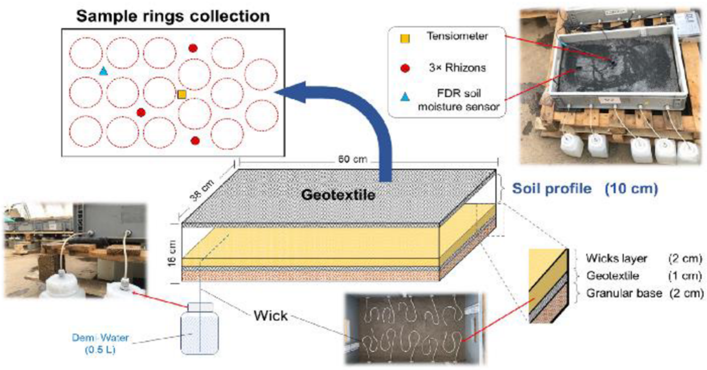
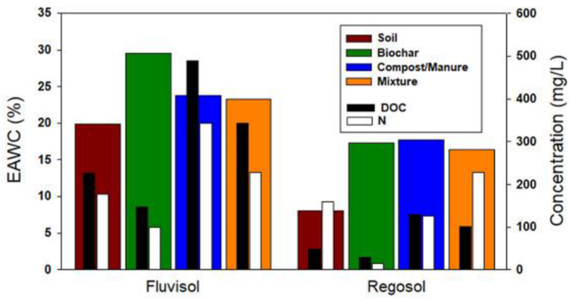
Application of biochar in order to enhance overall quality of low-organic soils

PhD Thesis





Samar Seyedsadr

Czech University of Life Sciences Prague

Aplikace biocharu za účelem zlepšení celkové kvality půd s nízkým obsahem organické hmoty

Samar Seyedsadr

To my true heroes; my parents!

For their endless love and support

To brave people in Iran, who sacrifice their lives for #Woman_Life_Freedom

Application of biochar in order to enhance overall quality of low-organic soils

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This thesis is submitted in fulfilment of the requirements for the PhD degree at

The Czech University of Life Sciences Prague
Faculty of Environmental Sciences
Department of Environmental Geosciences

Prague March/2023

Acknowledgement:

I would like to thank my supervisor, assoc.prof. Lukas Trakal for bringing the weight of his considerable experience and knowledge to this study. I would like to acknowledge and give my warmest thanks to my co-supervisors, Dr. Vaclav Sipek, Dr. Lukas Jacka and Dr. Luke Beesley for their guidance, which carried me through the laboratory works and paper preparation. I would also like to thank PhD students, my true friends, who gave me encourage not to give up. Special thanks to my parents; without them I could never come this far. Finally, I wish to acknowledge the Czech University of Life Sciences for providing me the doctoral scholarship.

All these research activities were supported by the Ministry of Agriculture of the Czech Republic (project QK1910056); Ministry of Education, Youth and Sports of the Czech Republic (projects LTE119008 and CZ.02.1.01/0.0/0.0/16_026/0008403); and Internal Grant Agency of the Faculty of Environmental Sciences, CZU Prague (project 2020B0003).

Abstract

Soil hydraulic properties of three low-organic matter soils from Czech Republic (Fluvisol; Regosol; Cambisol) were investigated in six experiments utilising various pot and boxed designs. The core of the experimental work was to amend the soils with biochar alone or in combination with manure, compost and co-composted biochar at 2 and 5% (w/w). Hydrogel (a synthetic soil moisture retention additive) was included by way of positive comparative control. Soil moisture sensors, soil porewater sampling devices, bulk density, porosity and derived soil water retention curves were applied to analyse the results. A consolidation (artificial manipulation of soil bulk density) experiment was also carried out to study the impact of compaction on soil hydrology in the Regosol with and without biochar amendment.

In the box experiments biochar significantly decreased bulk density and increased total porosity when compared to compost in the Fluvisol, while manure affected the greatest changes in the Regosol. All of the amendments adjusted the shape or extent of the soil water retention curves, but biochar addition resulted in the greatest increase (~50%) in plant easily available water content in both Fluvisol and Regosol, when compared to the control. Saturated hydraulic conductivity was not changed by any of the amendments which suggests a lack of influence on infiltration. An enhancement in nutrient retention occurred in co-composted biochar at 2% dosage and 5% manure-biochar mixture, as revealed by porewater analysis. The application of biochar with and without additional compost and manure enhanced soil water retention and maintained or enhancing nutrient retention in low organic drought-prone arable soils.

In the pot experiments the addition of biochar into the composting process hastened the stability of the resulting compost-char, which resulted in improved provision of available nutrients to soils and reduced potential leaching of metal(loid)s. Porewater analysis showed that nutrient leaching (e.g., NO_3^-, K^+) from manure addition to soil was reduced when biochar was blended with manure before soil application (by ≤86% compared to

manure alone). Higher doses of biochar also furthest reduced soil compaction. Compared to hydrogel biochar improved available and easily available water retention (by < 50%).

The results of these experiments demonstrate that biochar addition to drought prone soils offers multi-facetted benefits of improvements in soil hydraulic conditions which, especially in the presence of other organic amendments (composts, manures etc) can significantly improve the retention of nutrient laden soil moisture. Whilst these results are encouraging, field trials over longer time periods of time, will establish the longevity of the effects observed in this study.

Abstrakt

Hydraulické vlastnosti půdy tří půd s nízkým obsahem organických látek z České republiky (Fluvisol; Regosol; Cambisol) byly zkoumány v šesti pokusech s využitím různých nádobových a jiných bedýnkových inkubačních designů. Jádro experimentální práce bylo ošetření půdy samotným biocharem nebo v kombinaci s hnojem, kompostem a kompostovaným biocharem v množství 2 a 5 % (w/w). Hydrogel (syntetická přísada pro zadržování vlhkosti v půdě) byl také zařazen jako pozitivní srovnávací kontrola. K analýze výsledků byly použity senzory půdní vlhkosti, zařízení pro odběr vzorků půdní vody, stanovení objemové hmotnosti, pórovitosti a odvození retenčních křivek daných půd. Byl také proveden pokus s konsolidací (umělá manipulace se sypnou hmotností půdy), tak aby bylo možné studovat vliv zhutnění na hydrologii půdy v zemědělském Regosolu s přídavkem biocharu a bez něj.

V bedýnkových pokusech přítomnost biocharu významně snížila objemovou hmotnost a zvýšila celkovou pórovitost ve srovnání s kompostem, a to ve Fluvisolu, zatímco hnůj zapříčinil největší změny u Regosolu. Všechna aditiva způsobila změnu tvaru nebo rozsahu retenčních křivek dané půdy, ale přídavek biocharu vedl k největšímu nárůstu (o ~50 %) obsahu rostlinám snadno dostupné vody jak ve Fluvisolu, tak u Regosolu ve srovnání s kontrolou. Nasycená hydraulická vodivost se nezměnila po žádném z aditiv, což naznačuje neovlivnění výsledného vsaku (infiltrace). Ke zvýšení retence živin došlo u kompostovaného biocharu v dávce 2 % a 5 % směsi hnoje a biocharu, jak ukázala analýza půdní vody. Aplikace biocharu s přidaným kompostem a hnojem i bez nich zvýšila retenci vody v půdě a zachovala nebo zvýšila retenci živin v půdách s nízkým obsahem organických látek náchylných k suchu.

V rámci dalších pokusů přídavek biocharu do procesu kompostování urychlil stabilitu výsledného kompostovaného biocharu (kompocharu), což vedlo ke zlepšení zásobování půd dostupnými živinami a snížení potenciálního vyplavování kovů(loidů). Analýza pórové vody ukázala, že vyplavování živin (např. NO_3^-, K^+) u hnojem ošetřené půdy se snížilo,

pokud byl biochar do hnoje přimíchán před jeho aplikací do půdy (o ≤ 86 % ve srovnání se samotným hnojem). Vyšší dávky biocharu také nejvíce snížily kompaktnost půdy (daných konsolidací). V porovnání s aplikací hydrogelu zlepšil biochar dostupnou a snadno využitelnou retenci vody, a to o více jak 50 %.

Výsledky těchto pokusů ukazují, že přídavek biocharu do půdy náchylné k suchu nabízí mnohostranný přínos zlepšení hydraulických podmínek půdy, které zejména v přítomnosti dalších organických doplňků (kompostů, hnoje atd.) může výrazně zlepšit zadržování živin a rostlinám dostupné půdní vody. Ačkoli jsou tyto výsledky povzbudivé, až polní pokusy v delším časovém úseku umožní zjistit dlouhodobost účinků pozorovaných v této studii.

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CHAPTER ONE

Introduction

1.1. Background & scope of this study

Soil drought is an increasingly hot topic. Drought is known as one of the costliest recurring hydroclimatic extreme hazards in Europe that negatively impacts agricultural production (especially if occur during early growing season) and human livelihoods. It can be classified by its consequences on socioeconomic, direct (reduced crop yields), or indirect (increased food costs), (Duan and Mei, 2014; Blahut et al., 2016; Liu et al., 2019).

In the European Union (EU), over four thousand individual drought impacts have been reported in the European Drought Impact Report Inventory (EDII) across different wide range of categories, from agriculture to water quality (Blahut et al, 2016).

Drought is an anomalous lack of water at the land–atmosphere boundary. Since drought begins with a reduction of precipitation (meteorological drought), and the impacts can spread into decrease of soil moisture mostly in the root zone (agricultural drought), changes in stream discharges, low water storage in groundwater, and etc (hydrological drought), it makes soil moisture the main indicator in monitoring drought (Duan and Mei, 2014; Berg and Sheffield, 2018; Liu et al., 2019; Trnka et al., 2022). Along with soil moisture deficit, the increases in temperature, solar radiation, water vapor pressure deficits, magnify the soil drying for instance across the Czech Republic (Trnka et al., 2022).

Therefore, drought can have enormous impacts on all aspects of human activities, including water resources, agricultural production, etc (Berg and Sheffield, 2018). Human activities, on the other hand, e.g., intensive use of agricultural lands, erosion, soil compaction along with lack of proper managements can make soil degraded and more vulnerable to drought. (Trnka et al., 2022; Ferriera et al., 2022; Shukla, 2011)

According to the soil health and food report by European mission (2020), 60-70% of soils in the European Union are degraded as a direct result of unsustainable management practices. As a result, soils have lost significant capacity to provide ecological functions (EC, 2020b, ferriera et al., 2022). Improper anthropogenic practices (e.g., mining, deforestation, and heavy machinery), pushes soils to further dilemmas (e.g., contamination, flood, and compaction) that can disturb and destabilize vast amount of soil organic carbon (SOC) stocks in the subsoil (Lal, 2020).

Soil tillage and heavy machinery are among the major reasons for soil degradation, therefore loss of organic matter and low soil structure maintenance. The organic matter loss after improper activities are the results of increase in physical CO_2 release from soil pores and more SOM degradation via the broken aggregates (Shukla, 2011).

Drying soil, and consequently reduction of photosynthesis and growth in plants, decreases C inputs into soil, from above- (plants litter) and belowground biomass (roots). Therefore, drought issue is harmfully impacting soil as a short- and long-term carbon storage medium. Changes in soil organic matter (SOM) contents caused by increased temperature, plus accelerated biological decomposition activity in the upper horizons impacted soil fertility, with consequent influences on crop productivity and therefore food security.

Thus, drought not only reduces the nutritional resources directly but also changes soil microbial composition, and subsequently the consequences of soil C and N balance. The reason is that microorganisms, which are responsible for SOM decomposition are more sensitive to changes in temperature and moisture than to their nutritional resources (Shukla, 2011; Al-Kaisi, 2017; Lei et al., 2020; Deng et al., 2021).

Also, changes of C outputs from soil organic matter (SOM) mineralization are results of cyclic drying-wetting soil events. Some properties such as soil texture and aggregation, and cation exchange capacity affect diffusion rates of N compounds and overall affects biogeochemical cycles of all elements in soil. Crucial factors, such as increased temperature and soil moisture reduction, impact microbial composition and activities, which strongly decreases litter decomposition, therefore, unbalance the C and N content in the soil (Deng et al., 2021; Silva et al., 2020).

It is, therefore, necessary to reduce drought vulnerability by preparing appropriate adaptation strategies for drought mitigation. Such adaptations are reported as increasing soil available water content for instance by restoring the soil organic matter (Fig. 1) that can decrease the frequency, and impact of future agricultural droughts (Trnka et al., 2022; Lal, 2020).

Maintaining and enhancing SOM can make soils be physically, biologically, and chemically resilience to drought (Magdoff and Weil, 2004). For example, Soil structure improvements can enhance soil hydraulic properties (Rezaei et al., 2016), which are achieved through increases in porosity, aided by microbial activity and biological comminution of organic material called bioturbation.

At the same time, the application of organic matter can advantageously impact soil chemical characteristics, which has a favourable effect on crop growth. Such impact happens by making nutrients available both by the nutrients in the organic matter and by the favourable physical conditions to enhance the availability of those nutrients to crops (Magdoff and Weil, 2004). Biochar, as an example of OM, is known to improve soil properties, sequester soil carbon and heavy metals and organic matter stabilizer. For instance, the latter function can be seen in biochar produced from the straw of common crops and can be utilized in the acidic soil for soil quality improvement (Liu et al., 2022).

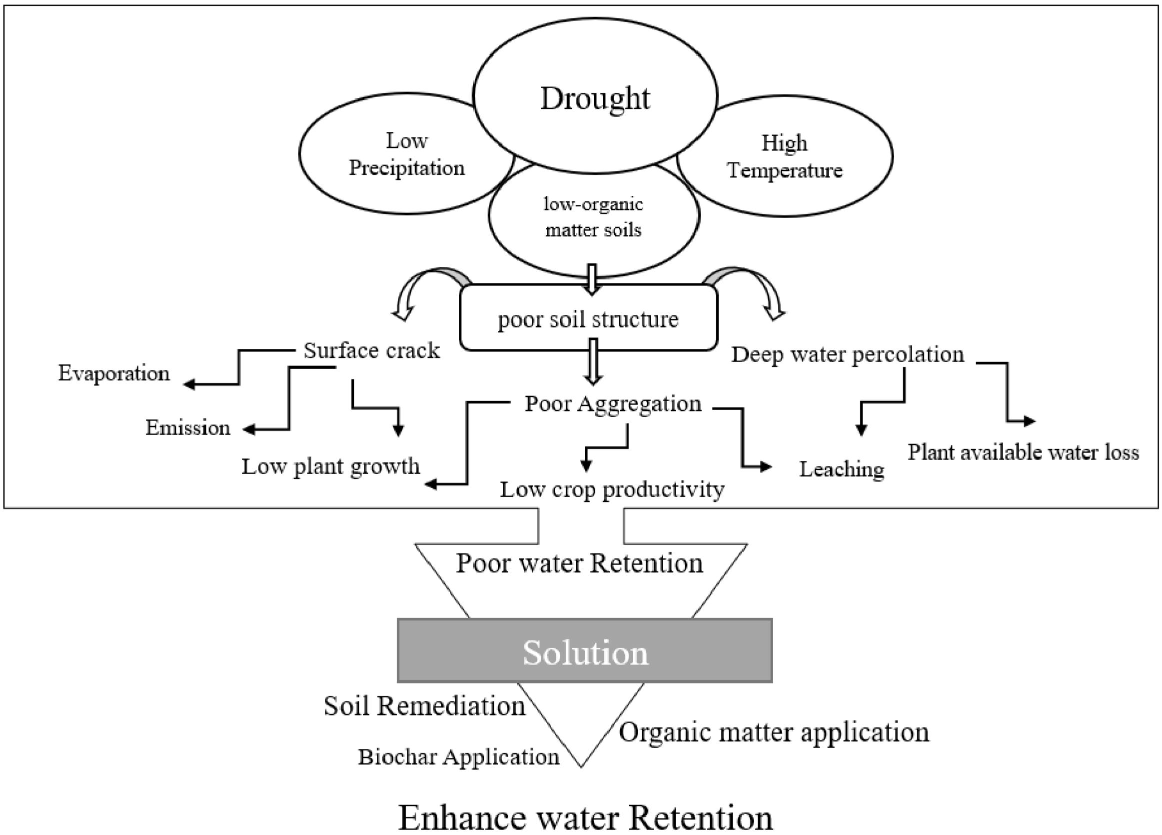

Fig. 1 Schematic representation of the importance of soil drought events and their impacts on soil and the possible solution examples.

1.2. Research Aims, Objectives and Hypothesis

The thesis is divided into the following four research aims, objectives, and hypothesis:

Aim 1: To measure the influence of biochar alone, or in combination with manure, compost, and co-composted biochar on the relevant soil hydraulic properties of two agricultural soils

Objective 1: To identify the most advantageous amendment combinations to enhance soil water retention

Hypothesis 1: Does biochar enhance water retention in sandy soils from the additional compost and manure amendments?

Aim 2. To measure the influence of different doses of biochar combined with manure on the relevant soil hydraulic properties of consolidated agricultural soil.

Objective 2: To investigate Biochar with/without manure on the relevant soil hydraulic properties of a consolidated soil.

Hypothesis 2: Does biochar application protect soil structure and retain plant available water in compacted agricultural soil?

Aim 3. To compare biochar and hydrogel application into sandy loam forest soil.

Objective 3: To investigate Biochar and hydrogel alone on the relevant soil hydraulic properties of a forest sandy loam soil.

Hypothesis 3: Can biochar improve soil moisture retention further than a synthetic soil-moisture enhancing additive (hydrogel) in a forest soil?

Aim 4. To investigate the synergic effects of biochar on the co-composting product and its time-reduction effects on the composting process.

Objective 4: to improve soil amendments by using co-composted and manured biochar through pot experiments.

Hypothesis 4: Does biochar addition into the amendment preparation process accelerate the stability of the resulting compost-char/manured biochar, with more favourable characteristics as a soil amendment than compost/manure alone?

