-72: N-$NH_4^+$ [mg/kg soil] in soil from Bangalore (above left), Mandya (above right), Hassan (below left) and Mangalore (below right) according to treatment applied.

P-$PO_4^{3-}$ concentration in the soil decreases from day 1 (mean 0.463 mg/kg soil) to day 14 (mean 0.201 mg/kg soil). At day 42, mean concentration is of 0.214 mg/kg soil.
Values for Bangalore range between 0.292 and 1.052 mg/kg soil. BCMF has highest initial concentration, but BCC has highest concentration at day 14 and day 42. BCC differs from the other treatments by having similar and relatively high values between sampling dates. Treatments generally have lower P-$PO_4^{3-}$ [mg/kg soil] than the control.
Value for soil from Mandya range from 0 to 0.796 P-$PO_4^{3-}$ mg/kg soil. Again, BCC has highest concentration at day 14 and day 42, differing significantly from the other samples that show relative lower values. This is true also when BCC is applied in soil from Hassan, but not for Mangalore. Value for Hassan range from 0.035 to 0.549 P-$PO_4^{3-}$ mg/kg soil.

Finally, soil from Mangalore has a range from 0 to 0.348 $P\text{-}PO_4^{3-}$ mg/kg soil. BCSJ is the treatment with lowest amounts during all experimental period and it is the only treatment having lower values than the control. BCMFSJ has highest amounts at day 14 and BC at day 42.

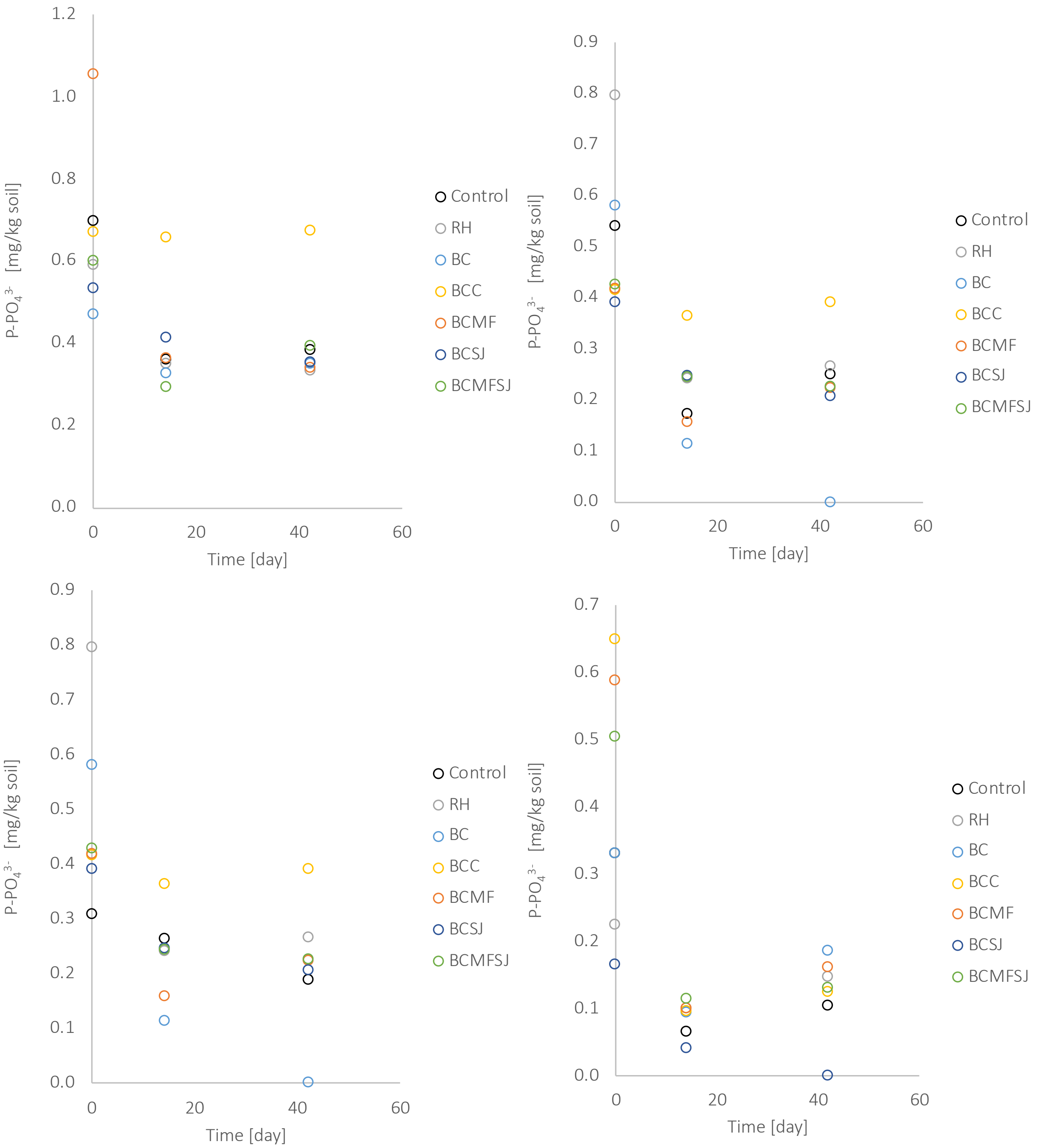


Figure 73-76: $P\text{-}PO_4^{3-}$ [mg/kg soil] in soil from Bangalore (above left), Mandya (above right), Hassan (below left) and Mangalore (below right) according to treatment applied.

## 4.4 Field trial

### 4.4.1 Yield

Table 23: mean straw and grain yield [t/ha] and change in yields [%] resulted from field trial.

| Treatment | straw yield [t/ha] | grain yield [t/ha] | Change in straw yield [%] compared to control | Change in straw yield [%] compared to BC | Change in grain yield [%] compared to control | Change in grain yield [%] compared to BC |
|---|---|---|---|---|---|---|
| Control | 6.20 ± 0.82 | 5.70 ± 0.74 | | -4.41 | | -5.20 |
| RH | 6.20 ± 0.17 | 5.67 ± 0.30 | +0.02 | -4.39 | -0.49 | -5.66 |
| BC | 6.48 ± 0.69 | 6.01 ± 0.60 | +4.62 | | +5.48 | |
| BCC | 6.59 ± 0.61 | 6.14 ± 0.68 | +6.28 | +1.59 | +7.78 | +2.18 |
| BCMF | 8.39 ± 0.38 | 7.82 ± 0.27 | +35.45 | +29.48 | +37.23 | +30.10 |
| BCSJ | 6.14 ± 0.63 | 5.73 ± 0.58 | -0.97 | -5.34 | +0.48 | -4.74 |
| BCMFSJ | 8.34 ± 0.39 | 7.83 ± 0.41 | +34.64 | +28.70 | +37.29 | +30.16 |

Table 23 shows mean straw and grain yields [t/ha] with their standard error and the change in straw and grain yield [%] in respect to control and untreated BC.
Straw yield ranges between 6.14 t/ha (BCSJ) and 8.39 t/ha (BCMF), whereas grain yield ranges between 5.67 t/ha (control) and 7.83 t/ha (BCMFSJ). Maximal change in straw yield compared to the control and to BC is given by BCMF, with respectively +35.45% and +29.48%. Maximal change in grain yield is whereas given by BCMFSJ with +37.29 % compared to the control and +30.16 compared to BC.