CHAPTER TWO

Literature Review

2.1. Soil Organic Matter

2.1.1. Why does soil organic matter 'matter'?

Any material produced originally by living organisms (plant or animal) is known as Soil Organic Matter (SOM). These materials are returned to the soil and go through the decomposition process. Therefore, SOM consists of the intact original tissues of plants and animals and the substantially decomposed mixture of materials known as humus. Non-humic organic molecules such as proteins, amino acids, sugars, and starches are released directly from cells of fresh residues, which are the active or easily decomposed fraction of soil organic matter. Mainly amino acids, nucleic acids, and amino sugars are the organic forms of soil N, which occurs over 90% in this form. The rest of soil N exists in the form of amines, vitamins, pesticides, and their degradation products, as well as in form of ammonium (NH_4^+). Ammonium is held by clay minerals.

The remaining part of organic matter that has been used and transformed by many different soil organisms into a relatively stable component is named as humus or humified organic matter. Humic substances are including humic acids, fulvic acids, hymatomelanic acids and humines. Humic substances have different functions in the soil. Humus improves fertilizer efficiency, makes N retain longer, improves nutrient uptake by plants, particularly of P and Ca, and manages salinity. Humic substances act like a catalyst for increasing soil C levels (Bot and Benites, 2005).

Plants are the primary input of organic matter to the soil, through the continued release of exudates from roots, root tissue turnover, and deposition of aboveground plant residues. The amounts of these inputs vary greatly in space and time and depend on the ecosystem type (Cotrufo and Lavallee, 2021; Juriga and Šimanský, 2018). In the process of SOM formation, soil enzymes play an important role in maintaining soil quality and ecosystem functions especially biogeochemical cycling (Wang, 2006). Traditionally, it is known that the SOM formation process begins when necromass enters the soil. Accordingly, more SOM is formed when the residue decomposition happens slower, and as a result more residue remains throughout the decomposition process (Cotrufo and Lavallee, 2021).

Figure 2 is an overview of key differences in dominant formation between particulate (POM) and mineral-associated organic matter (MAOM). POM is formed by fragmentation and translocation of structural litter residues. MAOM, on the other hand, is formed through a direct association (ex vivo) or microbe-mediated transformation and deposition (in vivo) of soluble and low molecular weight litter or exudate compounds. Unlike POM, MAOM tends to last longer in soil and has a higher density. MAOM contains less chemically complex compounds on average and has a lower C:N ratio compared to POM.

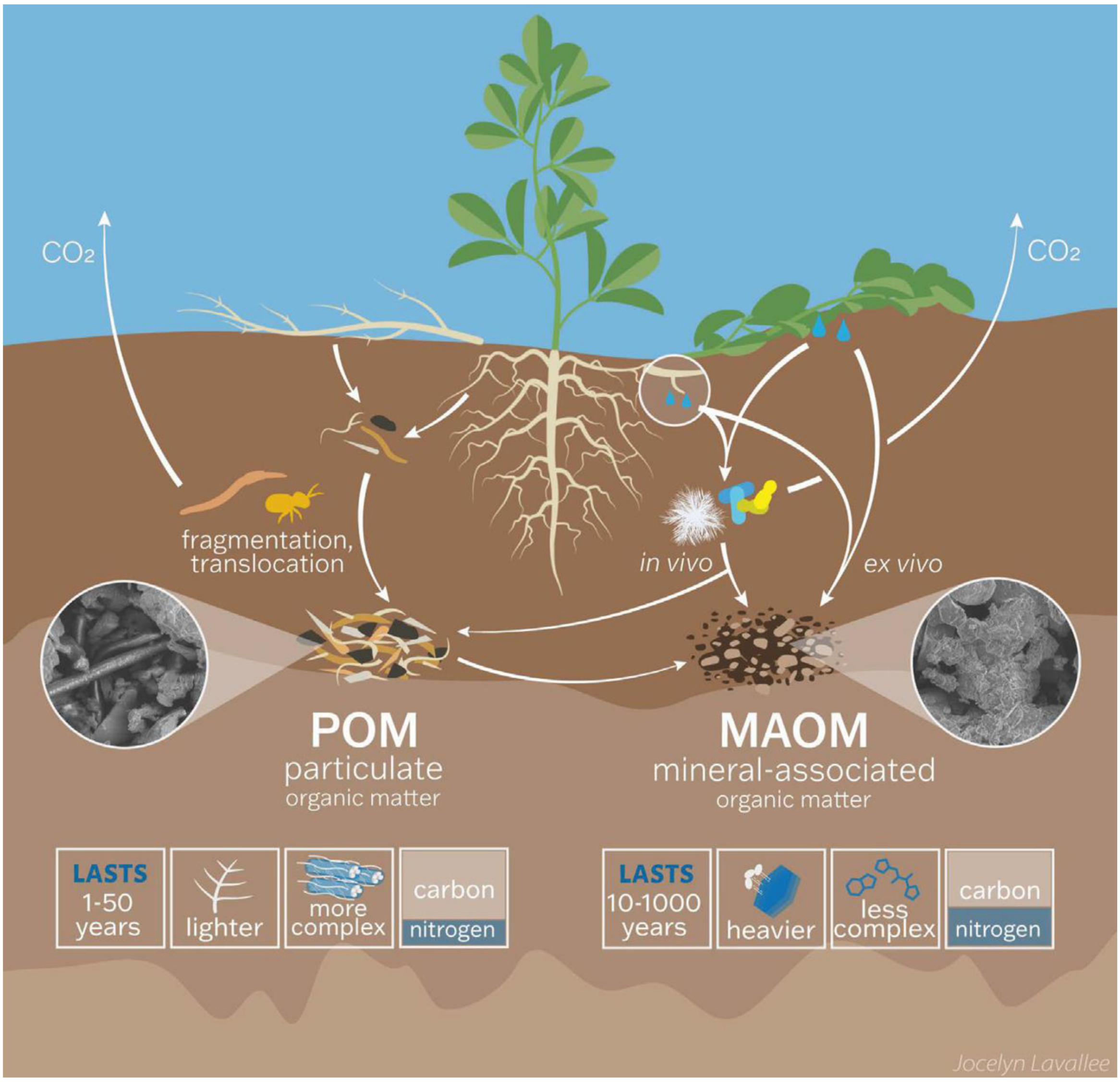

Fig. 2 Dominant formation pathways of particulate (POM) and mineral-associated organic matter (MAOM) and their differences (Cotrufo and Lavallee, 2021)

Organic matter inputs undergo a series of chemical and physical transformations when entering the soil. It can happen with or without the contribution of faunal and microbial processing, which together contribute to the formation and persistence of SOM. During this transformation process, CO_2 is produced through C mineralization in soil with a SOM formation efficiency. It is noted that the SOM formation process is initiated from the POM fraction, which means the structural residue of plant input decomposition is the dominant input to SOM. A large portion of organic matter inputs is also entering the soil in water-soluble forms (fig. 2) through exudation from living plants and leaching from decomposition residues on the soil surface and rhizosphere.

Soluble inputs are the readily available substrates for microbes, which are characterized by fast turnover. They may even cause an acceleration in the loss of native SOM by increasing microbial activity, or by releasing organic matter bonded to minerals. Particularly, dissolved organic matter (DOM) from water-soluble inputs is the main substrate of MAOM formation. On the contrary, POM is formed primarily from the polymeric structural residues of plant, animal, and microbial residues, in differing proportions, depend on the ecosystem. Although both seem to contain plant and microbial-derived compounds, POM is believed to be dominated by plant-derived compounds, while MAOM is mostly formed from microbial-derived compounds.

The movement of DOM into the soil is under the control of vertical water movement and interactions with minerals and microbes. DOM contributes to the formation of MAOM via either direct association with mineral surfaces (ex-vivo), or via microbes' assimilation and conversion to microbial extra-cellular and necromass compounds (in-vivo). It is suggested that the major controls of the formation of these SOM fractions are organic matter input chemistry and N levels. Therefore, the formation of MAOM can be promoted by inputs richer in water-soluble compounds and by inputs with low C/N ratios. Both could happen through the direct sorption of water-soluble compounds and efficient microbial transformation of the inputs (fig. 2; Cotrufo and Lavallee, 2021).

Although SOM formation and stabilization processes take place at very small scales, i.e., 1–1000μm, their aggregated outcomes appear at larger ranges (Cotrufo and Lavallee, 2021). The following conceptual representation (fig. 3) illustrates the soil organic matter formation processes and their primary controls. The illustration includes the relative formation of dissolved (DOM) and particulate organic matter (POM) from plant inputs highlighted as (1). It also, includes the relative formation of mineral-associated organic matter (MAOM) through in vivo and ex vivo pathways denoted as (2), and the relative formation of MAOM and POM from microbial products marked as (3).

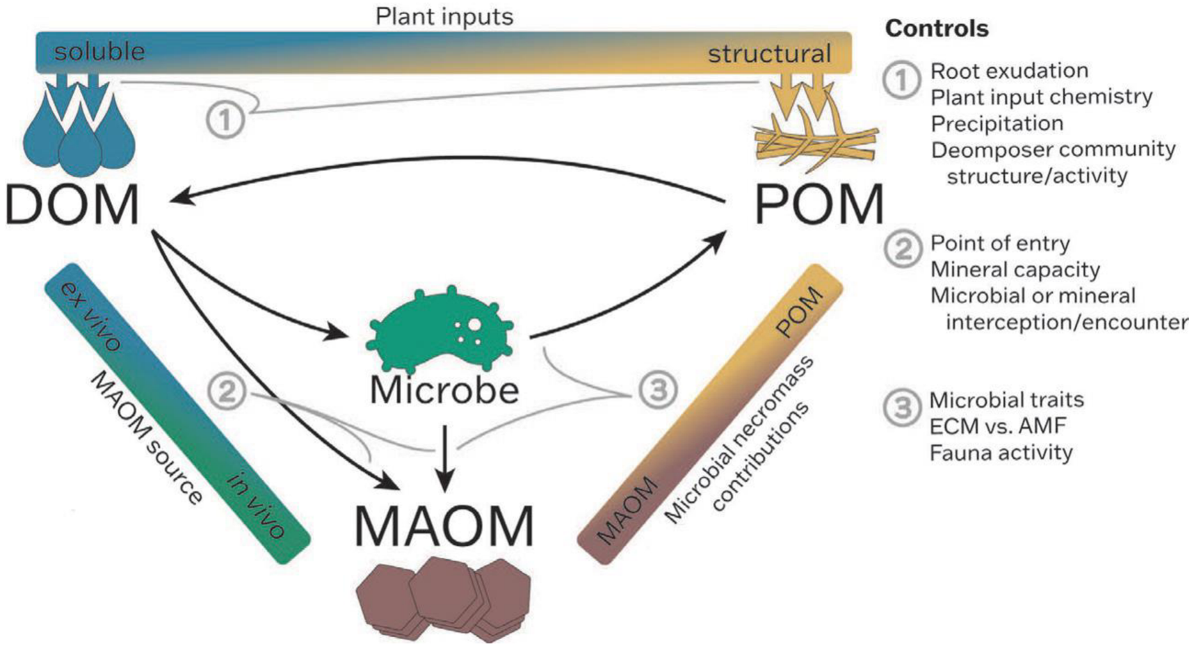

Fig. 3 Soil organic matter formation processes and their primary controls (Cotrufo and Lavallee, 2021)

2.1.2. The roles of SOM in soils

Soil organic matter is an extremely important renewable natural resource that supports many vital ecosystem services, such as regenerating fertility, nutrient cycling in ecosystems, regulating atmospheric CO_2 concentrations, enhance buffering capacity, and water retention, as well as structural stabilization and supporting a vast biodiversity of soils, which all lead to soil quality (e.g., sustaining soil fertility and productivity) and resilience. SOM is the major determinant factor of soil quality, which is closely related to soil fertility and productivity (Juriga and Šimanský, 2018; Lin et al., 2019). Humic substances, which are part of SOM, control buffering, cation exchange, and water retention capacity of soils. They also control the formation and stabilization of water-stable aggregates.

Soil organic carbon (SOC) binds soil mineral particles together creating an aggregate hierarchy. Therefore, the dynamics of aggregate formation are closely correlated with soil organic carbon storage in soils (Juriga and

Šimanský, 2018). With the positive impact of organic fertilizers on soil aggregation and aggregate stability, SOM will be immobilized within good aggregates, therefore by reducing accessibility to microbes and degradative enzymes, they retain longer (Lin et al., 2019).

The indirect effects of SOM on water dynamics operate through SOM influences on soil properties. For instance, improved soil structure is known to decrease erodibility and increase infiltration and water retention. The SOM content and composition of its fractions are stated among important inherent soil factors affecting soil water retention (SWR), along with texture (sand, silt, and clay content), type and the amount of clay, and nature of the clay minerals aggregation and stability of aggregates along with pore size distribution (i.e., the proportion of retention pores), internal drainage of the soil character (well-drained vs. poorly drained soil profile). Therefore, the soil humus content has a relatively high-water retention capacity due to its low bulk density, high porosity, low crusting, and high aggregation, surface area, and absorption capacity (Cotrufo and Lavallee, 2021; Somerville et al., 2019; Kirchhoff et al., 2003).

Organic products increase not only the strength and stability of intra-aggregate bonding but also promote aggregate stability. The aggregate stability is a result of wettability and swelling reduction by organic matter. Mechanisms such as adsorption, physical entanglement and envelopment, and cementation by excreted mucilaginous products are responsible for binding aggregates by soil micro-organisms activities. Dominantly, polysaccharides, hemicelluloses or uronides, levans, and numerous other natural polymers are the microbial products that are capable of binding soil aggregates. Through some mechanisms and forces, such as cation bridges, hydrogen bonding, van der Waals forces, and anion adsorption mechanisms, microbial products are attached to clay surfaces.

Polysaccharides are capable of forming multiple bonds with several particles at once due to their large, linear, and flexible molecules. In some other cases, organic polymers hardly be able to penetrate between the clay particles, however, they can form a protective capsule around soil aggregates. In other situations, natural polymers penetrate soil aggregates in the shape of solutions of active organic agents. Then they precipitate as insoluble, however, biologically decomposable cements. In summary, natural polymers, such as polysaccharides and polyuronides improve aggregate solidity by gluing particles together within aggregates as well as by coating aggregate surfaces. The gel-like glues undergo irreversible dehydration when the soil dries, then they become like stable cementing agents that bind soil particles (Hillel, 1980).

Accordingly, natural organic substances can be applied to degraded soils (due to intensive cultivation by ploughing and the removal of plant biomass during harvesting) as conditioners to improve soil structure, increase the SOM content, and subsequently enhance SWR and soil fertility. Agricultural technical practices and environmental changes alter the content and turnover of SOC. The initially physically protected carbon in soil can be biodegraded by intensive cultivation practices, and consequently, it could be responsible for the loss of SOC.

Restoration of the soil organic matter (SOM) content of degraded soils can boost soil water retention (SWR) and agronomic drought tolerance especially more at field capacity (FC) than that at the permanent wilting point (PWP), and consequently, enhance the plant available water capacity (PAWC; Lal, 2020; Seyedsadr et al., 2021). The impact of SOM content on PAWC depends on a range of internal and external factors. Among all, soil properties, texture (sand, silt, and clay content); soil structure/aggregation and stability of aggregates along with pore size distribution; soil permeability and of course, the SOM content and composition of its fractions, have key roles. Therefore, SOM loss in the soil alters soil physioco-chemical properties of the soil, which are critical for microorganisms, plant species and all beings to survive.

2.2. Key soil properties affected by soil organic matter

2.2.1. Chemical properties

pH is valuable and is a key factor because it affects the wide range of soil chemical and biological processes, including solubility, concentration in soil solution, ionic form, microbial mobility, and activity as well as nutrient availability for plant growth (Devkota et al., 2022; Naorem et al., 2021; Horrocks and Vallentine, 1999; Fageria and Nascente, 2014; Gatiboni, 2018).

In regions with continuous water percolation through the soil profile, Ca, Mg, and other basic cations is removing and replacing with hydrogen (H) ions, which causes soil acidity (Horrocks and Vallentine, 1999). Addition of organic matter (OM), mature wheat straw, to acid sulphate soils minimises acidification during dry periods. OM must be added annually for sustained amelioration of acid soil in the field. Organic matter increases the pH of the soil that improves plant growth. In long run, plants would act as organic carbon sources, which then could reduce the need for organic matter amendments (Jayalath et al., 2016).

The negative charge of a soil is known as the cation exchange capacity (CEC). Soils with high clay, silt, or organic matter content have a CEC number of 10 (meq/100g) or greater. However, water moving through these soil profile (which tends not to hold anions) with excess fertilizer utilization, causes negatively charged nutrients, such as chloride, nitrate, and sulfate to be leached out of the root zone. This can be leaded to contamination of groundwater, streams, and lakes or have other environmental implications. Sandy soils, on the other hand, have a lower CEC number (between 1 and 5 meq/100g), that adding organic matter to these soils can help increase the CEC (Gatiboni, 2018). Soil minerals and humus bound with the majority of metals, which are unavailable to plants. However, active organic matter increases CEC in soils, and the solubility of nutrients in soil solution, therefore, enhance nutrient availability to plants (Zeng et al., 2011).

Soil, which is the major source of nutrients needed for plants (6% of a plant's weight), contains the three main nutrients (primary macronutrients), nitrogen (N), phosphorus (P) and potassium (K), (SSL, 1992; Gatiboni, 2018). Nitrogen is a key element and a limiting factor in plant growth. Organic matters (e.g., composted manure) is a natural source of nitrogen in a soil that the leaching of nitrate can be reduced by their presents (Gatiboni, 2018). For instance, the mineralization of straw organic matter releases nutrients for crop growth and increases soil nitrogen (N), phosphorus (P), and potassium (K) contents (Huang et al., 2021). By providing the second major nutrient (P), OM improves the energy transfer from sunlight to plants, it increases early root and plant growth, and accelerates maturity. All kind of manures contain phosphorus especially those from grain-fed animals (Gatiboni, 2018; Huang et al., 2021).

An element must be in a chemical form used by the plant and dissolved in the soil water to be absorbable by plants. Carbon dioxide, which released after OM decomposition in soil, is dissolved by water in soil to form a weak acid. This solution reacts with soil minerals to release plant available nutrients. The chemical structures of soil organic matter released by microbial decomposition are the ones that are absorbable chemical groups (Gatiboni, 2018).