Between control and RH, no difference was measured for straw yield (6.2 t/ha) and also grain yield does not differ significantly (5.7 t/ha for control and 5.67 t/ha for RH). Charring rice husk increases straw and grain yield, even if the increase is not significant: BC leads to respectively 6.48 t/ha and 6.01 t/ha. BCC has relatively low impact to both yields in respect to BC alone (+ 1,59 % for straw yield and + 2.18 % for grain yield). Impregnating BC with SJ lowers the values obtained for untreated BC, in fact BCSJ leads to a loss of – 0.97 % for straw yield and – 4.76 % for grain yield. Especially when MF is used as amendment, yields result relatively high with 8.39 t/ha for BCMF and 8.34 t/ha for BCMFSJ considering straw yield and 7.82 t/ha for BCMF and 7.83 t/ha for BCMFSJ for grain yield.

Control is the samples with highest standard error. Replication raw 1 differs from raws 2 and 3 looking at both straw and yield values, generally by having relative higher values.

Thus, all amendments enhance grain yields in respect to the control and, except for BCSJ, also straw yield. The increase is higher when the added biomass is charred and even higher if BC is impregnated with amendments. Highest values are obtained for BCMF for straw yield and for BCMFSJ for grain yield.

### 4.4.2 N and P efficiencies

The rNUpE, rNUtE and rNUE of rice plants are shown in table 24. rNUpE ranges from 0.28 (BC) to 0.03 (BCMFSJ), rNUtE ranges from 2455.16 (BCMFSJ) to 1430.95 (BCSJ) and rNUE ranges from 441.91 (BC) to 68.26 (BCMFSJ).

Table 24: rNUpE, rNUtE and rNUE of rice plants according to treatment applied.

| Treatment | rNUpE | rNUtE | rNUE |
|---|---|---|---|
| RH | 0.27 | 1448.56 | 393.75 |

| | | | |
|---|---|---|---|
| BC | 0.28 | 1576.56 | 441.91 |
| BCC | 0.12 | 1777.22 | 207.43 |
| BCMF | 0.05 | 1540.05 | 84.56 |
| BCSJ | 0.08 | 1430.95 | 119.38 |
| BCMFSJ | 0.03 | 2455.16 | 68.26 |

Table 25 shows rPUpE of rice plants ranging from 0.09 (BCMF) to 0.38 (BC), rPUtE ranging from 821.78 (BCMF) to 1809.97 (RH) and rPUE ranging from 69.96 (BCMF) to 2025 (RH).

Table 25: rPUpE, rPUtE and rPUE of rice plants according to treatment applied.

| Treatment | rPUpE | rPUtE | rPUE |
|---|---|---|---|
| RH | 1.12 | 1809.97 | 2025.00 |
| BC | 0.38 | 1430.91 | 536.61 |
| BCC | 0.10 | 1635.07 | 163.30 |
| BCMF | 0.09 | 821.78 | 69.96 |
| BCSJ | 0.15 | 1291.48 | 188.49 |
| BCMFSJ | 0.18 | 823.99 | 145.50 |

# 5. Discussion

Results from BC and BBFs characterization carried out in the laboratory are discussed in chapter 5.1. The following sections investigate the influence of BC and BBFs on soil parameters, first looking at the results from the laboratory characterization, then looking at the effect of BC and BBFs on soil parameters when analysed under controlled conditions and finally, considering the results from the field trial.

## 5.1 Biochar and BBFs characterization

### 5.1.1 pH-value

How to measure pH and EC of BC is widely debated. Literature claims, that soil pH measured in $CaCl_2$ generally gives lower values than pH detected in $H_2O$ (Brady & Weil 2014). In case of my results, BC produced from SC has higher pH-values when measured in $CaCl_2$ in respect to $H_2O$, whereas BC from RH has lower pH-values when measured in $CaCl_2$. Measuring in $H_2O$ results in near to neutral values for all BC types and, between the replicates, the values obtained through this method were more homogeneous. This could lie on the fact that same amount of $H_2O$ was used to analyse all samples, whereas for $CaCl_2$, different amounts were needed because of the different floating properties of the samples.

According to literature, pH of BC is dependent on feedstock and on pyrolysis temperature (Singh et al. 2017). In case of my analysis, no trend resulted comparing BC produced at different temperatures, whereas considering feedstock type, RH biochar resulted more acidic than SC biochar when measured in $CaCl_2$. The acidity of biochar represents a problem for soil fertility if applied in tropical soils, where soil acidity already represents a major issue (Brady & Weil 2014). BBFs have more alkaline pH-values than untreated BC, resulting therefore more efficient for soil fertility increase.

### 5.1.2 EC

EC is an indicator for the amounts of soluble ions in a sample (Brewer et al. 2011). Similar to pH, EC values should be higher at higher pyrolysis temperature due to the increasing concentration of residues or ashes. In addition, the content of ashes is dependent of feedstock type (Singh et al. 2017). The trend related to charring temperature is not confirmed by my samples. For the feedstocks SC has higher EC than RH, even if more lignin-rich materials typically have lower EC values (Brewer et al. 2011; Shah et al. 2017). Samples produced in the field show EC values in the same range as samples from controlled conditions. Smallest EC [mS/cm] is given by BC, whereas BBFs show higher EC values and are therefore more favourable for soil fertility increase. BBFs containing MF have highest Na and Cl concentrations when looking for atomic elemental abundance, fact that could explain the highest EC [mS/cm] found for BCMF and BCMFSJ.

### 5.1.3 WHC

Only samples produced in the field were analysed for WHC. WHC increased by +449.81 % for $BC_{UAS}$ and +240.29 by $BC_{Kon\text{-}Tiki}$ compared to RH. In fact, pyrolysis increases porosity and surface area, which are able to absorb water (Jindo et al. 2014). When adding any amendment type, the WHC [%] decreases, maybe due to the occupation by the amendments of the pores, even if Chen et al. (2018) compared the pore structure of untreated biochar and BBFs arguing that fertilizers do not influence significantly biochar’s structure.

### 5.1.4 CEC

CEC values found in literature for biochar are highly variable, commonly ranging from 5 to 50 cmol/kg (Munera-Echeverri et al. 2018). My results range between 2.27 – 7.18 cmol/kg, thus they are in the lower end or even lower than the typical range for CEC for biochar. Between these values, both pyrolysis temperature and feedstock type have an effect: highest CEC for BC produced under controlled conditions can be found for SC and for a charring temperature of 450 °C, even if a greater CEC is expected through higher charring temperatures (Munera-Echeverri et al. 2018). The lower values found for high temperature BC could be linked to the weak chemical functional surface reactivity found for BC charred at 700°C, since this temperature may reduce the number of functional groups in the structure, limiting the chemical properties of the BC and thus also the CEC (Jindo et al. 2014). Between the two production methods applied in the field, UAS leads to higher CEC value than Kon-Tiki (4.03 cmol/kg compared to 3.17 cmol/kg). Having estimated a charring temperature of 650 °C for both production methods (see chapter 4.1.5), the trend of higher to lower CEC with lower to higher charring temperature is confirmed while considering both BC production under controlled conditions and field production.

### 5.1.5 Batch sorption experiment

BC adsorbs $NO_3^-$ contained in water. The adsorption rate is especially high at beginning of experiment, then the rate decreases linearly and stabilizes after approximately three days. This trend was already found in previous studies (Yao et al. 2012; Hale et al. 2013; Mizuta et al. 2004). For the BC produced under controlled conditions, replicates show significance differences during the experiment and looking at total adsorption amounts at the end of experimental period. Similarly, Yao et al. (2012) argue that the effect of biochar on the retention and release of nutrients is not uniform and varies between biochar and nutrient types. Furthermore, Hale et al. (2013) mention the heterogeneous nature of biochar when looking at sorption properties.

From my analysis, higher charring temperature leads to more homogeneous replicates and higher maximal adsorption rates. In fact, with an increase in charring temperature, porosity and surface area increase, which are the most critical physical properties of biochar for the improvement of soil adsorption capacity (Kalderis et al., cited in Jindo et al. 2014). Already Mizuta et al. (2004) reported that biochar made at higher temperatures (900°C) had relatively higher $NO_3^-$ adsorption capacity, which is consistent with the findings of this study.

Generally, little sorption and release was measured during my batch study, fact that is reflected by the literature: Hale et al. (2013) found very little sorption and also release of $NO_3^-$ from biochar and also Yao et al. (2012) found no or little sorption of $NO_3^-$ by biochar, and only for biochar produced at higher charring temperatures (600°C).

My results based on samples produced under controlled conditions show a weak desorption of $NO_3^-$ in the water at very beginning of experiment. Then the desorption rates stabilized, or it was the adsorption rather than the desorption that dominated. Replicate 1 had very little or no desorption at all, probably because for all samples, replicate 1 had lowest amounts of $NO_3^-$ at the end of the adsorption part of the experiment. The fact that for all samples replicate 1 had weaker adsorption and desorption rates could lie on an external factor during measurement time, like f.e. room temperature.

Probably, positive charged nutrients reach higher adsorption rates compared to $NO_3^-$ because of the net negative surface area that is typical for biochar. Batch sorption studies on ammonium ($NH_4^+$) gave in fact more relevant results compared to $NO_3^-$ (Yao et al. 2012; Hale et al. 2013).

SC samples are more homogeneous between to the replicates and the two charring temperatures compared to RH, but the differences are not significant.

For the BC produced in the field, no desorption was measured at all. The adsorption behaviour is very similar between the two production methods and between the replicates. Main adsorption trend is similar as described for the BC produced under controlled conditions. Even if producing under controlled conditions let assume a major homogeneity between replicates and a better control of the chemical and physical structure responsible for adsorption than producing BC in the field, this was not confirmed by my results.

At the end of experimental period, for all BC types and production methods, about 100 mg/L of $NO_3^-$ present in the water is adsorbed, thus, about 20 % of initial concentration of 500 mg/L. From the approximately 100 mg/L of $NO_3^-$ present in the BC when starting the desorption part of the experiment, just about 6 mg/L are desorbed and measured in the demineralized water with no initial $NO_3^-$ concentration at the end of experimental period, thus about 6%.

Weak desorption is one big issue considering soil fertility and the idea that stays behind BBFs. In fact, the impregnation of BC with different amendments should allow BC to release them once applied on the field. In addition, the release should be constant and over longer time periods to be sustainable compared to applying fertilizers alone (Chen et al. 2018; Hagemann et al. 2017; Khan 2008).

### 5.1.6 Atomic elemental abundance

Through charring, an enrichment in analysed elements was detected from atomic elemental abundance analysis for both BC and BBFs produced in field and under controlled conditions. The enrichment is due to the loss of volatile elements during charring procedure (Gupta et al. 2016). For Ca, P and Si, nonetheless, the abundance is lower with higher charring temperature, thus a part of these elements gets lost when temperature overcomes 450°C.

Feedstock type resulted as significant when looking at P, K, Ca, Mn, Na and Si concentrations, where only P was higher in abundance in RH in respect to SC. The selection of the feedstock material could therefore be carried out following specific needs and deficits. When comparing BC produced from RH but with different production methods, differences became visible looking at Si, K and Mn abundance that was higher in BC produced in the field in respect to BC produced under controlled conditions. These differences are explained by the different material applied and also probably because producing in the field leads to less control of the pyrolysis process with higher formation of ashes. Between the two BC production methods carried out in the field, UAS-method seems more suitable than Kon-Tiki for soil fertility enhancement because of the higher concentrations of a larger amount of macronutrients: $BC_{UAS}$ shows higher Mg, Al, Si, P, Cl, K, and Mn concentrations in respect to $BC_{Kon\text{-}Tiki}$, which has respectively higher Na, Ca and Fe concentrations. Reason for the differences are again the different amount of ashes that were formed during pyrolysis and probably also the fact, that wood was needed to enlighten the Kon-Tiki, thus this wood may be included in the analysis.

An increase in Al and Fe abundance and especially the high concentrations contained in compost should be taken into account when evaluating the application in in acidic soils which are typical for the tropics (Brady & Weil 2014). Generally, compost shows quite high abundances in all analysed elements and it is therefore suitable to increase nutrients' amount in soils. Between organic fertilizers, BCFL has significant higher elemental abundances than BCSJ. Thus, BBFs containing SJ are no suitable if willing to add nutrients to the soil. Interesting is the comparison between elemental abundance of BCFL and BCMF produced under controlled conditions: BCFL contains higher Na, Mg, Al, Cl, K and Ca concentrations, same amounts of P [%] and Mn [%], whereas BCMF only contain more Si [%] and Fe [%] than BCFL. I selected FL because of the low C:N ratio, relevant to increase N concentrations of N-poor soils in the tropical regions. BCFL resulted not only rich in N but also in other elements, which made this BBFs suitable for soil fertility enhancement. For field production, BBFs containing MF have highest concentration of macronutrients and are thus most promising treatments for soil fertility enhancement.

### 5.1.7 TC, TN and TC/TN

As seen in theory, the concentration of TC increases through charring and through an increase in charring temperature because of the loss of volatile elements (Gupta et al. 2016). BC charred at 450°C has +17.08 % of TC in respect to uncharred material and BC charred at 700°C +19.1 %. Thus, high temperature biochar is suitable for the purpose of C sequestration (Ippolito 2012). TC [%] resulted also significantly correlated to amendment type: BBFs show lower concentrations than BC and between BBFs, BCC leads to lowest TC abundance. Relative low value resulted also for BBFs containing SJ, since the juice itself contains relative low TC concentrations. Considering BC and BBFs produced in the field, $BC_{UAS}$ resulted by having relative highest TC abundance followed by BCMFSJ and BCMF. BC production through UAS-method is more effective than Kon-Tiki if willing to increase TC concentration in soils, but controlled pyrolysis in the laboratory leads to highest's values.

The concentration of TN is higher in BC produced under controlled conditions in respect to uncharred biomass, but there is no increase with charring temperature. For TN, much more relevant is the feedstock type: RH should be selected if willing to have high TN concentrations in the BC. For BC and BFFs produced in the field, $BC_{Kon\text{-}Tiki}$ leads to relative lowest TN [%] and BFFs enhanced with MF to relative highest abundance instead, especially for BCMFSJ.

Looking at the different TC/TN ratios, different amendment types could be selected in respect to which goal within the C cycle wants to be promoted: higher ratios indicate material that is more difficult to decompose, this means more C sequestration potential but also less mineralization rates and thus less nutrients being plant available; lower ratios favour decomposition instead (Brady & Weil 2014). The higher the TC/TN ratio, the more there is the potential that N is immobilized, thus microbes enter in competition for N with plants. Nonetheless, when material is decomposed slowly, higher OM concentration can be found in soil which promote soil structure or tilth, thus greater physical stability of the soil. This improves soil aeration and water drainage and retention and reduces risk of erosion and nutrient leaching. SOC is also important to chemical composition and biological productivity including fertility and nutrient holding capacity of a field (Corning et al. 2016).