It is noted that a sufficient soil moisture to support the microbiota involved in nitrogen cycling, and decomposition (nutrient release), is crucial. Further soil moisture supports are to mineralization of organic matter, and root symbionts that are involved in nutrient uptake (Whitford and Duval, 2020).

2.2.2. Soil physical properties

2.2.2.1. Particle Size Distribution (PSD)

The static properties of the soil solid phase include texture, particle size distribution, and specific surface, all are typically permanent characteristics of the soil material having a role on soil behaviour (Hillel, 1980). Soil particle compositions, which indirectly affect soil moisture characteristics, fertility, etc., are determined by soil particle size distribution (PSD). Therefore, PSD is an important index for the quantitatively evaluation of different soil compositions (Fig. 4) and to predict physical properties such as water retention, bulk density, permeability, and porosity (Deng et al., 2017; Qi et al., 2018). The basic units of soil structure are the soil aggregates of different particle size fractions, which are affected by soil substrate, organic matter and fertilizer addition, land use, and tillage (Zou et al., 2023).

It is suggested that soil texture affects both the decomposition of litter (organic matter formation) and the retention of litter-derived C in a soil. The soils rich in clay provide favourable conditions for a more effective microbial utilization of the litter material as compared to the sandy soil. Also, higher amounts of litter C retains in the clay-rich soils vs. sand-rich soils, thus, soil organic carbon contents generally increase with increasing clay and silt content (Angst et al., 2021; Li et al. 2022). Studies emphasized that litter decomposition, the formation of SOM, and soil texture are tightly associated, therefore, litter decomposition and SOM formation patterns are changed by any changes in soil texture for the same litter (Angst et al., 2021).

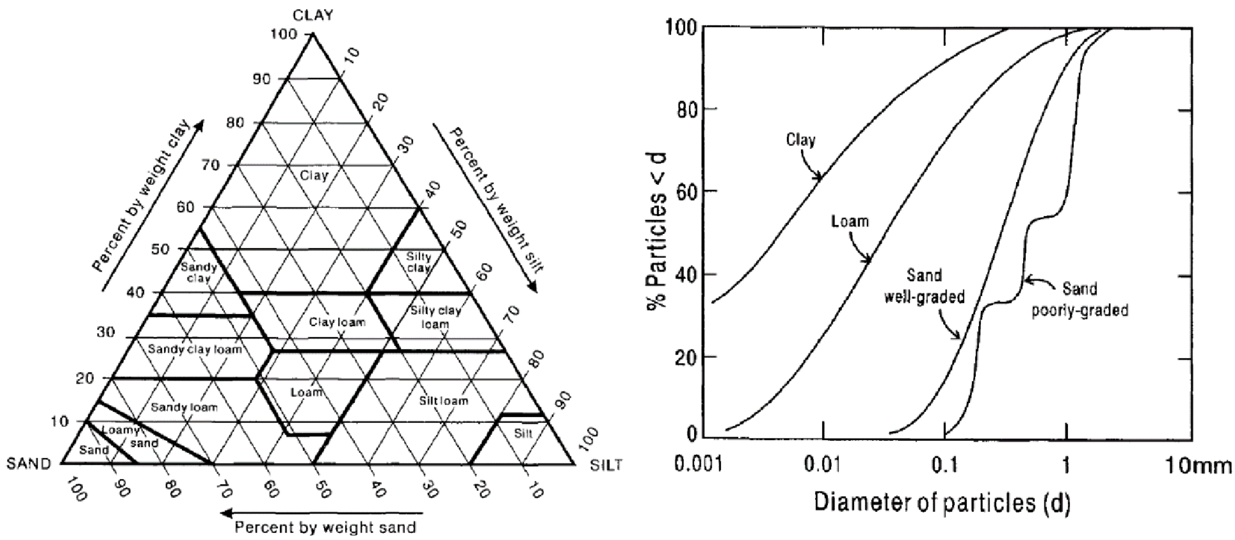

Fig. 4. Left) The conventional textural triangle to classify the soils regarding their texture. Right) various soil material particle size distribution curves (Hillel, 1980)

2.2.2.2. Soil structure, aggregate formation processes, Bulk density (ρ) and Soil Porosity

The arrangement of the particles in the soil is called soil structure (Fig. 5; Hillel, 1980). Soil structure is responsible for the content and transmission of both air and water in the soil. Therefore, any damage to the soil structure is a critical issue. Soil structure is strongly vulnerable to destructive mechanical and physicochemical forces, easily affected by changes in climate, OM content, biological activity, and soil management practices (Hillel, 1980).

In the clay soils (> 15% clay), the mineral particles (sand, silt, and clay) tend to create structured units known as aggregates. Aggregated soil structure is the most desirable condition for plant growth. The formation process of aggregates usually occurs when soils dry and swell (due to e.g., root water uptake) but also occurs because of biological (soil faunal activity and plant root growth; Qiu et al., 2023), and microbial activities (Hillel, 1980; Horn et al., 1994) due to higher OM content compared to sandy soils. Consequently, the inter-aggregate pore system in structured soils also differs due to pore diameter, continuity, and number. Particle rearrangement occurs during consecutive swelling and drying, which depends on the degree of soil wetness. Therefore, aggregate bulk density may decline but the aggregate strength increases at the same moment (Horn et al., 1994).

The soil macropores (several millimetres to several centimetres wide) are mostly the interaggregate voids, which are mainly responsible for the infiltration, drainage of water and aeration. The micropores or the intra-aggregate capillaries are responsible for the retention of water and solutes. Water retained in micropores is sometimes referred to as "residual" water, which is often discontinuous and does not participate in usual liquid flow phenomena. In addition to micro- and macropores, capillary pores (in width from several micrometres to a few millimetres) are the typical pores in a medium-textured soil. Unlike the water flow in micropores, water permeating in capillary pores obeys the capillarity and Darcy laws (Hillel, 1980).

The reason of aggregate strength can be assumed to be due to increased viscosity and surface tension forces, which depends on capillary forces, intensity of shrinkage, number of swelling and shrinkage cycles (repetition), mineral particle mobility, bonding energy between particles in/or between aggregates, biological/ microbial activities, as well as chemical composition of the soil solution and of the organic components (Horn et al., 1994). Therefore, aggregate stability can be improved by the organic matter presence due to decreasing the wettability or hydration effects of soil aggregates by water (Ekwue, 1989). Having a long run of aggregates stability depends on remaining of soil organic matter (SOM) which attaches soil mineral particles together, also on avoiding compaction by heavy machinery, and erosion mostly by water following, and falling raindrops (Hillel, 1980; Juriga and Šimanský, 2018). Humic substances (part of SOM) control formation and stabilization of water stable aggregates. Therefore, soil organic matter plays an important role in controlling soil quality and structural strength because of its key role in determining a wide range of soil properties (Juriga and Šimanský, 2018).

The structure of either single-grained or aggregated soils can be quantitatively considered in terms of the total porosity and the pore size distribution. A soil that having a porosity lower than bulk density, that soil has been under influence of for example compaction, which further can be modified by organic matter addition. Bulk density is generally measured by extracting undisturbed samples using known volume sample rings from various depths in the soil profile. It is calculated through the weight of dry soil mass divided by the total volume of the given soil (Hillel, 1980; Arora, 2008; Hopmans, 2011)

Soil structural conditions make the soil bulk density varies. Sand content reported as the most effective soil property that affected bulk density in soils after clay, silt, and organic matter content (Aşkin and Özdemir 2003; Chaudhari et al., 2013). In general, bulk density increases with soil profile depth, due to changes in organic matter content, porosity, and compaction. Capillary porosity, and noncapillary porosity reflect the soil porosity, which its changes may affect soil water pathways and therefore it is closely tied to soil infiltration capacities (Qiu et al., 2023).

Findings of studies (Chaudhari et al., 2013; Celik et al., 2010) show that normally when organic matter increases, the bulk density decreases, and porosity of soil increases. Bulk density decrease is resulted from dilution of the soil matrix with the less dense organic material (Minasny and Mcbratney, 2017). Swelling effects that can occur in soils with high ability of large amount of water absorption (Stell et al., 2019), can also lowered the bulk density level (Jacka et al., 2018). Therefore, in a soil amended by organic matter, which increases the water absorption of a soil, bulk density may decrease upon swelling, and shrinkage may alleviate due to higher water retention.

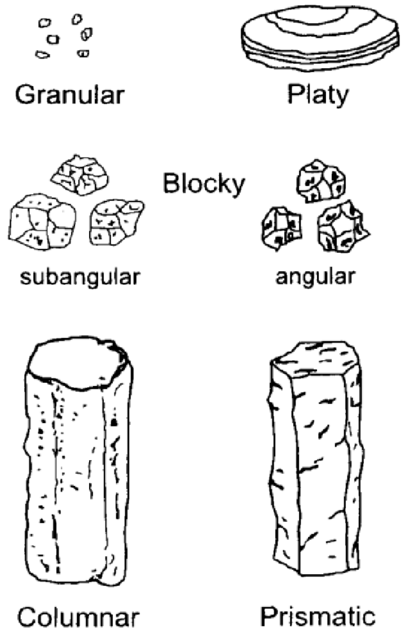

Fig. 5. Different forms of soil aggregation (Hillel, 1980)

2.2.2.3. Water movement in soil

The role of the stable aggregates at the surface is vital in the infiltration process to be able to infiltrate as much water as possible. Moreover, the process of infiltration is a necessary step in runoff generation, water distribution, and nutrient transport in the soil or watershed and soil water storage (Hatfield et al., 2018; Qiu et al., 2023). In a field, there are natural preferential paths such as cracks, worm holes, and root channels that may affect water flow in soil differently, depending on the direction and condition of the flow process (Hillel, 1980). On the other hand, vegetation restoration, decline in soil moisture and bulk density, increase in the total porosity, macroporosity and soil organic matter can cause higher soil infiltrability and preferential flow (Franklin et al., 2021; Qiu et al., 2023).

Among these factors in the Qiu et al., (2023) study, soil moisture and total porosity were the dominant factors affecting soil infiltrability, while macroporosity was the greatest contributor to variations in preferential flow. Preferential flow could contribute approximately 11 % – 94 % of the total infiltration, although it accounts for a limited proportion of the total soil volume. Thus, the existence of preferential flow path speeds up the deep water percolation into the soil, which means higher infiltration rate. Therefore, addition of organic matter to soils can boost both the activities of roots and soil fauna and further it promotes the soil structure improvement and soil permeability due to water aggregates and macroporosity formation (Qiu et al., 2023).

The hydraulic conductivity of a saturated soil often may change over time due to various chemical, physical, and biological processes as water permeates the soil and flows through. Other changes like shifts occurring in the composition of the exchangeable-ion complex or concentration of solutes from the original soil solution can significantly influence the structural stability and hydraulic conductivity (Hillel, 1980; Zhu et al., 2019). Changes (decay or addition) of organic matter in soil through time also can have influences on temporal hydraulic conductivity changes by breakdown or improve the soil aggregate and the aggregate stability due to altering the van der Waals attractive force and short-range bonding interactions between particles in soil aggregates (Li et al., 2022).

The greater organic matter content in the soil is often result in higher saturated hydraulic conductivity (Ks). An assumption for this effect is that better soil aggregation is linked to greater OM content, lower bulk density and greater porosity, which all supposed to lead to greater hydraulic conductivity. Greater organic matter can also have negative relation to Ks, by their ability of retaining water and therefore, allowing less water to flow freely (Nemes et al., 2005).

An investigation on a sandy loam soil with originally 2.3% organic matter content were done with the purpose of determination of OM influences on saturated hydraulic conductivity (SHC). OM rates of 1%, 2%, 4% and 8% on the dry basis of walnut sawdust, earthworm manure and farmyard manure mixture were mixed to the sandy loam soil. In general, a reduction of the hydraulic conductivity resulted from all treatments, which applied in 8% to the sandy soil. It was with farmyard manure application that the highest decrease in hydraulic conductivity was obtained (Demir and Doğan Demir, 2019).

2.2.2.4. Soil Water Retention

Soil water retention is the amount of water the soil can retain but it is effective when that amount can be available and affects plant growth and have impact on crop productivity. High crop productivity is when high water efficiency used, and that is denoted as plant available water (Hatfield et al., 2018). In literature, soil particle size distribution, soil organic matter and soil bulk density introduced as the most dominant factors that affect soil water retention (Yang et al., 2014). Existence of organic matter in soil can have several effects regarding water retention due to OM characters. For instance, with OM presents, water at saturation level, and water field capacity can be increased by larger pores formation (Fig. 6 showing the pore diameters associates to water retention; Eden et al., 2017). Since the amount of water retained at low suction pressure (0 and 100 kPa/1 bar) depends mainly on the capillary effect and the pore-size distribution, the soil structure is the main effective parameter in this suction range (Hillel, 1980).

water retention is due increasingly to adsorption at higher suctions, so the influence of the structure is less and negligible, and more affected by the texture and specific surface of the soil. Therefore, at this range the effect of OM would be limited (Saxton and Rawls, 2006) except for those with high surface area. Thus, at the lower limit of moisture availability to plants (wilting point / -15000 hpa) is quite well correlated with the surface area of a soil (Hillel, 1980). Accordingly, because of relatively large surface area of some OM more water can retain by their presence possibly even at higher suction pressure close to wilting point (Eden et al., 2017).

Similarly, Yang et al., (2014) introduced two mechanisms for explaining the influence of OM on water retention by investigating different soils in the cold alpine region. It was suggested that at higher matric potentials, soil organic matter affects soil water retention mainly by altering bulk density. However, a direct influence of soil organic matter functions at lower matric potentials was explained by increasing soil adsorbing capacity and therefore, retaining more water.

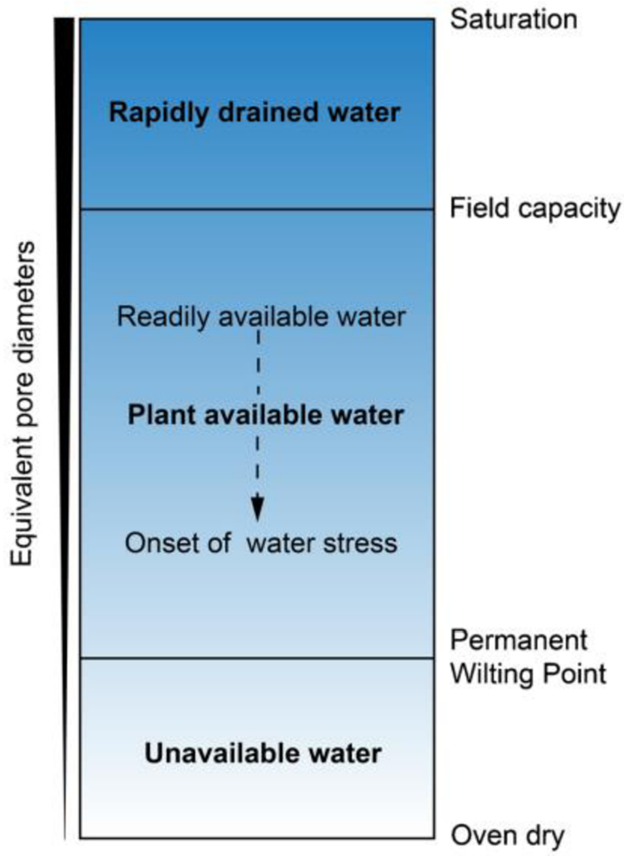

Fig. 6 Schematic correlation between pore diameters and water retention at different suction pressure (Eden et al., 2017).

Also, hydrophilic / hydrophobic character of an OM also indicates the changes of water retention in soil (Eden et al., 2017). Sandy soils may contain more hydrophobic alkyl compounds compared to clay soils. Therefore, hydrogel (a synthetic soil moisture retention additive) and other organic substances are used as soil conditioners to increase soil water retention as they contain hydrophilic compounds. Some hydrophobic organic substances can also enhance aggregate stability, such as stearic acid (Lal, 2020).

Organic Matter increases plant available water capacity via increasing organic carbon. In Several long-term field experiments it is found that total water holding capacity or total porosity was larger in organically amended soils than in unamended soils (Eden et al., 2017). Therefore, the shape of the soil-moisture characteristic curve depends on soil texture. Soils with more clay content, in general, retain a greater amount of water at any particular suction, and shows a gradual slope (Fig. 7; Left). This is explained by this fact that the pore-size distribution in a clayey soil is more uniform, and more of the water is adsorbed (Hillel, 1980).

Adding OM to degraded soils can help relieve several soil property problems common in different soils, simultaneously and improve the soil water holding capacity in some cases (Somerville et al., 2019; Dai et al., 2020). Since sand, unlike clay, has an inherently low OM and water holding capacity, it has been shown that the water holding capacity of sand was increased with OM additions (Somerville et al., 2019). Consequently, OM addition can change the sandy soil-moisture characteristic curve and can move it more towards clay soil curve, meaning higher water holding capacity at different pressure head. However, adding OM to clay can increase macro-porosity and therefore modify the drainage or infiltration of the soil (Somerville et al., 2019; Qiu et al., 2023). Moreover, a meta-analysis study stated that an increase in SOM content is more in sandy and loam soils but decreases in clay soils (Lal, 2020).

Total soil water holding capacity improvement by adding OM is not always lead to plant available water improvement, while water availability depends on the soil tension. Thus, plant roots may not be able to uptake soil water that held at more negative, or high tensions, close to a permanent wilting point (15 bar), (Somerville et al., 2019). It is also mentioned (Minasny and Mcbratney 2017) that increased aggregation can decrease the micropore volume, therefore, increased aggregation does not necessarily turn into an increase in PAWC.