For production under controlled conditions, higher TC/TN ratios were found for charred in respect to uncharred feedstock and for SC in respect to RH. As expected, samples enhanced through SJ have a higher TC/TN ratio than samples enhance through FL, thus provide more N to the soil, whereas the other promote mineralization. By containing N in his composition, MF increases the TC/TN if combined with other amendments. Compost is known to be labile (Agegnehu 2015), in fact BCC and BCCMF have a low TC/TN favourable for a fast C mineralization and thus nutrients availability for plants, nonetheless with a short-term effect (Gupta et al. 2016). For field production, RH and untreated BC are the treatments there are most difficult to degrade, whereas BCMFSJ is the BBFs with relative lowest TC/TN ratio.

### 5.1.8 Chemical surface reactivity

The chemical surface reactivity analysis shows that pyrolysis increases the reactivity of uncharred feedstock material. As shown by my results, the charring temperature modifies the functional groups resulting in a decrease in reactivity for aliphatic C groups and an increase in reactivity for aromatic C groups (Lee et al., cited in Jindo et al. 2014). An increase in reactivity for aromatic C, nonetheless, is not linear to the increase in number of functional groups. As explained by Jindo et al. (2014), higher temperature biochar has a predominantly aromatic presence in chemical composition, which leads to a recalcitrant structure. Charring at 600 °C increases also the number of functional groups being therefore a suitable method for carbon sequestration (Jindo et al. 2014). Nonetheless, even if getting more aromatic, there is not much need to produce biochar at temperature of 700–800 °C in order to preserve stability character, since these temperatures may reduce the number of functional groups in the structure, limiting the chemical properties of the biochar as soil amendment (Jindo et al. 2014). Additionally, during pyrolysis, biochar firstly forms abundant functional groups due to decomposition, subsequently and with higher charring temperature the product become more porous with many micropores. At 600 °C, biochar may have suitable porosity and functional groups for its application (Chen et al. 2017).

In alignment with these findings, my results show a much weaker reactiveness of BC surface charred at 700°C than 450°C while irradiated with IR. The low reactivity is also due to the more stable structure of high temperature BC. Furthermore, C rich materials (thus particularly high temperature biochar) are usually difficult to analyse by MIR because of the degree of chemical condensation level resulting in flat and noisy spectra (Cotrufo et al. 2016), what is the case of my results. Therefore, for soil fertility enhancement, attention should be given to maintain charring temperatures between 450°C and 600°C.

As feedstock type, SC resulted to be more suitable if willing to increase the chemical surface reactivity. Even if plant structural constituents like lignin and cellulose are largely replaced by aromatic structures during pyrolysis (Chatterjee et al. 2012), from my results, a higher reactiveness for wavelengths associated to cellulose and lignin can be detected for samples based on SC, thus a slower decomposition rate is expected for biochar from SC than biochar from RH. RH for production under controlled conditions has relative higher reflectance for aliphatic $CH_2$ compared to RH from the field production, but less reactivity looking at wavelengths associated to cellulose.

Between production methods adopted in the field, similar reflectance was found when analysing $BC_{UAS}$ and $BC_{Kon\text{-}Tiki}$. Field BC has higher reflectance at bands associated to aliphatic C-H and lignin in respect to BC produced under controlled conditions.

Generally, and for samples produced under controlled conditions, the impregnation of BC with different amendments leads to a relative higher reactivity along the analysed spectra than for untreated BC, especially for BCC. For samples produced in the field, a decline in reactivity was measured from BC to BBFs. BCC had especially low values looking at chemical functional surface reactivity whereas BCMFSJ especially high values. Thus, between production method, amendment type leads to significant differences. MF is relatively less suitable for surface activation, since the results were not unanimous and, when combined, MF does not overwrite the effect of the other amendments.

## 5.2 Influence of biochar and BBFs on soil parameters

### 5.2.1 Laboratory analysis

Characterizing the soils from the different pedo-climatic locations, I expected to see a trend by which I could say that the more arid the research site, the less suitable the values found would be if willing to have a fertile soil and thus, the more the soil could profit from a BBF application.

My results could confirm that Bangalore, the soil sample from the most arid zone along the analysed gradient, could profit most in respect to the other sampling locations from BBFs application, since showing the lowest clay and OC content and the most acidic pH-value. Nonetheless, even if lower OC and clay contents should lead to a smaller CEC (Brady & Weil 2014), this is not true in case of Bangalore, which has the highest CEC of 3 cmol/kg. Considering that the soils of the four research sites had CEC ranging from 0.5 to 3 cmol/kg, whereas CEC of the BC produced in the field vary between 3.17 and 4.03 cmol/kg, their application would increase the CEC values of the soils of all research sites. All research sites could profit significantly from the WHC [%] of the treatments that are higher than the values of the soils (between 32.27 to 39.91 % for the soils and between 162.4 to 609.43 % for the treatments).

High WHC is expected for soil samples with large clay and silt sized particles percentages, because of the large surface area able to hold larger quantities of water, and for samples with large OM amounts, due to the affinity of OM to water (Brady & Weil 2014). This pattern is not visible looking at my results. Also not confirmed by my data, the fact that BD values should be smaller for higher OC concentrations. OC represents the only value from the laboratory characterization for which the effect of the pedo-climatic gradient is visible: higher abundances can be found were temperatures are warmer and precipitation more abundant. Except for Bangalore with 0.73 % of OC, the values found for OC [%] are included in the typical range for soils of 1-6 % (Brady & Weil 2014). The EC [mS/m] of the soil samples reflect typical values for soils rich in sand (Grisso et al. 2009). The EC of all four soils (0.04 to 0.31 mS/m) from the different research sites is lower in respect to the values found for the treatments (0.73 to 7.41 mS/cm), thus BC and BBFs' application increases the EC what's favourable considering soil fertility. The BC and BBFs, apart for RH when analysed in $CaCl_2$, have a rather alkaline pH-value what's profitable for soils from Bangalore, Hassan and Mangalore, which have a rather acidic pH-value. Liming to optimum pH not only increases the availability of essential nutrients but improves soil conditions for microorganisms and improves soil structure (Ketterings et al. 2005).

The results of Hassan's soil characterization could be located in-between those of Bangalore and Mangalore and thus, together with the results of these other two locations, confirm my hypothesis, that BFFs increase relatively more soil fertility in arid zones in respect to more humid zones along the analysed pedo-climatic gradient. Nonetheless, this is not true if considering the results from Mandya: this research site shows the relative highest pH-value, EC-value, $NO_3^-$ concentration, TC and TN abundance and the relative lowest CEC, BD as well as WHC. A possible explanation for Mandya's values is the management practice applied in this location, that is influenced by a river, from which sediments are collected and spread over the fields. These sediments could come from different locations spread along the river flow. The soil collected in Mandya is therefore not reliable for the pedo-climatic situation of the site. Not only the neutral pH of Mandya and the high levels of $NO_3^-$ let assume a fertile soil in this research site, but also the higher abundance of atomic elements. In fact, Mandya was the most concentrated site considering the abundance of Na, Mg, P, Cl, K and Ca, nutrients that are essential for plant growth.