Variable results such as positive, negative, or no changes have been found in different studies with different soils after SOM enrichment. For instance, by adding a higher rate of OM, a lower increase of plant available water can be seen in some soils, where enrichment of SOM content has a more positive effect on soil water retention at FC than at the Plant Wilting Point (PWP). Although in such cases, PAWC increased when OM increased (Fig. 7a. Left; Lal, 2020). However, there are some soils in which the effects of SOM content are similar both at FC and at PWP (Fig. 7b. Left). In such cases, an increase in OM to soil may have no effect on plant AWC. Increasing of OM rate in light-textured soils can have more favorable effects at field capacity than in heavy-textured (Fig. 7b. Right). Such a negative response to the SOM increase has been seen in peat soils (Lal, 2020).

Therefore, Lal (2020) introduced texture, SOM content, and a specific fraction (i.e., hydrophilic or hydrophobic, polysaccharides, and uronic acids), land use history, in-field biomass burning, type of soil amendment, etc., as the important determinants to OM rate response.

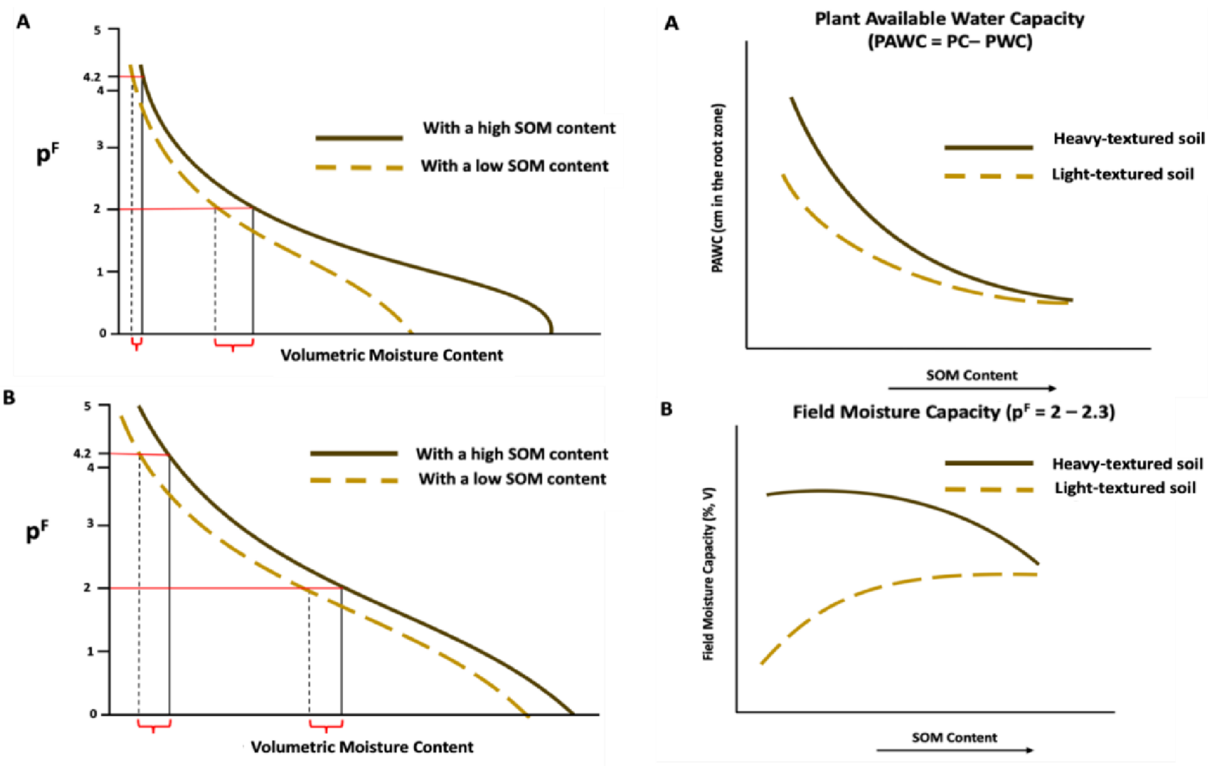

Fig. 7. A schematic of pF curve in soils, showing different cases of OM application responses (Lal, 2020)

Furthermore, it is expected that compaction, which destroys the aggregated structure, is to reduce the total porosity, especially the volume of the large interaggregate pores. Therefore, compaction may cause a reduction in the saturation water content, and the initial decrease of water content with the application of low suction. In such disturbed soils, because of the possible squeeze of originally large pores into intermediate size by compaction, the volume of intermediate-size pores is likely to be somewhat greater, however, as figure 8 (right) shows the micropores remain unaffected (Hillel, 1980). A Proctor Compaction Test on three soils, sandy soil, a silt loam, and clay soil, revealed that OM is most effective to improve compaction when applied to soils with a high propensity for compaction. However, the structure recovery of compacted soils was not improved. The study showed that penetration resistance after compaction is not consistently related to the utilized OM (Zhang et al., 1997).

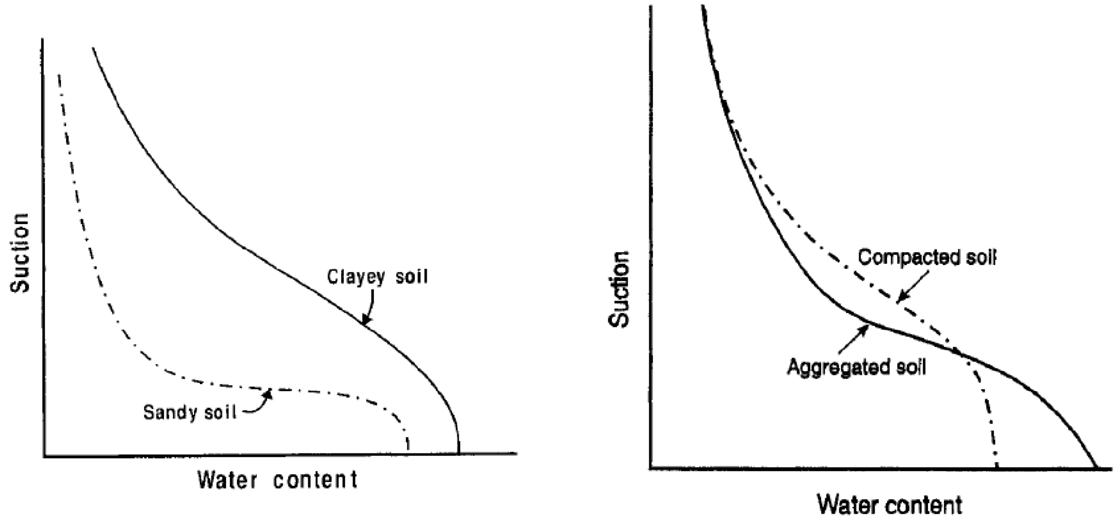

Fig 8. The effect of texture (Left) and structure (right) on soil water retention (Hillel, 1980).

2.3. Amendments to enhance Soil water retention

Organic and inorganic amendments have a wide range of soil utilization purposes due to their properties. They can be applied into degraded soils to improve soil structure and porosity and therefore, to enhance water-holding capacity. Amendments via direct or indirect mechanisms, either by feeding microorganisms (aggregation formation agents) or their high surface area can increase optimal water that plants need at the range of field capacity to wilting point (plant available water content) and/or to retain water longer in the soil. Besides, amendments as soil conditioners can also either retain more nutrients for plants or be produced as nutrient-rich products. Some more, on the other hand, can modify the infiltration in poorly drained soils.

In the following sections some amendments, their effects on physical / chemical soil properties (summarized in table 1), as well as some of their advantages and possible limiting factors (further in 2.5 section, table 2) are introduced.

Table 1. A summary of some recent studies on soil inorganic and organic amendments

Soil	(In)organic amendments	Rates	The effect	References
Silty loam	Zeolite	5 t ha^{-1}, 30 kg ha^{-1} K, 60 kg ha^{-1} K	increased water use efficiency under stress, mitigated the reductions in grain yield, Soil K fixation, reduced K leaching losses	Li et al. (2022)
clay loam	Zeolite	15 t ha^{-1}	mitigated N_2O emissions, increased rice grain yield	Liu et al. (2022)
Perlite	Zeolite+ hydrogel	1%, 2%	reduce the required irrigation water, boosted cucumber production	Gholamhosseini et al. (2018)
Sandy	Hydrogel	0.1 g	positive effect on the growth of plants, improvement the water absorbing and retention capacity of the soil	Liu et al. (2021)
____	Hydrogel	0, 4.2, 6 g	N and P leaching loss, increased of porosity, and soil moisture, decreased of temperature	Zhao et al. (2022)
loam	Hydrogel	0.15 g + 110 ml distilled water	reduces moisture loss, effective irrigation	Dehkordi and Shamsnia, (2020)
Sandy	Hydrogel	1%, 0.75%, 0.50%, 0.25% w/w	the water holding capacity of soil was increased with the concentration of hydrogel	Relleve et al. (2020)
Calcic Cambisols	Hydrogel	1% w/w	decrease in pH under water deficit, reduced the amount of Actinobacteria, Bacteroidetes and increase the amount of Firmicutes	Wang et al. (2019)
Sandy	Hydrogel	0, 0.08%, 0.2%, 0.5% and 1% w/w	the water holding capacity of soil was increased with the concentration of hydrogel, decreases the saturated hydraulic conductivity	Zhuang et al. (2013)
silt, loam, clay, sand	Manure	10 t ha-1 dry matter	reduced bulk density, improved soil water retention, plant available water and Water Stable Aggregates	Fu et al. (2022)
Agricultural soil	Manure	0, 10 and 20 t ha^{-1}	regulating soil temperature, moderating crop ET and increasing okra water use efficiency	Busari et al. (2022)
clay	Pig Manure	___	increased the SOM content and aggregation	Lin et al. (2019)
acid loamy clay	Pig Manure	0; low manure with 150 kg N ha^{-1} y^{-1}; high	provided a large quantity of Phosphorus, with lime	Tao et al. (2021)

		manure with 600 kg N ha^{-1} y^{-1}; high manure with 600 kg N ha^{-1} y^{-1} and lime applied at 3000 kg Ca $(OH)^2$ ha^{-1} $3y^{-1}$	significantly mitigated soil acidification	
loamy sand	cattle manure	0; first year:37.5 Mg ha-1; 12.5 Mg h^{-1} y^{-1}	improved soil water retention and soil structural stability at low oreseare head	Nyamangara et al., (2001)
clay	co-composted biochar	25 t h^{-1}	Improved soil water retention and nutrient uptake by plants, and lowered N_2O emissions over time, Increased SOC, available P, Ca and CEC	Agegnehu et al. (2016a)
clay	co-composted biochar	10 t h^{-1}	Improved soil moisture retention, Increased SOC by 34% and CEC by 24%, and improved soil fertility	Agegnehu et al. (2016b)
clay	co-composted biochar	25 t h^{-1}	Enhanced soil water content and reduced N_2O emissions	Bass et al. (2016)
Silt loam & fine sand	Biochar	10 t h^{-1} (0.5% wt.)	Biochar improved soil nutrient content, water retention and reduced N_2O emissions. significantly reduced banana yield performance and did not affect papaya yield.	Wang et al. (2019)
Grey desert soil	biochar-based fertilizers	3g of CSRFs per 200g of pepper seeds	Leaching loss of P reduced, Promoted pepper seedling growth (root length, fresh weight and dry Weight, height)	An et al. (2020)
Oxisols	biochar-based fertilizers	Equivalence of 240 mg kg^{-1} of P	Increase soil P content, increase in crop yields Better plant P uptake	Carneiro et al. (2021)

2.3.1. Inorganic amendments

"Krilium," was the first soil conditioner that was introduced commercially, a hydrolyzed polyacrylonitrile (HPAN), and a copolymer of vinyl acetate and maleic acid (VAMA). Later, some more products were offered commercially including polyvinyl acetate (PVAc), polyvinyl alcohol (PVA), polyacrylic acid (PAA), and polyacrylamide (PAM). Conditioners attributes differently and can be applied in various situations with different techniques. Some of them could be applied in water-soluble form or some more in an emulsifiable form; some act as polyanions, or polycations, and others as nonionic binders (Hillel, 1980).

The activity of soil-conditioning polymers depends on their active groups (e.g., carboxyl amide or sulfonic groups, acrylamide, acrylic acid, acrylate, etc), (Hillel, 1980; Santos and Silva, 2019), which present per unit mass of the polymer. Their effectiveness is associated to the molecular weight or polymer chain length (Hillel, 1980). They can absorb a large amount of water and chemical solutions via their hydrophilic functional groups in their three-dimensional structure (Nascimento et al., 2022). When these polymers, with the acid groups attached to their main chain, are put in water, the water enters the hydrogel system by osmosis. This cause hydrogen atoms to react and to come out as positive ions. Hence the hydrogel now has several negative charges along its length repelling each other. Therefore, they attract water molecules and attach them to hydrogen bonding (Fig. 9; Santos and Silva, 2019), Water then fills the space between polymers macromolecules. Such structures in an equilibrium can contain plenty of water, which depends on the polymers' characteristics and on the nature and density of the joints in their network (Ahmed et al., 2015).

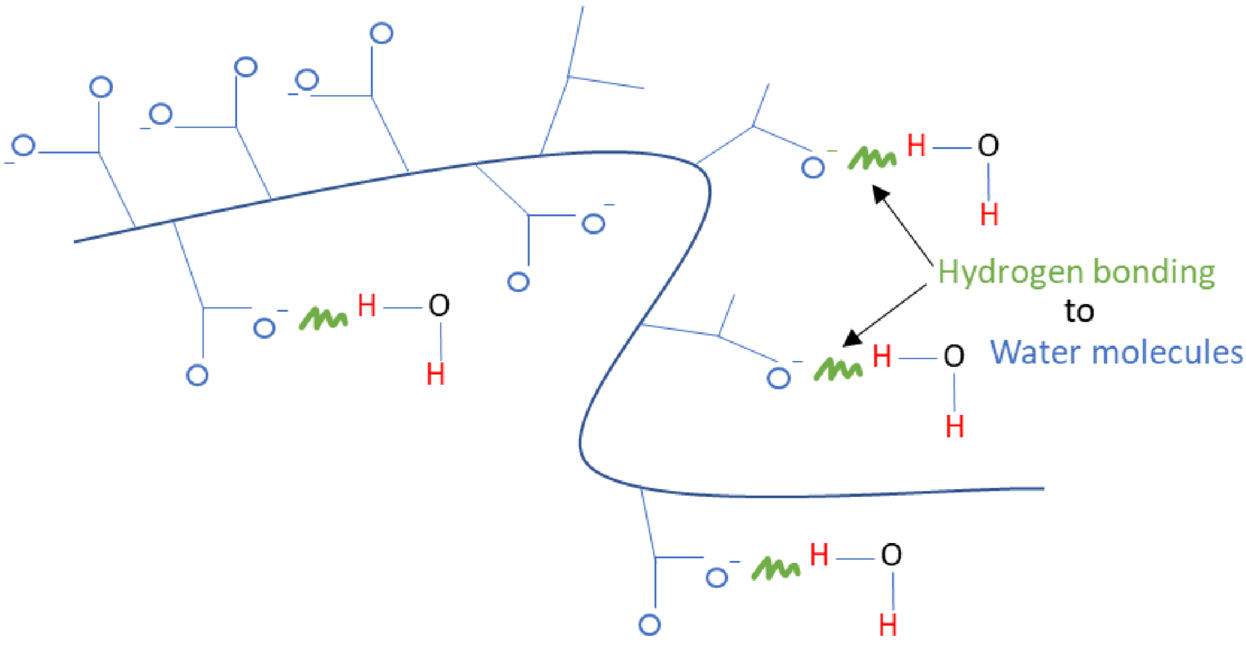

Fig 9. The mechanism of water absorption in a hydrogel polymer (modified from Santos and Silva, 2019)

Synthetic compounds have been produced being capable of duplicating the effect of natural polymers. In degraded soils that natural aggregation or aggregate stability is lacking, such synthetic polymers (so-called conditioners; Hillel, 1980) can artificially formed stabilized aggregates.

Their application is effective in relatively small quantities (e.g., 0.1% of the treated soil mass). Even the small amount can produce a dramatic improvement of soil structure (Table 1), with consequent beneficial impacts e.g., on infiltration, aeration, and the prevention of crusting and erosion.

Synthetic water retaining agent, which is a super absorbent resin and polymer with special ultrahigh macromolecular structure and plenty of hydrophilic groups, have a capacity to retain water about many hundred times higher than its own dry weight. Their favourable characteristics are high gel content, swelling capacity, fast swelling, and good mechanical strength of the swollen gel. They modify soil structure through bonding with soil particles and swelling (Geesing and Schmidhalter, 2004; Zhuang et al., 2013; Relleve et al., 2020; Dehkordi and Shamsnia, 2020). If the super water absorbent (SWA) product be 100% polyacrylate based, therefore it wouldn't be biodegradable, which is a very important property to protect the environment (Relleve et al., 2020).

Advantageous of superabsorbent polymers (SAP) are that they are energy-saving soil conditioners due to the reduced time required for watering plants and causes more effective irrigation, because of its high water-retention and moisture absorption abilities (Table 2). Moreover, it increases the growth and rooting of plants and therefore, improves their yield. SAP is used in the field of agriculture and forestry regarding its ability to retain organic matters in the soil and can be adapted to an environment characterized by irregular wet and dry conditions (Dehkordi and Shamsnia, 2020). Dehkordi and Shamsnia, (2020) concluded that by applying hydrogel to loamy soil, the moisture needed for irrigation may reduce by 10–30%.

An experiment on a sandy soil showed that after the application of crosslinked polyacrylamide (0.03% and 0.07%) the moisture capacity at the water suction of 0.01 MPa was increased (23% and 95% respectively) in comparison with the control. Besides, in another case study, the application of three kinds of polymers (polyacrylic acid, polyvinyl alcohol, urea formaldehyde resin) were tested for soil water-stable aggregates and water holding capacity. Polymers made soil water-stable aggregate content increased by 17% averagely and density decreased by 11%, and soil water holding capacity increased 2.8 times compared to control (Zhuang et al., 2013).

In some more articles reported by Zhuang et al., (2013), it is found that the application of polymer into soil could enhance the bonding force between particles, which can form larger aggregate structures, especially the aggregate ratio of particles larger than 1 mm. An experiment under a constant water head, showed a reduction in the saturated hydraulic conductivity and infiltration rate after the application of polymer.