Weathered soils in tropics are known to be acidic and having abundant Fe and Al concentrations (Brady & Weil 2014). Looking to temperature, the increase of both Fe and Al concentration with increasing pyrolysis temperature found for charred samples could represent a problem when applied to already Al and Fe rich soils that additionally are acidic ($pH<5.2$), as Bangalore and Hassan are, because of the potential toxicity of the soluble part of these elements (Brady & Weil 2014). Especially compost had high Fe [%] and Al [%], thus attention should be given if willing to apply this BBF.

Generally, in well-weathered soils, which is the case for the tropics, silicate clays, Fe and Al oxide clays and quartz remain as mostly available minerals (Brady & Weil 2014). These was confirmed from the chemical functional surface analysis: peaks near 3690-3620 $cm^{-1}$ and near 1100-1000 $cm^{-1}$ are associated with quartz and kaolinite clays (Waruru et al. 2015). Another indication for weathered soils is the absence of reactivity for $CaCO_3$ in all of the analysed samples (Du & Zhou 2009).

In Mangalore, the most humid area along the analysed gradient, the soil is rich in Si but less rich in Al, Mn and Fe than the soil from Bangalore, probably because of the washing out of the elements. Between the research sites, Mangalore resulted generally more reactive along the analysed spectra, including at the bands for lignin (1510-1500 $cm^{-1}$) and cellulose (1260-1210 $cm^{-1}$) (Chatterjee et al. 2012), which indicate that the decomposition rate on this site is slower compared to the other research sites. The relative highest reactivity and the slowest decomposition rates are reflected by the highest OC as well as clay and silt concentrations found for Mangalore; nonetheless, not by the TC/TN ratio, which is relatively low for this research site and should therefore promote decomposition.

N deficiency is typical for both lateritic soil and red soil, which are the soil types of my research sites (table 5), and the deficiency is confirmed by my analysis which shows a mean TN from 0.04 % to 0.06 %. All BC and BBFs have higher TN [%] than the soils and increase therefore TN concentration when applied, especially when containing MF.

### 5.2.2 Analysis under controlled conditions

#### 5.2.2.1 C dynamics

Soil respiration, thus $CO_2$ emission, is the result of decomposition of OM by microbial communities. Temperature, water and C input are the main factors influencing decomposition patterns (Yuste et al. 2007). I expected soils from more hot and humid location having higher respiration rates. In addition, I expected soil from Mangalore having highest cumulative respiration since being of lateritic type, thus being characterized by fast decomposition of OM (table 5). Furthermore, I supposed that all treatments based on BC would increase respiration rate of the control soils.

Generally, the effect of soil type on respiration is greater than for amendment type applied. Final cumulative respiration is highest for Mandya with 2.6 g C-$CO_2$/kg soil, followed by Mangalore with 2.2 g C-$CO_2$/kg soil, Bangalore with 2.06 g C-$CO_2$/kg soil and Hassan with 1.64 g C-$CO_2$/kg soil. The gradient of highest to lowest respiration does not reflect the pedo-climatic gradient of the locations.

Priming effects were observed in laboratory and field studies about biochar and could explain the respiration patterns found during the incubation experiment. Priming effects are changes in the mineralization of native SOM due to the addition of new substrates (Zimmerman et al. 2011). Most commonly it is a positive priming that is observed, thus the accelerated mineralization of more refractory SOM components, when stimulated by the addition of a labile C source. For BBFs, biochar acts as mineralizable C source whereas the amendments may also provide nutrients or even a habitat favouring increased microbial activity (Thies and Rillig, Chan and Xu, cited in Zimmerman et al. 2011). Negative priming is any retardation in SOM mineralization due to a treatment's addition and it may occur due to the divergence of microbes or their enzymes to the more easily available substrate, or to the inhibition of microbial activity because of some change in the soil environment (Kuzyakov et al., cited in Zimmerman et al. 2011). C in biochar is nonetheless hardly degradable and, given the porous structure and high affinity of biochar, it could be that it sequesters SOM within its pores, protecting it from degradation (Zimmerman et al. 2011).

Zimmerman et al. (2011) tried to shed light on the interaction mechanism between soil and biochar that may lead to variability in priming effects and they observed that C mineralization caused negative priming in soils rich in OC and enhanced with biochars produced from hard woods at high temperatures (up to 650 °C). According to Zimmerman et al (2011), my results should show negative priming since produced at about 650 °C. Negative priming occurred between week 2 and 4 for some treatments when applied in the soils from more arid regions (Bangalore and Mandya). BC is one of these treatments but, when applied in soils from more humid locations (Hassan and Mangalore), it leads to a positive priming. Between week 2 and 4 no observation carried out during analysis of N and P dynamics can be relevantly adopted to explain the negative priming. Furthermore, I expected that soils with relative lower OC [%] (Bangalore and Mandya) would increase decomposition rate through C input more than soils with relative higher OC [%] (Hassan and Mangalore), as argued by Zimmerman et al. (2011). The opposite trend was confirmed by my results.

Considering the final cumulative respiration independently from soil type, control is the treatment with lowest respired amounts, thus BC and BFFs generally lead to a positive priming as suggested by Zimmerman et al. (2011). BBFs increase respiration rate more than untreated BC in case of BCC and BCMFSJ. BCC was the treatment with highest cumulative respiration, thus the microbes where stimulated more. In fact, compost, unlike biochar, is quickly broken down by microbial action in soil (Agegnehu 2015). BCMF also reaches relatively high cumulative respiration since it provides nutrients to soil microbial community. More interesting is the comparison between RH an BC, having very similar respiration rates. If biochar sequestered SOM in his porous structure protecting it from degradation (Zimmerman et al. 2011) is not verifiable through my results.

In the average, BCSJ leads to higher final total respiration compared to the control, but not compared to all other treatments. The relative high TC/TN ratio of BCSJ could explain the relative low respiration rate.

I supposed that the trend is of a rapid increase of respiration rate at the beginning of the incubation period followed by a more constant increase with time, due to the initial mineralization of the more labile pool while the remaining fraction has a slow turnover and is more recalcitrant (Townsend et al., cited in Yuste et al. 2007). The trend is confirmed by my results: the respiration increases exponentially at the beginning of experiment and the increase gets weaker with time.
BCC and BCMFSJ show similar cumulative respiration amount independently from soil type, whereas the other treatments show relative higher variability. Especially the high variability of BC's cumulative respiration depending on soil type in which it is applied confirm the heterogeneous nature of this material (Hale et al. 2013) and the need to focus on developing designed biochar systems for individual applications (Abiven et al. 2014).

#### 5.2.2.2 N and P dynamics

In the average, at day 1 soils contained 0.379 mg/kg soil of N-$NH_4^+$, 1.250 mg/kg soil of N-$NO_3^-$ and 0.463 mg/kg soil of P-$PO_4^{3-}$. Bangalore is the soil with highest concentration of the analysed nutrients. At the end of the experiment, soils contained in the average 0.050 mg/kg of N-$NH_4^+$, 0.194 mg/kg soil of N-$NO_3^-$ and 0.214 mg/kg soil of P-$PO_4^{3-}$. The decrease in abundance that is visible comparing values of day 1 and day 14 can be explained majorly by flushing. Between day 14 and the end of the experiment other processes could have played a role instead.

Processes that lead to an increase of plant available N in soil systems are fixation, mineralization and nitrification. Denitrification, volatilization, immobilization and leaching lead to a loss of N available for plants instead. Fixation occurs when not enough N is available in the soil and thus N is taken from the atmosphere (Johnson et al. 2005). Nonetheless, since energy, enzyme and minerals are needed to carry out this process, and since the systems during the incubation were closed, I would exclude this process form the analysis. Mineralization is the process that decomposes organic N from amendments to $NH_4^+$, thus probably is the cause of the increase from day 14 to day 42. Nitrification, the conversion of $NH_4^+$ to $NO_3^-$ carried out by soil organism to obtain energy, can be excluded from explanation instead, since in the overall a decrease in N-$NO_3^-$ was measured with time. Volatilization, the loss of N through conversion of $NH_4^+$ to ammonia gas that is released to the atmosphere, could have played a role during incubation, since $NH_4^+$ concentration decreased with time. Volatilization was tried to be avoided by incorporating the amendments and not by surface applying them. Finally, soil particles do not retain $NO_3^-$ very well because both are negative charged, thus $NO_3^-$ easily moves with water in the soil promoting leaching (Johnson et al. 2005). This was also confirmed by the low values obtained for $NO_3^-$ through the batch sorption experiment. In case of $NH_4^+$, which is positively charged, adsorption on soil particles but also on biochar could be greater than for $NO_3^-$. Nonetheless, since the experiment was short term and the absorbance happed fast, probably the physical and not chemical absorbance is responsible for change in concentrations.

Soils from Bangalore and Mandya have higher abundance of $N\text{-}NH_4^+$ than soils from Hassan and Mangalore. Soil from Hassan has significant higher abundance of $N\text{-}NO_3^-$ than soil from the other research sites. Surprisingly, when RH is applied in Mangalore's soil it represents the treatment with highest abundance of $N\text{-}NO_3^-$. The values could be explained the higher absorption capacity of treatments containing BC in respect to RH. In case of Mandya, it is BCC that leads to highest mineralization of $N\text{-}NO_3^-$, probably because compost is labile. BBFs enhanced with MF contain N in mineral form, therefore these treatments have highest initial concentration when analysing both $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$. In the other treatments, N is contained in organic form and must therefore first be converted by microbes to become plant available. Even if starting with significant higher amounts of nutrients, BBFs containing MF are not the treatments with highest abundance at the end of the experiment. Thus, MF does not promote mineralization, rather the nutrients are flushed away or absorbed by the BC.

To understand P dynamics, it is important to differentiate between P that is present in plant available form as inorganic P, and between P in forms that are not plant available: organic P, adsorbed P (organic) and primary mineral P. Processes that increase plant available P include weathering, mineralization and desorption. Precipitation, immobilization and adsorption decrease the amount of plant available P instead (Hyland et al. 2005).

Soil naturally contain P-rich minerals that are weathered over longer time periods. Initial P content of soil is therefore crucial to know the P application amounts required to promote plant growth. Between my research sites, no significant differences in initial P abundance were measured (from 0.04 to 0.1 %). pH has an effect on plant availability of P with ideal values around 6 and 7 (Hyland et al. 2005), what is not the case of my research sites. In addition, soil with higher Fe and Al content, as is Bangalore's soil compared to the other research sites, has the potential to adsorb more P. In fact, Bangalore represent the research site with highest $P\text{-}PO_4^{3-}$ amount. Also, BCC contained relatively highest Fe and Al abundance compared to the other treatments, resulting in highest $P\text{-}PO_4^{3-}$ [mg/kg soil] during all experimental period.

Similar as for N, mineralization is the microbial conversion of organic P to orthophosphates as $PO_4^{3-}$. This mineralization process explains the increase in $P\text{-}PO_4^{3-}$ measured from day 14 to day 42 in all soil types. The decrease in $P\text{-}PO_4^{3-}$ amount between day 1 and day 14 can instead be explained by the flushing. In farms also the major loss of P in farms is generally given by runoff, since P is dissolved is water or bounded to soil particles which are carried away with water (Hyland et al. 2005).

Immobilization occurs when plant available P is consumed by microbes turning it into organic P. Immobilization could be the cause for the decrease in $P\text{-}PO_4^{3-}$ amount of BC from day 14 to day 42. Since the processes happened quickly, nonetheless, more probably than immobilization it is the physical absorbance that caused the decrease. Chemical adsorption of $P\text{-}PO_4^{3-}$ also occurs quickly (Hyland et al. 2005) and could therefore be partly responsible.

To conclude, the data about N and P dynamics can be majorly explained by physical processes. Both treatment application and soil type had an influence on the results.

### 5.2.3 Field trial

#### *5.2.3.1 Yield*

Despite for BCSJ, results indicate a greater increase in straw and grain yields [%] for BC and BBFs application in respect to RH and compared to the control. Always with BCSJ as exception, BBFs enhanced yields [t/ha] more than untreated BC.

The fact that charring is favourable for increasing yields [t/ha] was already demonstrated by the characterization: BC has higher elemental abundance, higher surface reactivity and greater suitability to enhance soil fertility looking at pH, WHC, CEC and EC than RH. In addition, laboratory incubation demonstrated how in soil from Mandya BC increases microbial activity and leads to higher mineralization rates of $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$ if compared to RH.

Surprisingly, BCC leads to relative low yields [t/ha]. From characterization, this treatment resulted having relatively high elemental abundance and relative low TC/TN ratio, which favours decomposition. In fact, BCC had highest cumulative respiration during incubation experiment. Looking at the nutrient's dynamics investigated through incubation experiment, BCC differed from the other treatments by having relative highest $P\text{-}PO_4^{3-}$ mineralization rate but average $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$ amounts. Thus, variables that could take into account to explain the low yields are the relatively low functional surface reactivity and relatively low TN [%] found for BCC.

Similarly, BCSJ has relatively low chemical functional surface reactivity, relative low TC/TN ratio and overall low nutrients abundance when analysed in the laboratory. Both straw and grain yields [t/ha] resulted relatively low for BCSJ. From incubation experiment for Mandya's soil, BCSJ has relative highest respiration amounts but the mineralization rates obtained analysing nutrients' dynamics were relatively low. Thus, even if decomposition is stimulated, nutrients and functional groups able to hold them are missing.

The plots enhanced with MF show relative highest yields [t/ha]. Between BCMF and BCMFSJ the values are similar, with BCMF having relatively highest straw yield with 8.39 t/ha and BCMFSJ having relatively highest grain yield with 7.83 t/ha. Considering the need of only half of RDF for BCMFSJ, this BBFs seems promising as sustainable and cost reducing technology to improve yields. If the SJ influenced the results or if BC with half RDF would have led to the same yields' amount cannot be tested through this study.

Possible reason for the suitability of BCMFSJ to enhance yields are the relative highest Ca, Cl, P, K and Na abundances found for this treatment and the highest chemical surface reactivity measured along the IR spectra. Furthermore, BCMFSJ produced in the field had relative highest TC/TN ratio compared to the other BBFs. Again, respiration and mineralization rates obtained from the incubation experiment for Mandya's soil do not explain the relative highest yields of BCMFSJ.

The Directorate of Economics and Statistics of India (2016) investigated grain yields in Karnataka for the year 2015-2016 and, for the same season as my field trial (Rabi), mean yields were of 2.98 t/ha, thus about half the values of my treatments. Specifically for the district of Mandya, Rajanna (n.d.) cited a grain yield of 3.14 t/ha whereas the Karnataka State Department of Agriculture (2015) indicated a mean grain yield of 3.19 t/ha. Thus, considering values from literature for Mandya, the yields obtained from the field trial are higher than usual. Nonetheless, the plots without any treatment, thus the control, had relative high yields as well and additionally, being a field trial, the farmer's attention in managing the field could be higher than usual.