The application of sodium polyacrylate in a sandy soil can increase the water holding capacity (positive corelation with application rate) under different water potentials, including the maximum capillary water content (the wilting point). This hydrogel significantly decreases the saturated hydraulic conductivity, the migration velocity of water to the deep layer, and the infiltration rate of sandy soil. Application of 1% hydrogel causes an extremely low infiltration, which hinders infiltration of water into soil, therefore, the amount of 1% is too high, and not desired to be applied. The amount of hydrogel that can be applied in sandy soils is suggested to be at 0.2%-0.5% rate. In order not to have a high rate of evaporation from the soil surface, it is recommended to apply hydrogel in a proper depth around the root zone under the soil surface (Zhuang et al., 2013).

Zeolites are crystalline, microporous hydrated alkaline aluminosilicate minerals. They have three-dimensional crystal structures. Zeolites are characterized to have the ability to lose and gain water reversibly. They are able to exchange their elements without any major changes to their structure (Gholamhosseini et al., 2018). It has been used for water and fertilizer-efficient agricultural management (as a soil conditioner) because of its potential functionalities like its high nutrient adsorption and drought resistance properties. Accordingly, zeolite can absorb more than 60% of its water weight to provide long-term moisture availability during dry periods, alleviating the undesirable effect of water stress on plants. Zeolite can retain K nutrients in the root zone for plant uptake (suited for e.g., rice) when required (Li et al., 2022).

Studies have shown that zeolite applied as a soil conditioner increases rice yield and reduces irrigation, ammonia volatilization, and N leaching in paddy fields. Zeolite also helps reduce soil drought stress by increasing the water permeability in soils. As a result, the gas production, transport, and diffusion in the soil profile also can be affected (Liu et al., 2022).

With a 2% zeolite-hydrogel application in Perlite the maximum cucumber yield can be obtained even under low water availability conditions. In general, the application of zeolite and hydrogel could reduce the required irrigation water, especially at partial root-zone drying compared to full irrigation and deficit irrigation without any dangerous effect on cucumber physiological qualities (Gholamhosseini et al., 2018).

2.3.2. Natural (organic) amendments

Natural conditioners due to their renewability, availability with reasonable cost, biocompatibility, and biodegradability are known as good candidates. Among them, polysaccharides (e.g., starch), carrageenan (an extract from a red seaweed commonly known as Irish Moss; Reinagel, 2015), cellulose derivatives, etc. are rather well known. Starch is one of the most abundant substances in nature, which is produced from grain or root crops.

Cassava is one of the main agricultural crops in the Philippines that about 20 % of this production is utilized for starch processing. Relleve et al, (2020) investigated a radiation technology, which is environment-friendly technology with broad applications in ecological agriculture and industry to modify polysaccharides, kappa-carrageenan, and cassava to be used as soil water retainers.

For this purpose, different super water absorbents were prepared from different polysaccharides and acrylic acid. Important outcomes of the study through synthesis include providing effective gelatinization of polysaccharide with alkali method, a partial neutralization of acrylic acid which creates an osmotic force for swelling, the improvement of biodegradability of polyacrylate-based-SWA with the incorporation of starch, production of cassava starch-based SWA as a promising SWA material for agriculture due to its biodegradability, gel properties, and low cost (Relleve et al., 2020).

The natural soil amendments used in agriculture, were introduced by Garbowski et al. (2023) in three categories as organic (livestock manures, compost, plant residues, slaughterhouse wastes, sewage sludge, biochar), organic-mineral, and mineral (volcanic rocks, gypsum, clay minerals, lime, eggshells) amendments.

Soils from Sweden (silty clay, SiC), Germany (silt loam, SiL) and Denmark (sandy loam, SL) were used for a long-term experiment treated with cattle manure (Table 1). Water retention, air permeability, and gas diffusivity were measured at five suction pressure (-3, -5, -10, -30 and -50 kPa), along with saturated hydraulic conductivity (Ksat), bulk density (ρb), and water-stable aggregates (WSA). Results showed bulk density reduction by an average of 3–6 % for all sites. soil water retention, plant available water and WSA for most investigated plots were improved. There was no further improvement by the higher dose of manure for the SiL and SL sites. The results varied depending on soil and crop type regarding the effect of manure on soil pore size distribution, gas transport, and Ksat. The porosity of pores lower than 30 μm in the two fine-textured sites increased after manure addition and the porosity of pores over 30 μm increased for wheat and maize plots in the SL site (Fu et al., 2022).
The same article states that manure application is one of the common agricultural practices to increase soil organic carbon (Fu et al., 2022). According to studies, poultry manure improved the soil's physical, chemical, and biological fertility. Therefore, the benefit of poultry manure (PM) is that it has the potential of holding water tightly in the soil even at higher suction pressures. Along with their high-water retention capacity, organic manures are good sources of macro and micronutrients that are important for optimal plant growth. Compared with mineral fertilizers, nutrients in PM are released more slowly and therefore can be resulted in good crop development and higher yields due to a higher nutrient recovery rate (Busari et al., 2022).

In a study by Busari et al., (2022) soil temperature, crop evapotranspiration (ET), and water use efficiency in an agricultural soil treated with 0, 10, and 20 t ha-1 of manure were measured. Besides using manure alone, a combined manure application with mulching (M) reduced water loss via evapotranspiration more efficiently. The joint application of 20 t ha-1 PM and M significantly reduced soil temperature at 5 cm and 10 cm soil depth. Therefore, the results indicated that M together with the application of PM is an effective strategy for regulating soil temperature, moderating ET, and increasing okra water use efficiency, especially during dry seasons (Busari et al., 2022).

Since it takes years to detect the change in SOC, a long-term pig manure application boosts the clay soil quality and crop yield by increasing the mass proportion of macro aggregates. 27 years of pig manure application indicated that SOM soil content and aggregation increased more effectively than plant residues or fertilizers (Lin et al., 2019).

Increasing the SOC effectively influences soil structural properties in terms of decreasing bulk density (ρ) and thus increasing water retention by increasing water-stable aggregates (as a binding agent). Changes in water-stable aggregates also affect the soil pore size distribution. Changes in pore structure also alter the saturated hydraulic conductivity (K_{sat}), which depends on the manure application rate. Furthermore, water-stable aggregates contribute to infiltration controlling runoff and erosion, and physically protect soil organic matter (SOM) leading to increased soil C storage. (Wang 2022; Fu et al., 2022)

Furthermore, manure also alters soil pH and electrical conductivity (EC), which both influence microbial activity and soil aggregation (Lin et al., 2019; Fu et al., 2022). By enhancing earthworm activities, manure can increase the macro-porosity in soil, in which the magnitude of changes depends on soil texture (Fu et al., 2022).

Manure long-term application to an acid-loamy clay soil provided a large quantity of Phosphorus (P) in soil colloids, which is one of the most abundant elements in living organisms and a macronutrient required for plant growth to soils within soil colloids. Continuous manure inputs influenced the microbial biomass as well (Tao et al., 2021).

According to a long-term experiment (Nyamangara et al., 2001), cattle manure application to a loamy sand soil, improved soil water retention, and soil structural stability (shows sensitivity to changes in soil organic C) at low suctions. Since manure improves soil macro-porosity, it is responsible for the significantly increased readily available water in the same study. Clay soil texture was not affected by manure application, therefore in this case the texture becomes the key factor at high suctions controlling the volume of small and intra-aggregate pores.

Composted organic yard waste is stable and free of pathogens. It can be beneficially applied to land. During composting in the presence of optimal amounts of air (oxygen) and moisture, organic matter is converted to a humus-like product by microorganisms. The organic matter content of most composted bio-materials is in the 30 to 60 % range, the moisture content in the 30 to 50 % range, and it also contains higher values of N, P, K, and salts than in typical agricultural soils. Accordingly, utilizing composted biosolids, improves soil through the addition of organic matter, nutrients, and beneficial microbes. Besides the rate of compost, the soil type is also a factor. For instance, higher rates of decomposition were observed in silt loam than in clay loam (Kirchhoff et al., 2003).

Compost improves plant growth, controls erosion, stabilizes slopes, and reduces the use of chemical fertilizers and herbicides. It is expected that by application of compost to soils, the chemical and physical properties of the soil change regarding the decomposition of the organic matter. Through these changes, compost-amended soil will be more resistant to runoff and erosion. Therefore, compost application to the soil reduces potential pollution of surface water and groundwater via the transport of N, P, heavy metals, and sediment by limiting the runoff. Compost also increases the pH of acid soils and the soil CEC as a result of the addition of organic matter (Kirchhoff et al., 2003).

The bulk density decreases, and the total porosity increases in the soils, to which organic matter was added. It is known that by having greater porosity more area for gas and water interchange is provided, which is beneficial to plant growth. It is believed that bulk density reduction is attributed to a dilution effect because of mixing organic matter with the denser mineral soil fraction. But it is also suggested that the change in bulk density seems to be more pronounced in coarse soils than in finely textured soils. Both, decrease in bulk and increase in porosity density, led to an increase in water holding capacity in the soil. In both kind of textured (fine and course textured) soils, increases in water holding capacity at field capacity and wilting point were reported (Kirchhoff et al., 2003).

Therefore, compost application also improves soil drought resistance, along with other benefits to soil and plants, e.g., it increases the availability of soil nutrients, increases the favourable microbial population and activities, as well as reduces the frequency of soil nematodes and pathogens. The pH of most composts (composted organic matter) is in the neutral range. Therefore, compost addition may improve the capacity of the soil to immobilize heavy metals by altering soil chemistry, including pH and CEC. In this case, crop yields may increase (Kirchhoff et al., 2003).

2.4. Biochar

Biochar is a solid, dark, carbon-rich, high porosity by-product of thermal decomposition of organic matter/ residual biomass at a temperature between 400 °C and 900 °C under conditions of limited or oxygen deficit. Studies (Abel et al., 2013; Abrol et al., 2016; Cornelissen et al., 2013; Juriga and Šimanský, 2018; Abbas et al., 2019) showed that application of biochar as a conditioner into soil can be a sustainable way of improving physical, chemical, and biological properties to enhance crop production by its ability to increase soil water-holding capacity and plant available water at the root zone, particularly in coarse-textured soils (Philips et al., 2020) and remediate soil pollution (Juriga and Šimanský, 2018).

2.4.1. Biochar production methods and their resultant properties

Characteristics of biochar depend on the feedstock and the conversion technique; thus, it is important to understand the processes and how the parameters can highlight a particular property in the by-product so-called biochar. Biochar with certain properties is desired to meet the specific requirements of each application. In other words, the properties of a biochar production influence the action and function of the biochar. Therefore, the decision-making on the inputs and the thermal conversion method is a crucial step to optimize the utility of biochar effectiveness, as both have effects on biochar properties (Xie et al., 2022; Uday et al., 2022; Amalina et al., 2022).

Amongst countless organic materials utilised for the purpose of soil amendment, different kinds of biochars from different feedstock (biomass, sludge, municipal waste, etc.) pyrolyzed by different techniques (slow/fast pyrolysis, etc) have received much attention within the last c.10 years. Biochar production under none or limited oxygen presence (pyrolysis) results in a value-added material characterised by high porosity (attained by improved carbonization process e.g., Brynda et al., 2020) and a stable carbon core (C). Different thermochemical conversion methods along with various characterization techniques are illustrated in figure 10 with different physical and chemical methods (Uday et al., 2022).

Production techniques in oxygen-limited conditions for producing biochar from various lignocellulosic biomass sources include slow or fast pyrolysis or devolatilization process (Jesudoss et al., 2020; Uday et al., 2022), gasification (Gopinath et al., 2021; Brynda et al., 2020; Grosso et al., 2022; Kong et al., 22), hydrothermal Carbonization HTC (Mbarki et al., 2019; Seyedsadr et al., 2019), Microwave pyrolysis/torrefaction (Ge et al., 2021), and flash carbonization (Li et al., 2020; Amalina et al., 2022; Grosso et al., 2022). Therefore, there is a wide selection of thermochemical technologies, where each technology has its own benefits, and their selection depends on the type of feedstock as inputs, scale, and desired biochar utility Grosso et al., 2022. However, biochar is mostly considered as the secondary product for thermochemical technologies.

The structure and properties of biochar are in association with the conditions of pyrolysis (parameters like temperature (250 to 900°C; Uday et al., 2022 or 300 to 1000; Rabaiai et al., 2022), time, and heating rate; Amalina et al., 2022; Grosso et al., 2022). With increasing temperatures of pyrolysis, the carbon content in biochar increases, while its hydrogen and oxygen contents decrease. Pyrolysis temperature in the range from 400 to 700 °C leads to a higher aromatic and hydrophobic biochar with a higher volume of pores and specific surface area (Juriga and Šimanský, 2018).

There are three categories of pyrolysis that are divided based on the process parameter as slow, moderate, and fast pyrolysis. The final products of the process are bio-oil (liquid), synthetic gas (gas), and biochar (solid) Uday et al., 2022. The temperature range in slow pyrolysis is between 400 to 600 ◦C, the residence time can be several hours to several days, with a low heating rate. Slow pyrolysis, which is primarily used for biochar formation, is considered as the optimal pyrolysis technique since the produced biochar yield is 30–60 %, with a relatively high specific surface (Amalina et al., 2022). However, specific surface area has a wide range depends on feedstock and pyrolysis temperature (Lehmann and Joseph, 2012).
On the contrary, fast pyrolysis is conducted at temperatures between 450 and 600 ◦C, with a higher heating rate of ∼1000 °C s^{-1} (Brewer and Brown, 2012) and a shorter residence time, of only a few seconds. The impacts of heat and mass transfer during this process, along with other factors significantly influence the product yield and process efficiency. A fast-heating rate in a process could overcome heat and mass transfer resistance and speed up the breakdown degradation. These conditions during rapid pyrolysis were considered as a favourable method if the desire is to have a low biochar yield (10–20 %). The result of a short residence time in rapid pyrolysis may cause a low calorific value and high oxygen content of biochar product (Amalina et al., 2022).
Pyrolysis temperature also affects the physicochemical parameters of biochar, including pH, surface area, carbon content, stability, surface charge, volatile content, etc. Therefore, the increase in temperature is a key factor to produce a more stable biochar (higher carbon content) with higher surface area, although with reduced yields. The reduced yield of biochar is also obtained with a more oxidative environment (Grosso et al., 2022; Amalina et al., 2022).

During pyrolysis with high temperatures, biochar's surface area develops due to the gaseous compounds produced from biomass. The biochar produced at low temperatures has a high polarity, acidic nature, low hydrophobicity, and aromaticity. Biomass degradation typically occurs between 200 and 500 ◦C during a pyrolysis process. During biomass degradation, hemicellulose may break down partially or entirely followed by the total breakdown of cellulose and the partial decomposition of lignin (Amalina et al., 2022; Grosso et al., 2022).

Biomass degradation is limited if the heating rate is slow, hence it leads to a boosted biochar yield. While the pyrolysis process at a high heating rate generates vast quantities of liquid, volatile compounds, and in contrast minimising biochar yield at the same time. Also, the functional groups of the biochar, and its carbon content are lost. The speed of heating controls biochar's porosity and surface (Amalina et al., 2022).

An optimal condition for high-yield biochar production is suggested to be low temperature and extended residence time. The polymerisation of biomass is facilitated by increasing the residence time for vapour. In contrast, if the biomass is given less residence time, polymerisation remains unfinished, affecting biochar production (Amalina et al., 2022).

Among different biochar production techniques, gasified biochars at high temperatures are expected to be well-suited, especially for moisture retention. Internal biochar porosity is increased at higher temperatures and subsequently, the biochar potential of increasing water-holding capacity is enhanced. It is due to the high abundance of oxygenated functional groups on gasified biochar that increases hydrophilic characteristics and water retention of this valuable by-product (Philips et al., 2020, Brynda et al., 2020).

Microwave pyrolysis has been introduced as a promising technique to valorise agricultural residues into biofuels, producing biochar, bio-oil, and syngas. Pyrolysis is the most promising route to transform agricultural residues into biofuels (biochar, bio-oil, and syngas) as it causes lower NO_x and SO_x emissions (compared to combustion; Ge et al., 2021).

Gasification of woody biomass coupled with combined heat and power (CHP) production is reported as an effective way to produce a char with a high specific surface area and low content of volatile matter. This carbonaceous by-product meets the parameters of the biochar as a valuable product (fulfilled certain requirements of elemental composition, textural properties, and content of problematic components, such as heavy metals, etc.) in soil application for agricultural purposes (Brynda et al., 2020). Also, by another report, a steam gasification process is recommended when a larger porous structure and high fixed biochar carbon content are required (Grosso et al., 2022). Another successful increase in surface area during the preparation of activated carbons from Corn Stigmata was reported in 2019 using preliminary hydrothermal carbonisation (HTC), (Mbarki et al., 2019).

Moreover, the main reason behind the biochar activation after production is to make the biochar more a valuable product. The biochar produced from pyrolysis has rather less surface area, low pore volume, and less functional groups. Therefore, activating biochar can enhance its characteristics as well as its adsorption capacity of the biochar. By activating the biochar, its surface area and the pore density are escalated by physical and/or chemical activation. Since the two parameters, temperature and time of the activation is directly proportional to the porosity growth and pore size distribution, in the physical way of activation for example, the porosity of biochar at high temperature and as a result specific surface area can be increased (Uday et al., 2022).

2.4.2 Biochar feedstock impacting biochar properties

Figure 10 is also illustrated a wide range of different feedstocks that can be used and transformed into value-added biochar (Uday et al., 2022). Five categories of biochar feedstock such as agricultural, forestry, manure, wood, and algae are introduced by Uday et al., (2022) in terms of their behaviour under different temperatures on carbon content. With the increase in temperature, the carbon content also increases with the highest determination coefficient for forestry waste, followed by wood waste. However, regarding the use of algae, there was a slight decrease in carbon content with a change in temperature. Therefore, in addition to temperature, heating rate, and residence time, feedstock influences biochar parameters as well (Uday et al., 2022; Amalina et al., 2022).