What is showed clearly by the results, is that an increase in yields [t/ha] can be obtained through BC application but especially through BBFs application, with BCSJ as exception. MF resulted as the amendment whereby the impregnation process with BC is most effective, even if MF is combined with SJ and applied with half of the recommended doses. Between the analysed variables, TC/TN ratio and chemical functional surface reactivity resulted to be directly related to yields.

### 5.2.3.2 N and P efficiencies

rNUE is determined by plant seed yield relative to the amount of N applied and is generally composed of both N uptake and N utilization efficiency (Moll et al., cited in Perchlik & Tegeder 2017). The uptake of N by the root (NUpE) is influenced by the availability of soil N and controlled by plant N assimilation processes and N metabolite levels as well as the N demand of the plant (Perchlik & Tegeder 2017). NUtE is whereas affected by several physiological factors, including N uptake, metabolism, allocation and remobilization (Perchlik & Tegeder 2017).

Rice plants from the field trial did not focused their energy on increasing rather straw or grain yield. The less N was supplied, the more this N was used in an efficient way. The amount of N supplied from RH and BC is same, but BC has a higher rNUE resulting also in higher yields. In contrast, BCSJ has especially low grain and straw yields if compared to the amount of N supplied.
BCMF and especially BCMFSJ have low rNUE since the supply of N was relatively high. These treatments behave similarly comparing rNUpE and rNUE, but not in terms of rNUtE: BCMFSJ has significant higher rNUtE than BCMF. The yields obtained from BCMF and BCMFSJ are nonetheless similar again.

rPUE depends mainly by the soil environment as soil water status, soil mineralogy and soil pH (Hyland et al. 2005). The less P amount is supplied from the treatments, the higher is the rPUE, rPUpE and rPUtE. For RH, P is supplied in significantly lower amounts than for the other treatments and, even if the yields of RH are relatively lowest, the difference in yields is not as significant. RH has higher rPUE, rPUpE and rPUtE than BC, but again, it is explained by the P amount supplied. For RH, soil P reserved were mined since the P amount that was up taken is greater than the supplied amount. Between BBFs, BCMF supplied largest P amount and resulting in lower efficiencies than BCSJ and BCMFSJ. The rPUtE is lower for BBFs in respect to BC apart for BCC. The rPUpE and the rPUE are lower for all BBFs compared to untreated BC.

## 6. Conclusion

This study demonstrates that BC and BBFs meet nowadays agricultural challenges. Generally, BBFs are more effective than BC in increasing the analysed chemical, physical and biological properties of soil fertility. Especially promising are BBFs enhanced with compost, leading to the highest mineralization and decomposition rates, and BCMFSJ, for increasing yields while avoiding excessive MF use. Soil type and management practices have nonetheless a greater impact on soil fertility than treatment type applied, indicating careful evaluation of the site before application.

This thesis found heterogeneous but generally weak nutrient's desorption of BC when analysed through batch sorption experiment. Further research should investigate the desorption properties of BBFs once applied in the field. Furthermore, the hypothesis that between the analysed properties yields obtained through BBFs can be predicted primary by their TC/TN ratio and functional surface reactivity has to be further investigated. Finally, a cost-analysis that takes into account biochar production, higher yields, environmental benefits on the long term and minor mineral fertilizer need is required before spreading the technology.

## 7. Literature

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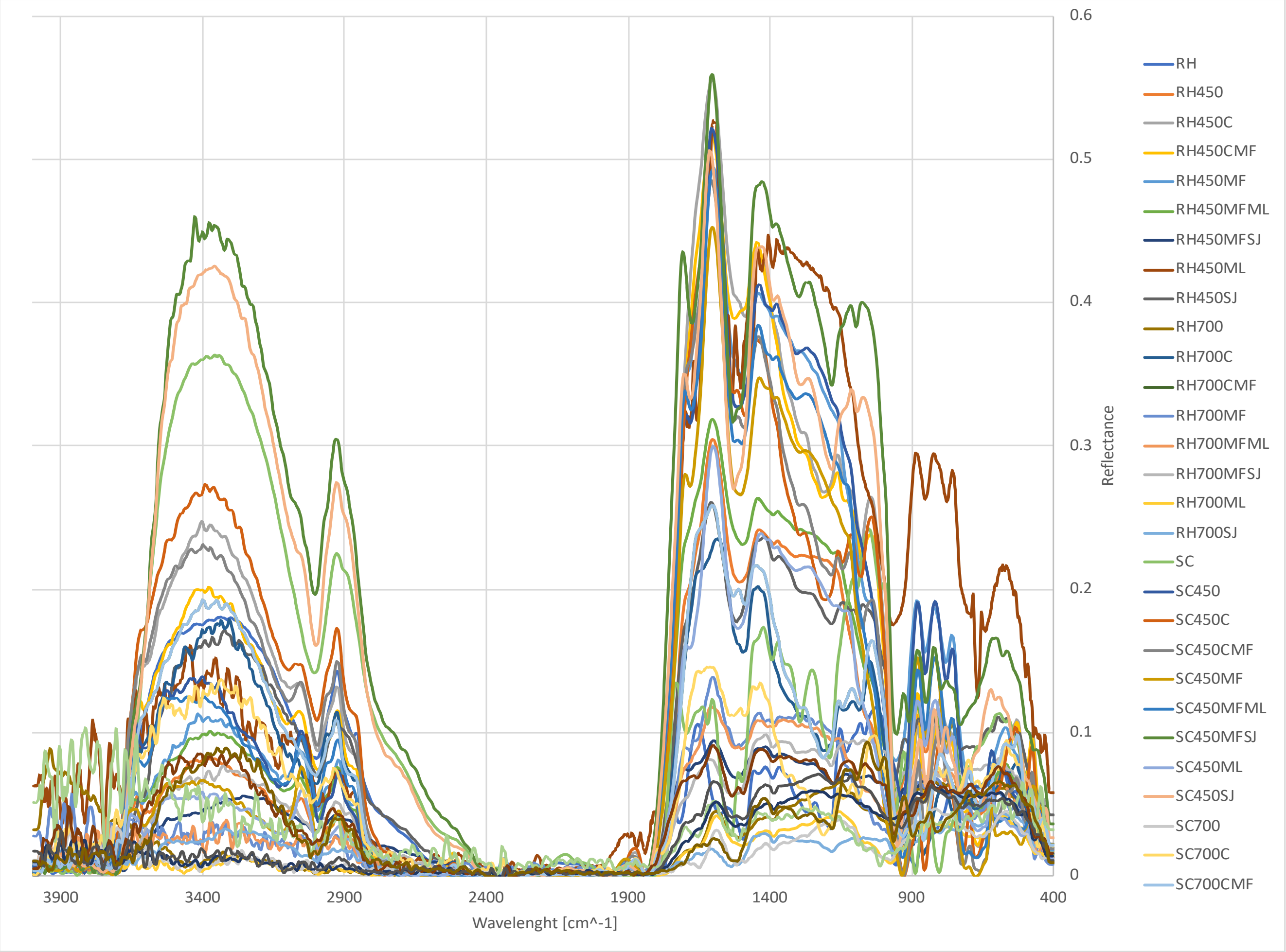
# 8. Annexe

Table 26: atomic elemental abundance, TC [%] and TN [%] of biochar and BBFs produced under controlled conditions.

| Feedstock | Temperature [°C] | Amendment | TC [%] | TN [%] | Na [%] | Mg [%] | Al [%] | Si [%] | P [%] | Cl [%] | K [%] | Ca [%] | Mn [%] | Fe [%] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RH | 0 | RAW | 37.64 | 0.82 | 1.07 | 0.54 | 0 | 0.03 | 0.43 | 0.01 | 0.27 | 0.01 | 0 | 0 |
| RH | 450 | BC | 69.69 | 2.91 | 1.17 | 0.57 | 0 | 0.06 | 0.82 | 0 | 0.77 | 0.03 | 0 | 0.01 |
| RH | 450 | BCC | 48.18 | 2.51 | 1.09 | 0.85 | 1.01 | 5.8 | 0.86 | 0.11 | 1.43 | 1.84 | 0.02 | 0.75 |
| RH | 450 | BCCMF | 47.56 | 2.45 | 1.25 | 0.96 | 1.02 | 6.22 | 1 | 0.09 | 1.53 | 3.29 | 0.02 | 0.69 |
| RH | 450 | BCMF | 60.73 | 2.9 | 1.27 | 0.6 | 0 | 0.06 | 0.9 | 0.01 | 0.94 | 0.03 | 0.01 | 0.01 |
| RH | 450 | BCMFFL | 64.55 | 3.09 | 1.1 | 0.59 | 0 | 0.06 | 0.83 | 0.02 | 0.8 | 0.03 | 0 | 0.01 |
| RH | 450 | BCMFSJ | 50.24 | 1.69 | 1.3 | 0.42 | 0 | 0.09 | 0.43 | 0.06 | 0.71 | 0.1 | 0 | 0.01 |
| RH | 450 | BCFL | 59.71 | 2.84 | 1.3 | 0.65 | 0 | 0.07 | 0.92 | 0.02 | 0.89 | 0.04 | 0.01 | 0.02 |
| RH | 450 | BCSJ | 42.12 | 1.43 | 1.07 | 0.39 | 0 | 0.07 | 0.44 | 0.04 | 0.58 | 0.08 | 0 | 0.01 |
| RH | 700 | BC | 70.11 | 1.72 | 1.08 | 0.38 | 0 | 0.07 | 0.68 | 0 | 0.76 | 0.03 | 0.01 | 0.08 |
| RH | 700 | BCC | 49.24 | 1.89 | 1.07 | 0.72 | 0.78 | 4.16 | 0.77 | 0.15 | 1.34 | 2.05 | 0.02 | 0.63 |
| RH | 700 | BCCMF | 41.22 | 1.9 | 1.41 | 1.01 | 1.7 | 9.31 | 0.96 | 0.2 | 2.15 | 3.48 | 0.03 | 1.08 |
| RH | 700 | BCMF | 64.94 | 2.01 | 1.28 | 0.67 | 0 | 0.21 | 1.02 | 0 | 1.04 | 0.09 | 0.01 | 0.29 |
| RH | 700 | BCMFFL | 67.06 | 1.89 | 1.02 | 0.5 | 0.24 | 0.08 | 0.76 | 0 | 0.76 | 0.04 | 0.01 | 0.06 |
| RH | 700 | BCMFSJ | 52.58 | 1.43 | 1.11 | 0.38 | 0 | 0.07 | 0.48 | 0.04 | 0.67 | 0.07 | 0 | 0.02 |
| RH | 700 | BCFL | 67.62 | 1.72 | 1.06 | 0.58 | 0.17 | 0.08 | 0.88 | 0.01 | 0.93 | 0.04 | 0.01 | 0.1 |
| RH | 700 | BCSJ | 47.93 | 0.93 | 1.06 | 0.34 | 0 | 0.1 | 0.38 | 0.05 | 0.58 | 0.08 | 0 | 0.02 |
| SC | 0 | RAW | 38.12 | 0.22 | 1.01 | 0.23 | 0 | 0.24 | 0.03 | 0.06 | 0.58 | 0.03 | 0 | 0 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SC | 450 | BC | 66.73 | 0.35 | 1.85 | 0.63 | 0 | 1.85 | 0.36 | 0.23 | 2.52 | 0.19 | 0.01 | 0.07 |
| SC | 450 | BCFL | 64.36 | 0.36 | 1.91 | 0.56 | 0.43 | 1.28 | 0.29 | 0.31 | 3.01 | 0.17 | 0.02 | 0.04 |
| SC | 450 | BCC | 38.36 | 1.5 | 1.43 | 0.87 | 1.75 | 10.65 | 0.45 | 0.34 | 2.52 | 3.28 | 0.04 | 1.29 |
| SC | 450 | BCCMF | 45.81 | 1.24 | 1.64 | 0.77 | 1.22 | 7.97 | 0.42 | 0.43 | 2.77 | 2.98 | 0.03 | 0.89 |
| SC | 450 | BCMF | 66.16 | 0.6 | 2.17 | 0.7 | 0 | 2.2 | 0.46 | 0.32 | 3.11 | 0.26 | 0.03 | 0.17 |
| SC | 450 | BCMFFL | 57.37 | 0.49 | 2.64 | 0.7 | 0.01 | 1.83 | 0.4 | 0.53 | 4.27 | 0.21 | 0.02 | 0.03 |
| SC | 450 | BCMFSJ | 50.78 | 0.27 | 1.07 | 0.3 | 0 | 0.43 | 0.09 | 0.13 | 0.79 | 0.11 | 0 | 0.01 |
| SC | 450 | BCSJ | 46.8 | 0.22 | 1.06 | 0.3 | 0 | 0.33 | 0.07 | 0.16 | 0.77 | 0.11 | 0 | 0.01 |
| SC | 700 | BC | 64.06 | 0.42 | 1.68 | 0.45 | 0 | 1.82 | 0.26 | 0.4 | 3.7 | 0.14 | 0.02 | 0.08 |
| SC | 700 | BCFL | 65.07 | 0.52 | 2.38 | 0.64 | 0.11 | 1.28 | 0.39 | 0.71 | 4.97 | 0.18 | 0.02 | 0.16 |
| SC | 700 | BCC | 38.44 | 1.47 | 1.31 | 0.83 | 2.24 | 9.21 | 0.4 | 0.22 | 2.19 | 4.79 | 0.04 | 1.52 |
| SC | 700 | BCCMF | 48.91 | 1.18 | 1.41 | 0.77 | 1.72 | 7.86 | 0.41 | 0.24 | 2.55 | 3.12 | 0.04 | 1.04 |
| SC | 700 | BCMF | 69.04 | 0.43 | 1.57 | 0.37 | 0.01 | 0.94 | 0.22 | 0.19 | 2.35 | 0.14 | 0.01 | 0.18 |
| SC | 700 | BCMFFL | 49.05 | 0.31 | 1.98 | 0.58 | 1.17 | 1.54 | 0.33 | 0.4 | 3.52 | 0.19 | 0.03 | 0.09 |
| SC | 700 | BCMFSJ | 54.31 | 0.31 | 1.62 | 0.43 | 0.1 | 0.62 | 0.14 | 0.25 | 2.1 | 0.17 | 0.01 | 0.01 |
| SC | 700 | BCSJ | 62.15 | 0.45 | 1.1 | 0.31 | 0.17 | 0.39 | 0.08 | 0.12 | 1.07 | 0.17 | 0.01 | 0.02 |

Figure 77: chemical functional surface reactivity of biochar and BBFs produced under controlled conditions.



“<u>Personal declaration</u>: I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.”