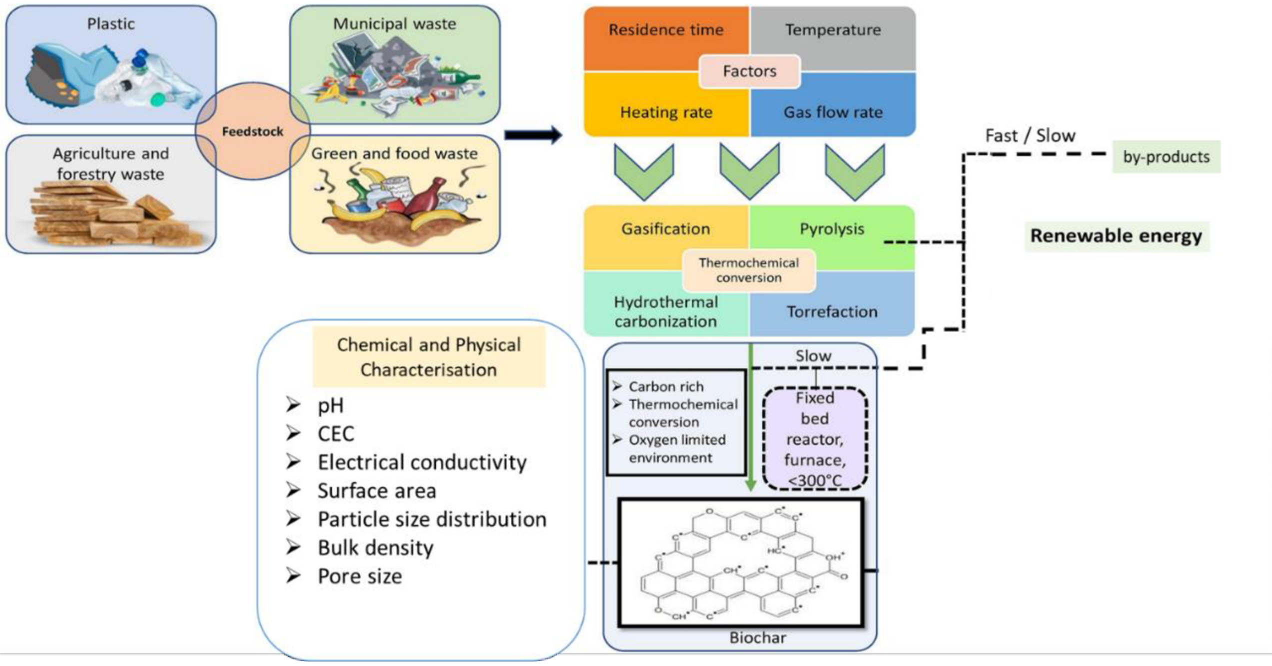

Fig. 10. Different source material and thermochemical methods to convert biomass/waste to biochar. various activation and characterization techniques are also schematically summarized (modified from Uday et al., 2022).

For instance, biochar produced from manures usually has a smaller specific surface area than biochar which has been produced from wood (Brynda et al., 2020) and biomass (Juriga and Šimanský, 2018). Biochar produced from sludge compost (wastewater + woody materials) is highly mineral with low organic content, which therefore should be avoided to prevent soil contamination. The biochar produced from woody biomass, strongly reduced soil microbes, especially fungi. Although this antimicrobial activity is unwelcomed for conserving and increasing soil health, it can be considered to apply it in other several applications e.g., the inhibition of soil-borne pathogens (Rabaiai et al., 2022).

Biomass source material is one of the parameters that have significant effects on the yield and the physicochemical properties of biochar, hence directly determining its application. Lignocellulosic biomass, as one of the bio-resource examples, consists of carbohydrate polymers (hemicellulose and cellulose) and aromatic polymers (lignin). Accordingly, biomass with a high lignin content results in more biochar formation (higher in yield) compared to cellulose, and hemicellulose (Amalina et al., 2022).

The biochar obtained from date palm leaves at the pyrolysis temperature of 600◦C was the most promising product due to its lower impact on soil microbes, high organic content, surface area, cation exchange capacity, and thermostability, compare to sewage sludge treatment mixed with woody materials, and Mesquite plant wood (Rabaiai et al., 2022).

The type of feedstock may affect the immobilization of heavy metals in soil too. For example, crop straw, wood, and animal manure-derived biochar resulted in immobilizing heavy metals in soil effectively and a reduction of heavy metals' mobility (Li et al., 2022; Teodoro et al., 2020). However, different wood-derived biochars (from different plant species) show different effects. Biochar from vinegar residue is introduced as an effective material for alleviating Pb stress in alkaline loam soil. In the same study, it is reported that the biochar also facilitated Pb transformation from mobile fractions to non-mobile fractions as well as increasing the organic carbon (OC), dissolved OC, enzymes activity of soil, and the growth of plants (Li et al., 2022).

Another resource to produce biochar is sewage sludge, which resolves two main issues at once; minimizes the cost of disposal and acts as a resource to eliminate the toxic contaminants from drinking water and wastewater (Gopinath et al., 2021).

2.4.3. Biochar characteristics and its functions as the soil conditioner

The properties of biochar can be described not only in terms of yield (means the ratio of pyrolyzed product mass to raw biomass dry weight), but also in several physical and chemical properties. The purpose of using biochar as a soil amendment is to improve water retention, fertilizer use efficiency or nutrient use efficiency as well as soil carbon sequestration. In this case, the biochar requirements are high pH and CEC, large SSA and porosity, high yield of biochar, and high stability (Xie et al., 2022).

2.4.3.1. Biochar and physical properties of the soil

A high total surface area of a biochar per unit of mass (SSA) indicates greater adsorption capacity and water holding capacity of that particular biochar. Mechanisms of aggregations such as hierarchical theory of aggregation, phosphates and carbonates enhances aggregation, and formation of bridges between clay and SOM particles by cations, etc., or the combination of those mechanisms resulting in aggregation can be responsible for the formation and stabilization of soil structure after application of biochar to the soil.

Therefore, applied biochar can be joined with mineral particles in the soil or can be part of the soil aggregates. Accordingly, biochar in soil occurs not only as free particles, but also, they can be connected with water-stable aggregates through hydroxyl and carboxylic groups on its surface that could adsorb soil particles and clays and form macro-aggregates. Biochar can enhance aggregation, due to its highly carbon content (aromatic C structure), by changes of soil pH and helping to bind native SOM, which leads to increase the resistance of soil aggregates to water. This phenomenon makes aggregates more resistant to physical disturbance and water stresses (e.g., wet-dry cycles).

Biochar provides feedstock to microbial communities to produce extracellular polymeric substances, which act as cementing agents for soil aggregates. On the other hand, earthworms can affect aggregate stability in soil by making mechanical bonding between soil and biochar particles. Different effects of biochar particles in soil are the results of different amount of reactive functional groups in biochar that strongly depends on its production conditions and feedstock as well as the time length of contact between biochar and soil particles. Applied doses of biochar and its particle sizes are the key roles of the magnitude of biochar effects (Juriga and Šimanský, 2018; Abbas et al., 2019).

Pore volume meaning total volume of openings and pores in biochar and the pore-size distribution, which is the relative abundance of each pore size, considerably influence hydrophobicity, that decreases the mobility of water (higher capacity to retain water), deep percolation and reduce water stress in plants (Xie et al., 2022).

According to its high surface, porosity, and carbon content, the experimental application of biochars to soils has been shown to enhance carbon, water, and nutrient retention (Guo et al., 2020; Teodoro et al., 2020; Uday et al., 2022). This is partially achieved through reduced soil bulk density, improving SHP such as saturated hydraulic conductivity (Ksat) and soil water retention (SWR; Phillips et al., 2020; Teodoro et al., 2020). For example, it has been reported that biochar addition decreases Ksat in sandy (course-textured) soil and increases Ksat in clay-rich (fine-textured) soils (Barnes et al., 2014; Lim et al., 2016; Guo et al., 2020; Razzaghi et al., 2020). In agreement, a comparison between sand, sandy loam, and clay-loam has shown that the decrease in Ksat after wood-based biochar application was 92% in sandy soil and 67% in sandy loam soil. In contrast, Ksat increased by 328% in the treated clay-rich soil (Barnes et al., 2014).

Clearly therefore the impact of biochar on the Ksat is specific to particle size distribution (Edeh et al., 2020; Lim et al., 2016; Phillips et al., 2020). Biochar laboratory scale experiments showed not only an increased plant-available water capacity in sandy soils (Abel et al., 2013; Liu et al., 2017), but also the results confirmed biochar potential to decrease hydraulic conductivity in sandy soils to reduce water losses to deep drainage (Philips et al., 2020; Lim et al., 2016).

The biochar application rates suggested for coarse-textured soils are 30 and 70 t/ha to improve soil water properties most effectively. In the contrary, in soils with >50% of clay, <30 t/ha of a high surface area biochar is ideal (Edeh et al., 2020). Biochar causes a net increase in the total soil-specific surface area when added as an amendment, due to its specific surfaces, being generally higher than sand and higher than (or comparable to) clay (Lehmann and Joseph, 2012). Along with key factors, specific surface area and porosity, both soil-biochar inter-particle and biochar intra-particle pores are indicated to be important factors as well. In soils with >60% sand, biochar with a small particle size (<2 mm), high specific surface, and high porosity should be applied to gain optimum water relations (Fig. 11; Edeh et al., 2020).

By an overview, in general, soil bulk density was reduced, and AW increased after biochar application. Also, changes in soil water content retained at field capacity and wilting point are suggesting that the impact of biochar on soil water content may be soil type-dependent since they were increased in the coarse- and medium-textured soils but decreased in the fine-textured soils (Razzaghi et al., 2020).

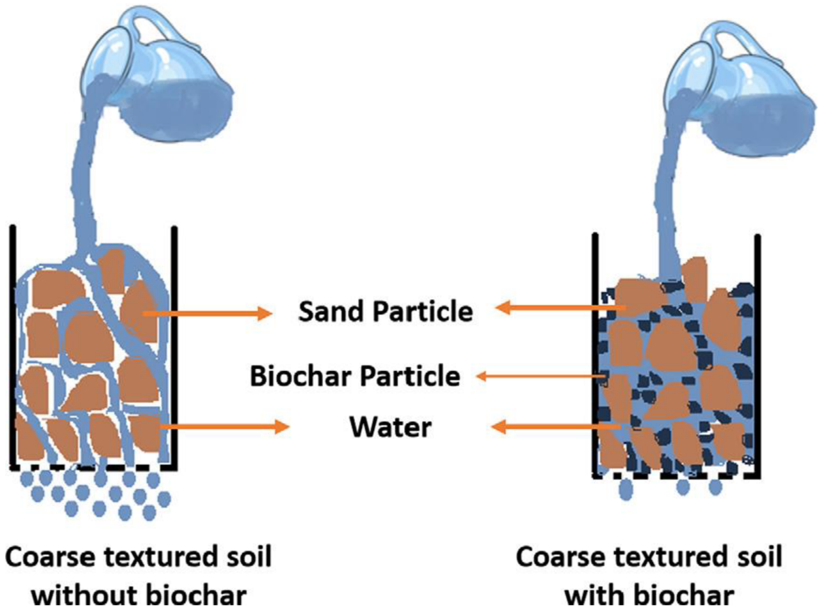

Fig.11. Diagram demonstrating how the addition of biochar with fine particle size results in the soil's large pores filling reducing water movement (K_{sat}) and consequently increasing water retention (Edeh et al., 2020)

In summary, biochar utilization as soil amendment increases the pore fraction of the soil. Microorganisms grow in the pore fraction increasing the moisture, air, and nutrients residence time. As a result, the growth, survival, and activity of microbes are improved that consequently enhancing plant growth. The biochar produced at high temperatures is more stable and difficult to degrade. Such biochar remains in the soil for a longer time. That is why biochar application is considered as a long-term solution to improve the productivity of soils and simultaneously reduce the impact of harmful pollutants in the soil. Besides, the emission of global warming gases is reduced when carbon is restored in the soil by the biochar present (Yaashikaa et al., 2020; James et al., 2022).

2.4.3.2. Biochar and chemical properties of the soil

Typically, biochar has porous structure with large functional groups rich in surface free radicals and surface charges, which gives it a high functionality ranges from agriculture (soil amendment) to wastewater remediation (removal of heavy metals). It also comprises of minerals and trace metals (Amalina et al., 2022; Xie et al., 2022). Since main purpose of soil remediation is to control, modify or adsorb pollutants, biochar is considered as an effective material for soil remediation purposes due to oxygen-containing functional groups on its surface. Therefore, biochar can be used to immobilize and convert soil pollutants (e.g., organic contaminants, heavy metals, Polycyclic Aromatic Hydrocarbons), (Xie et al., 2022; Uday et al., 2022). Thus, biochar is applicable for agricultural fields in order to enhance fertility and structure of the soil, increase the cation exchange capacity of soil and minimize aluminum toxicity, support carbon sequestration and reduce the effect of greenhouse gases, and enhance microbial activity by alleviating nutrient leaching (Xie et al., 2022).

The degree of carbonization, stability and amorphous carbon structure are represented by the content of elements C, H, N, and S. Low O/C and H/C mole ratios normally imply high stability of biochar. To have potential agronomic and environmental benefits in a biochar for fertilizing soil and enhancing soil quality, elements like Ca and K (inorganic elements) content of a biochar are important (Xie et al., 2022; Uday et al., 2022).

In chemical point of view, biochar can influence soil aggregation also by altering the ionic composition of the soil solution. Aromatic and heterocyclic carbons on biochar surfaces, are indicators of biochar's capacity to adsorb pollutants and contaminants in liquid solution, activity of biochar in anaerobic digestion, and performance of biochar as catalyst. Ratio between the volumes of voids or pore space and the total volume (porosity), together with the specific surface area influence the ability of biochar as adsorbent, soil amendment and reactivity. Functional groups (carboxylic (_COOH), hydroxyl (_OH), amine, amide and lactonic groups) present at surface of biochar increase its sorption properties. These are indicator of biochar's capacity to adsorb organic and heavily pollutants, and its catalytic performance (Yaashikaa et al., 2020; Xie et al., 2022; Uday et al., 2022).

Moreover, the number of anions that biochar can adsorb (Anion exchange capacity) is an indicator of biochar's effect to reduce leaching of anionic nutrients in soil (Xie et al., 2022).

The basic cations of biochar resources are transferred into the soil after biochar application, thus enhancing the soil's cation exchange capacity by increasing the surface area of the soil for adsorbing more cations. The presence of a high concentration of Ca, K, N, and P in biochar either adds nutrients to the soil or would be used as a nutrient source for microbial communities in the soil (Yaashikaa et al., 2020; James et al., 2022)

Biochar has the potential to be a great benefit to soil as an amendment if develop as an optimal material for minimizing the loss of nutrient (e.g., N, P, and K) in the soil. Enriching biochar with Mg helps the biochar to have a much higher soil nutrient adsorption capacity. Therefore, the mineral composition of biochar influences its soil nutrient retention capacity. The adsorption of nutrients onto biochar is mainly controlled by the chemical sorption process in those having small specific surface areas (Shen and Yuan, 2021).

Therefore, the biochar application in degraded soils not only helps the carbon isolation process in soil, but also due to being an electron acceptor and donor reservoir, enhances the quality of soil by neutralizing the soil pH, increasing soil cation exchange capacity, and strengthening microbial growth. Interaction between the functional groups present in biochar with hydrogen ions in soil reduces the concentration of hydrogen ions thus increasing soil pH (increase in pH also increases CEC of soil). Soil pH also is neutralized by the reaction of carbonates, bicarbonates, and silicates in biochar with H^+ ions in the soil (Amalina et al., 2022; Xie et al., 2022).

2.4.4. Advantages and limiting factors of biochar application and other amendments

Uday et al., (2022) portrayed the ecosystem with and without biochar highlighting that biochar application enhances the carbon sequestration, which reduces the emission of carbon and greenhouse gases to the atmosphere. Biochar mixture into the soil also improves the nutrient retention and water holding capacity, and thus increases agricultural yield. While, in the ecosystem without biochar, the biomass is transferred to the soil by decomposition and combustion; the two uncontrolled methods. Combustion causes global warming and climate change, due to carbon dioxide emission. Decomposition process of biomass on the other hand, causes greenhouse gas emissions. Also, the negative effects (reduction of humus and organic matter contents, etc.) while using fertilizers in soil are clarified in the picture (Uday et al., 2022).

According to table 2 the advantages and disadvantages of soil conditioners, which were reported in different studies, can be discussed, and compared. Biochar unlike hydrogel that can be degradable through time (Relleve et al., 2020) with some trace of its residues (depends on the hydrogel type), can stay longer and there would be no residues that negatively impacts environment. Swelling effect of hydrogel also is reported to be sensitive to salt concentration in soil and soil PH (Womack et al., 2022). Amendments like animal waste (manure) cannot be applied immediately into the soil due to their possible pollutant leachate to groundwater, however, biochar is an active and biomaterial with no or negligible trace elements, that can be used directly into the soil. On the other hand, manure and compost have to be annually applied continuously (Somervill, 2019; Busari et al., 2022) unlike biochar, which can stay and have a long-term effect.

However, biochar can be more effective if applied in corporation with other amendments like manure / compost, in order to overcome biochar and other traditional bio-amendments limiting factors. More details are discussed in section 2.4.5.2.

Table 2. advantages and disadvantages of soil organic and inorganic amendments

	Advantages	Disadvantages
Hydrogel	super water absorbent, high cation adsorption, slow-release fertilizer and reduced irrigation time required	degrade-residues might have negative environmental impact, sharply reduced water retention under water deficit, swelling capacity is sensitive to salt content and pH value
Manure / compost	increases soil organic carbon, slowly-release nutrient, improvement of the soil physical, chemical, and biological fertility, increased the SOM content and aggregation, increased of readily available water	needs annual application, OM not an 'always win' scenario regarding tropical agriculture.
Biochar	Improve moisture and nutrient retention, moderate Ksat, heavy metal immobilization, stabile	application difficulties, plane in nutrients
Biochar-based fertilizer	Easy application of pallets, Rich in nutrient	Costly
Co-composted /manured /nutrient-rich biochar	long term effect, economic, feasible in application, nutrient-rich fertilizer	_____

2.4.5. Different biochar products to overcome the limiting factors of biochar application

Although biochars have been proven to be efficient at retaining nutrients in soils (Hossain et al., 2020; Razzaghi et al., 2020), in themselves biochars are poor in nutrient content (Lehmann and Joseph, 2012). Therefore, the main difficulties that can make farmers to hinder using biochar in their fields are the financial and nutritional obstacles. On the other hand, the fine particles of biochar and its super light nature tend to fly easily in the application processes. It is another crucial obstacle that has to be considered. To overcome these limits, some methods are developed to create products more suited to large-scale applications. Developing biochar products into biochar-based fertilizers (BCFs), and biochar blending with compost and manure (co-composted /manured biochar) are two examples to conquer the difficulties in this process.

2.4.5.1. Biochar-based fertilizers

Biochar-based fertilizers (BCFs) are alternatives to enhance biochar's properties and make them more complete from the nutritional perspective. BCFs can be produced through direct pyrolysis of nutrient-rich feedstocks, and pre- and post-pyrolysis treatments. In the pre-treatment method, feedstock first is treated with nutrient-rich material (soluble mineral fertilizers, waste from the fertilizer industry, animal waste) and then undergoes pyrolysis. In the contrary, pyrolyzed feedstock (biochar) can be mixed with nutrient-rich materials as another alternative method, called post pyrolysis treatments.

The addition of concentrated mineral and nutrient sources to feedstock through the pre-pyrolysis process, improves biochar properties such as heavy metal stabilization capacity and moisture retention making them more effective. As an example, P-enriched biochar, which was a sawdust and grass biomass mixed with phosphate fertilizer, were highly P concentrated with high carbon retention. With 3% application to an experimental artificial contaminated soil, it enhanced heavy metal stabilization (Ndoung et al., 2021; Zhao et al., 2016).

The post-pyrolysis technique is used in about 60% of the studies on biochar enrichment, in which biochars are treated with a nutrient-rich source such as soluble mineral fertilizers, clays, ground rock, composts, wastewater, etc., after the pyrolysis process. A very recent example of a post-treatment is a Fe-enriched biochar produced from wheat enriched with iron chloride (FeCl3) and iron sulphate (FeSO4). Fe-enriched biochar reduced Cd toxicity in plants and immobilized Cd from polluted clay loamy soils (Dad et al., 2021).

Based on some pot experiments, biochar-based fertilizers can enhance plant development under stress conditions, such as in contaminated soils by heavy metals or even under salinity stress (Ndoung et al., 2021; Carneiro et al. 2021). For instance, the application of 5, 10, 20, and 30 g kg^{-1} palm leaf waste biochar (phosphorous loaded) produced from a post-treatment mixed into a contaminated soil for a pot experiment, enhanced plant (Maize) growth parameters (shoot and root lengths and dry matter) and boosted the uptake of P (Ahmad et al. 2018).

According to some field trials, there was a 30% loss of fine biochar by wind-blown during distribution, transport to the field, and soil application during spreading to the field. Besides, 20–53% of biochar added into soil was also lost by surface runoff during intense rainfalls (Kim et al., 2014; Shin et al., 2019). Therefore, it is vital to design a biochar product that can be suited for field application with stable structure and minimum loss of its nutrients.

Pelletizing of biochar is considered as a potential way to reduce loss of biochar during soil application. For the purpose of soil application, biochar pellets can be produced from a blend of, for example, lignocellulosic and poultry litter feedstocks (Kim et al., 2014; Shin et al., 2019). The mixture then is pelletized and either can be slowly or fast pyrolyzed. Some biochar pellets produced through fast pyrolysis also made to be embedded with plant fertilizers as an environmentally slow-release fertilizer.

The resulting biochar pellets produced from fast pyrolysis of a switchgrass that were blended with fertilizer and lignin that processed at temperature higher than the lignin's glass transition temperature, showed more stability with smaller pore sizes and lower total surface areas and pore volumes. These properties of the biochar pellets helped holding nutrients for a longer period and participate in their slow controlled release (Kim et al., 2014). Therefore, nutrient-rich biochar pellets are a potential alternative for a cost-effective slow-release fertilizer in soil. Slow-release fertilizer gradually discharges the plant nutrient to soil to be available during crop cultivation (Kim et al., 2014; Dinh et al., 2022).

2.4.5.2. Co-composted and manured biochar

Studies on co-produced biochar-compost or biochar-manure mixes have been initiated to try to match biochars' nutrient retention characteristics to the contrasting and unfavourable nutrient leaching traits of some organic matter (e.g., manures and composts). An enhancement of soil moisture retention as well as reduction of nutrient leaching is achievable by co-producing and/or co-applying biochars along with other organic materials, which are utilized traditionally blended to soils (manures, composts etc). All can be improved even greater than the singular application of those materials. Besides, the result of co-composted biochar COMBI (with manure, sludge, etc) is not only a value-added nutrient-rich (plant macro- and micro-nutrients) material but also is to facilitate field trials applications (having a higher density than pure biochar) and moderates the cost compared with using pure biochar.

Biochar reduced the N losses (via NO_3^- leaching) via a slower release of inorganic N during composting or land application (Adolfo et al., 2022). Thus, nutrient leaching from compost or manure within this blend has been moderated (Guo et al., 2020; Teodoro et al., 2020).

In similar results, carbon loss during the preparation of the compost (rice straw / sugarcane bagasse) and co-composted biochar (10% biochar) was significantly lower than in biochar (rice straw- / sugarcane bagasse-based) undergone a pyrolysis process. Also, the C/N ratios of the compost and co-composted biochar were narrower than the corresponding values of biochar (Farid et al., 2022). Co-composted biochar (waste willow wood-based) increased SOC, available P, Ca and CEC of an acidic clay soil. This amendment (contained 12% biochar; applied 25 t ha^{-1}) increased maize grain yield significantly by 10–29% and improved soil water retention and nutrient uptake by plants (Agegnehu et al., 2016). Several other study results indicated the positive effectiveness of co-composting that increased plant yield and soil moisture / nutrient retention (Antonangelo et al., 2021). Moreover, compost maturation time has been reduced by the addition of biochar during the composting process (Teodoro et al., 2020).

Some studies (Somervill, et al., 2019; Teodoro, et al., 2020) have investigated the effects of blending, and co-composting, biochar, and compost/manure before being added to soils, with the aim of finding synergistic impacts upon soil properties and water retention. For that matter, two contrasted texture soils (turf sand and sandy clay loam) were treated with biochar, compost, and a mixture of both, all at 20% v/v. All OM amendments increased the water in the sandy soil at field capacity. Biochar and the combination of biochar and compost increased plant available water. In the contrary, adding OM to the clay soil decreased both the FC and PAWC. It is stated that the contrast result was probably due to the increased macro-pore distribution and connectivity within clay soil (Somerville et al., 2019).

Results of a pot experiment (Teodoro et al., 2020) showed that biochar presence in compost enhanced mainly the amount of water between field capacity and the drought stress zone, pF = 3.7 (easily available water). It is highlighted that co-composted biochar improved moisture and nutrient status when added to the soil. In conditions like tropical areas, the breakdown of non-stable soil organic amendments such as compost / manure is rapid, and biochar is considered as an alternative soil-stable amendment with a long-lasting impact on soil properties due to the synergistic effects on soil nutrient status and water-holding capacity as well as soil structure stabilization (Rabaiai et al., 2022).

The co-composted biochar (COMBI) utilities can be mentioned not only as environmentally and economically way of enrichment of infertile agricultural lands, but also an effective approach to manage the discharge of variety of organic wastes, such as crop and animal production, food processing, and municipal wastewater treatment. Addition of biochar to the composting process accelerates biological and physiochemical degradation of organic wasting materials in a controlled way, not to have further toxic compounds leaching and emission. Moreover, application of COMBI to arable land has great potential to enhance crop productivity and to decrease heavy metal contamination Antonangelo et al., 2021. Salinity in soils can be moderated by COMBI addition through the improvement of physical and chemical conditions of salt-stressed soils as well.

CHAPTER Three

Studies

3.1. Overview of the studies

In the following section the materials and methods utilised over the four years of this work are detailed. The schematic view of each study is also illustrated in Fig. 15, section 3.3.1 for ease of navigation Details are discussed in the following sections.

3.2. Materials

3.2.1. Sites descriptions and soil characterisation

3.2.1.1. Zvěřínek village / **Regosol**

A Regosol (denoted as R), an agricultural low-organic (drought-prone) soil, was collected at a location around Zvěřínek village (Fig. 12), Czech Republic (50°149′N, 15°026′E) from the arable horizon (<35 cm). A Regosol typically is a very weakly developed mineral soil in unconsolidated materials having formed of only a limited surface horizon. Regosols are widespread in eroding lands, in particular, in arid and semi-arid areas (Soil Atlas of Europe).

Particle size analyses of the Regosol showed a high proportion of sand fraction applying the standard hydrometer method (CEN ISO/TS 17892-4, 2004). Particles contained sand (0.05–2 mm) at 85.5% of the solid phase compared to 5.5% silt (0.002–0.05 mm) and 9.0% clay (<0.002 mm) particles (Gee and Or, 2002). Hence, the soil according to the United State Department of Agriculture (USDA) classification was defined as a loamy sand. The average bulk density of the Regosol, which was sampled in the field was 1.59 g cm^{-3}, the total porosity and the field capacity equalled 41.1% 13.7%, respectively (Seyedsadr et al., 2021).

Fig. 12. The maps (top) show the location of the study area. Profiles show thin surface horizons overlaying generally unstructured deposits (below).

3.2.1.2. Trhové Dušníky village/ **Fluvisol**

The Fluvisol was collected in the floodplain of Litavka River located near Trhové Dušníky village (Fig. 13), Czech Republic (49°72′N 14°01′E) in an area of a bare pasture field (Šípek et al., 2019). Characteristically, Fluvisols are common in periodically flooded areas, and river sides, in all climate zones. Fluvisols show layering of the sediments as they develop due to the deposition of sediments following flood events (Soil Atlas of Europe). The soil can be classified as sandy loam (USDA) as the particle size fractions represented sand 56.5%, silt 34.8%, and clay 8.7%. The average bulk density of the soil was 1.33 g cm−3 (Šípek et al., 2019). According to the soil characteristics (table 3), its low carbon content, and poor water retention makes it highly vulnerable to drought.

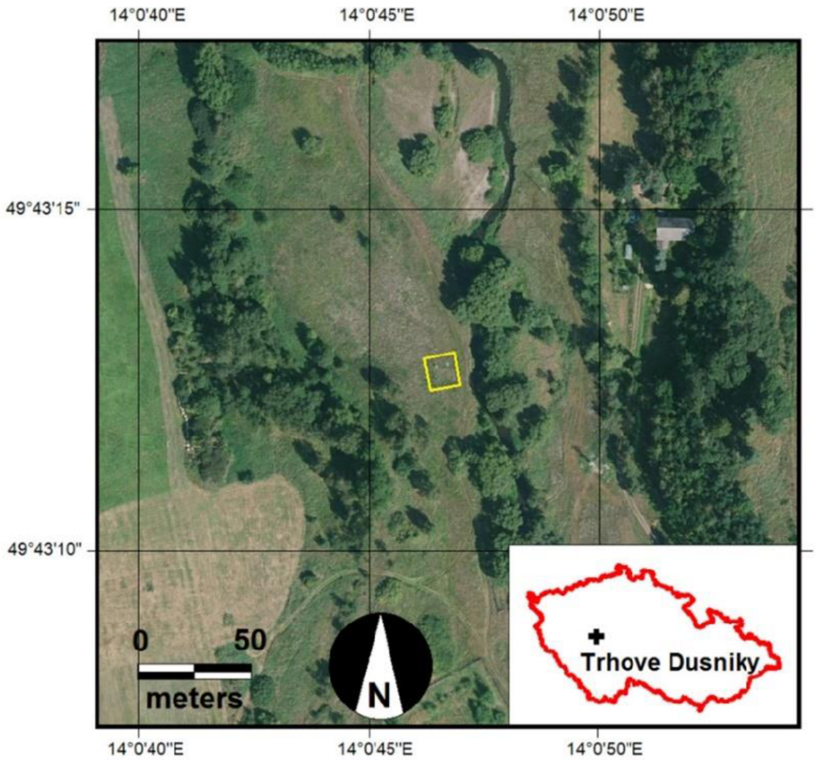

Fig. 13. The study area at Trhové Dušníky village, Czech Republic (Šípek et al., 2019).

Compared to the Regosol, Fluvisol had a higher water holding capacity at saturated state. The total porosity of the Fluvisol was 52.0% (Table 3), having a field capacity double that of the Regosol and lower permeability (Seyedsadr et al., 2021).

3.2.1.3. Jevany village / **Cambisol**

A Cambisol from a conifer forest area around Jevany village (Fig. 14 (top); 49°95′N, 14°.82′E) was selected, which is known as a young soil that appeared in a wide variety of environments and under all many kinds of vegetation. Cambisols are reported as one of the common soils in Europe (Fig. 14 (below)), which can be highly productive agriculturally. The forest area has been suffering from mass mortality due to drought and biotic attacks (mainly spruce bark beetle) in recent years. The field is also characterized as having a shallow organic horizon with a mineral horizon beneath, which is poor in soil organic matter. Therefore, it is partly under a field study and a reforestation process.

The grain size analysis, using the standard hydrometer method (CEN ISO/TS 17892-4) showed that the Cambisol contains 83 % sand particles (0.05-2mm), 7 % silt (0.002-0.05) and 10% clay (<0.002mm). According to the USDA, this soil was defined as Sandy loam. The average bulk density is 1.10 gcm^{-3}.

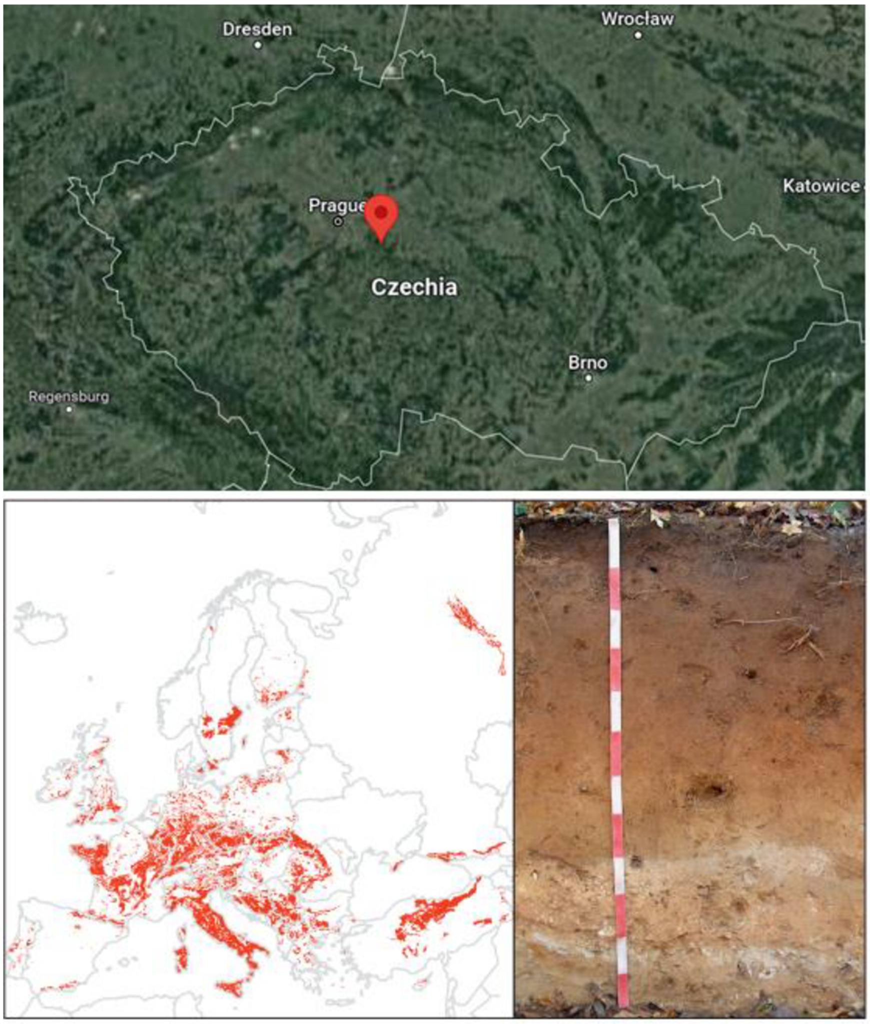

Fig. 14. The study area at Jevany village, Czech Republic (top); a typical Cambisol profile and the location of areas in Europe where it is the dominant soil type (below; Soil Atlas of Europe).

The selected soils for this study are reflecting the major soil types of Europe, according to Soil Atlas of Europe. All soils were characterised by their low organic matter content (see table 3; Seyedsadr et al., 2021) and their vulnerability to drought. A same procedure of soil preparation applied for all the study soils. They were all air-dried, homogenized, and sieved through <2 mm mesh size for the following experiments.

3.2.2. Amendments characteristics and preparation

3.2.2.1. Biochar

One biochar (registered as a soil additive by the Central Institute for Supervising and Testing in Agriculture, CZE) was used through the entirety of this work; Biochar was produced through gasification of wood chips in a fixed-bed multi-stage GP750 gasifier. Through a very efficient gasifier 36 kg of biochar per tonne of dry fuel on average, was produced. It was reported that this biochar had a surface area in the range of 350–700 m2/g (table 3) and very low content of volatile matter and PAHs. All biochar samples, which were taken and analysed periodically during the gasification, proved high specific surface area, low volatile matter content (and therefore low O/C and H/C ratios) and high fixed carbon content. Also, an analysis to understand the influence of the particle size distribution on char properties, was performed at the Institute of Chemical Process Fundamentals of the Czech Academy of Sciences, which showed a decreasing ash content with increasing particle diameter in the case of small particles with diameter up to 2 mm. The results indicated the potential of the char to be sold and used as biochar, certified as a soil amendment medium (Table S1).

It was sieved through <2 mm mesh size before use. The detailed characteristics of the biochar are available in (Table 3; Seyedsadr et al., 2021).

3.2.2.2. Manure

Manure (cow faeces and bedding straw), representing a conventional organic fertilizer, was collected from a farm in Zvěřínek, close to the origin of the Regosol. Fresh manure and biochar were mixed in ratio of 90%, 80% and 50% manure with 10%, 20% and 50% (w/w) of biochar and then left for 1 month to equilibrate.

3.2.2.3. Compost

Compost was prepared at the campus of Czech University of Life Sciences Prague (Suchdol, Prague). It was prepared from woody components such as off cuts of maple, oak and other green material, as well as freshly cut grass and leaves, at a ratio of 1:5 (vol.). Materials composted by adding them to a 200-L spinning plastic drum (Fig. S1). To prepare co-composted biochar 10% biochar (w/w) was mixed with the same components and left in another drum to be stabilized. The drums were placed in a greenhouse at approximately 20 °C, and they were rotated to be mixed and aerated 3 times per week for 16 weeks following the procedure used by Teodoro et al. (2020). The co-composted biochar was prepared to achieve an appreciably improvement of compost as well as the composting process following (Li et al., 2020).

3.2.2.4. Hydrogel

Sodium polyacrylate so-called hydrogel, which is a polymer of synthetic origin were used in this study. Sodium polyacrylate is one of the water retaining agents, and has strong water absorbent capacity, as well as higher water absorption rate in lower price, therefore has a wide application potential. Hydrogel was prepared by Faculty of Forestry and Wood Sciences (FLP).

Table 3. Physical and chemical properties of Fluvisol, Regosol, cambisol and all organic amendments (Seyedsadr et al., 2021); data are shown as means (n = 5).

Property	Unit	Soil			Organic amendment				
		Fluvisol	Regosol	Cambisol	Biochar	Compost	Manure	Co-composted biochar	Manure with biochar
Bulk density	*[g cm^{-3}]*	1.33†	1.59†	1.10	0.17	0.25	0.16	0.35	0.20
Porosity	*[-]*	0.52†	0.37†	0.44	0.74‡	/	/	/	/
pH$_{H2O}$	*[-]*	5.89	5.02	4.92	11.2	6.93	8.51	7.60	10.1
EC	*[μS cm^{-1}]*	67.8	32.1	83	1400	3850	4210	2770	4300
C$_{org}$	*[g kg^{-1}]*	2.87¥	9.33		817	359	373	356	488
N$_{tot}$	*[g kg^{-1}]*	0.20¥	0.54	0.50	3.59	24.0	25.0	14.0	16.0
C/N	*[-]*	14.4¥	17.3	44.1	228	15.0	14.9	25.4	30.5
P$_{tot}$	*[g kg^{-1}]*	0.58	0.45	0.35	0.89	3.05	7.48	1.44	5.62
K	*[g kg^{-1}]*	8.12	9.28	22.24	3.90	14.6	36.0	10.2	36.0
Ca	*[g kg^{-1}]*	0.74	0.87	1.32	16.4	37.5	19.1	16.1	16.0
Mg	*[g kg^{-1}]*	0.26	0.17	1.92	2.85	3.89	4.90	2.74	4.44

†bulk density of the original undisturbed soil collected from the fields
‡biochar porosity (ε) from Brynda et al. (2020)
¥data from Teodoro et al. (2020), also see Table S2.

3.3. Methods

3.3.1. Experimental designs

A summary of the experiments that has been introduced in this chapter are illustrated in figure 15. The scheme is divided to different experiments, each answering one of the above-mentioned questions followed by the related locations, types of the soil and the treatments. More details of the experimental design of each study are discussed in the following sections.

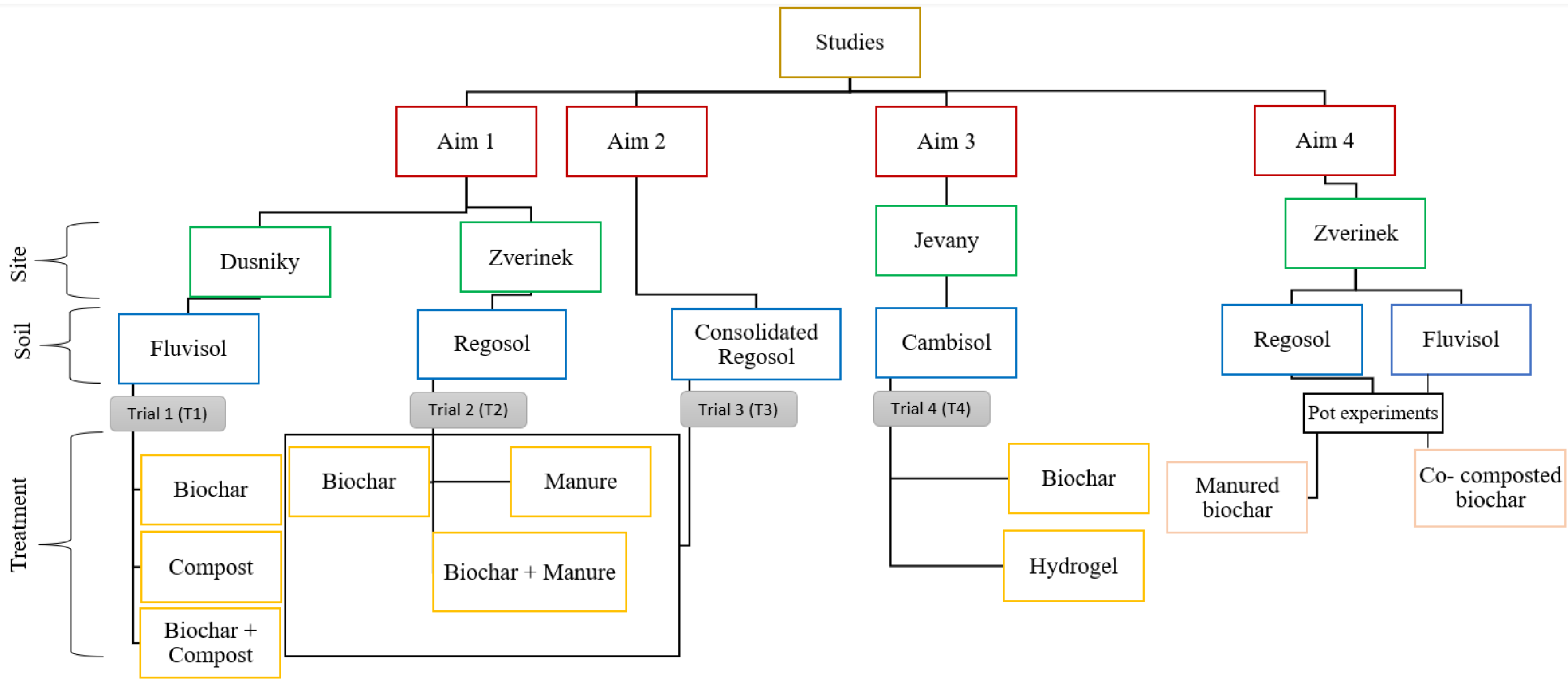

Fig. 15 A schematic summary of the studies by their locations, soils and the treatments used in each experiment. The experiment results are presented on the page 83 / chapter 4

3.3.1.1. Applying biochar with/ without amendments to two agricultural soils (T1, T2)

Two experiments were performed to achieve the first aim and the objective of the study. Both experiments had a control versus a treatment with biochar. The Fluvisol (F) in the first experiment (T1) was mixed with the biochar (FB), compost (FC), and co-composted biochar (FCB). In the second (T2) the agricultural Regosol (R) was mixed with the biochar (RB), manure (RM), and the mixture of manure with biochar (RMB). Traditionally, manure is the standard locally sourced amendment applied to this soil in the field, therefore, it was used here in substitute for compost. In both trials (T1 &T2) treatments were mixed with the F and R soil at 0% (control), 2% and 5% (w/w). These dosages represent those commonly found in other soil-amendment studies, by which doses upwards to 5% are considered to nourish soils, and significantly turned the effects induced. All samples are identified using the combination of the soil (F/R), amendment (B/M/C/MB/CB) and its dose (i.e., RCB5 and RCB2 stands for Regosol with compost-biochar mixture at 5% and 2% dose, respectively).

Fourteen rectangular perforated vessels (60 × 38 × 16 cm) were prepared to be filled with soil mixture in the amount of 25 kg for each (Fig. 16). Soil mixtures were placed in each box layer by layer (1 cm) to a homogeneous coverage in a way to enable distribution of water uniformly. To ensure the drainage of excess water from each vessel, each one of them was equipped with a geotextile and a 2 cm of gravel layer at the bottom. To irrigate the soil automatically, ten silica fibre wicks (five on each side of the box situated at the lowermost part of the soil profile) were applied into 2 cm thick soil layer connected to the water storage flask placed below the vessel. A 10 cm thick layer of compact soil were covered the wicked soil. Soil samples then was collected from this thick layer. A piece of a geotextile covered each filled vessel to minimize evaporation. Initially these prepared vessels were manually saturated with water equal to pre-estimated volumes of all pores (= total porosity). After the saturation, free water drained gradually. Thereafter, a stable water content was further maintained by the installed irrigation wicks. One T5 tensiometer (METER Group, Inc. USA) as well as one FDR soil moisture sensor 5TM (Decagon, USA) were installed into each vessel (Fig. 16). During the experiment, the wetness of the soil was controlled by the installed FDR and 5TM, by monitoring the recorded soil water potential (from T5) and volumetric water content (from FDR) regularly (Fig. S2). The filled vessels were left in a greenhouse under laboratory conditions, to be stabilized and settled for 6 weeks. Afterwards, undisturbed soil samples were carefully collected (Fig. S3) from the upper 10 cm thick layer of each box using standard stainless-steel soil sample rings (length 4.06 cm, inner diameter 5.6 cm, volume 100 cm3; Eijkelkamp, NED). Further, the collected samples were used for soil hydraulic properties (SHP) measurements. At the end of the experiment to test the nutrient retention, 50 ml of porewater was collected from each vessel using 10 cm long rhizon samplers (Eijkelkamp, NED), (seyedsadr et al., 2021).

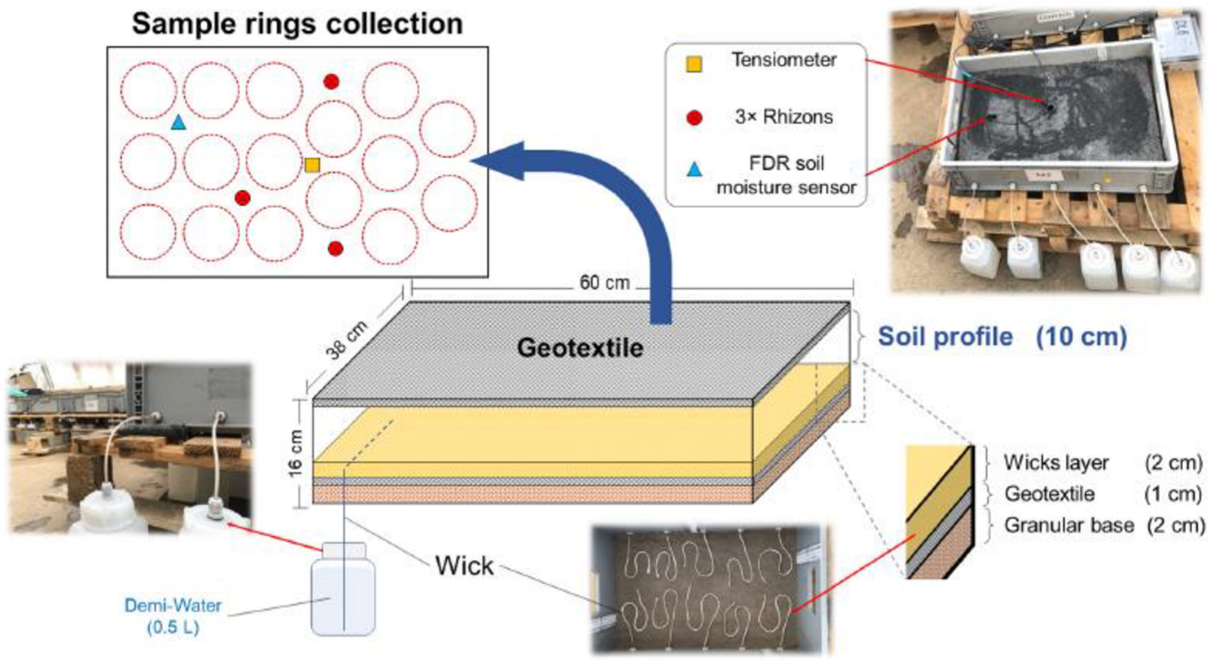

Fig. 16. Schematic view of the experimental set-up showing rectangular and perforated vessels filled up to 10 cm with soil (+5 cm of water balancing layer), covered by geotextile and connected to bottles through 5 wicks at each side. Position of sample rings collection, soil moisture sensors (T5 and FDR), and rhizons (for porewater collection) are visible in the scheme.

3.3.1.2. Applying consolidation method on Regosol treated by biochar with/without manure (T3)

In order to fulfil the second aim, the agricultural Regosol (R) was mixed with the biochar (RB), manure (RM), and the mixture of manure with biochar (RMB). Biochar and manure were mixed in three different doses (10%, 20%, and 50%; w/w). The mixture samples were labelled using the combination of amendments (MB) and biochar dose (i.e., MB10 stands for biochar with manure at 10% biochar dose). Unlike T1 and T2, all the treatments were mixed with the R soil at only 5% dose (w/w) in T3. The same system of sample labelling as for T1 and T2 were also used here (i.e., RMB10 stands for Regosol with 5% manure-biochar mixture at 10% biochar dose). A total of 24, 4 replicates for each 6 amendments, were used in each of the trials (consolidated ($T3_1$), non-consolidated ($T3_2$)).

A total of 48 sample rings (standard stainless-steel soil sample rings, length 4.06 cm, inner diameter 5.6 cm, volume 100 cm^3; Eijkelkamp, NED) were needed in $T3_1$, to prepare 24 samples following Stock (2008) methodology. Accordingly, to achieve a comparable stress situation, 2 sample rings attached together by a tape making a cylinder and filled with soil.

Each cylinder was filled with the Regosol up to 1 cm bellow the upper ring. All samples were left for 2 days to be consolidated by its own soil weight and then decrease in sample volume were noted. Then samples were gradually saturated in period of one week.

Consequently, suction of 1 meter (100 hpa) were applied on the samples. After one day of the suction application, a static load of 600 g to achieve a comparable and replicable stress situation to the samples (Fig. 17, Glab et al., 2018; Stock and Downes, 2008) was placed on each sample and applied for period of 4 weeks to stabilize soil treatments under the same controlled conditions. Further, samples were removed from sandbox and changes in sample volume were noted. Then, the tape connecting rings were stripped off and the lower ring were separated with the aid of the fishing line and knife. This lower ring was weighted for actual moisture content and used for further SWRC measurement.

Also, 24 more sample rings for $T3_2$ were filled, taped to an upper ring, and left for 2 days. The same procedure was applied on these sample rings except that this trial was operated without loads.

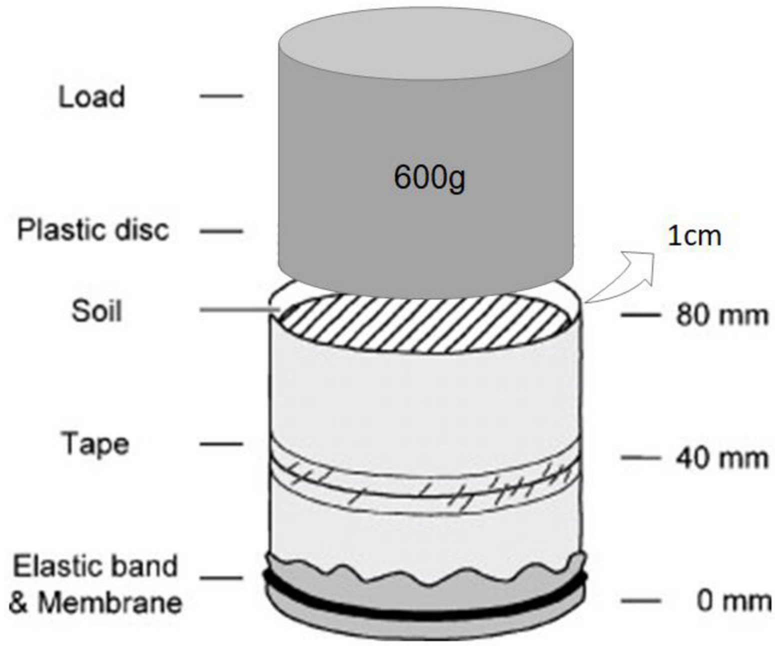

Fig.17 A scheme (modified from Stock and Downes, 2008) of a double ring attached together with a heavy load of 600g on top to achieve a comparable stress situation to 15–20 cm soil depth applied to all soil samples used in trial 1

3.3.1.3. Applying biochar and hydrogel to the forest soil (T4)

The same box preparation method was followed to achieve the third aim. Each box was filled with the same amount with a mixture of Jevany soil (J), at 0% (control), 2 % and 0.1% (w/w) dose of biochar (B) and hydrogel (H), respectively. Biochar and hydrogel doses are selected at their optimal forest field usage as suggested for the afforestation field experiment. A total of 27 samples, 9 replicates for each 3 amendments were gathered from self-irrigated vessels.

3.3.1.4. Pot Experiments

3.3.1.4.1. Co-composting experiment

Materials were prepared for two purposes of analysis: 1) Soil water retention and available water content, 2) Growing pot experiment.

The same procedure as T1 and T2 for composting were performed making compost only (C0), and compost mixed with 4 and 10 %wt. of biochar (C4, C10). Four treatments (Fluvisol only, soil mixture with C0, soil mixture with C4, and soil mixture with FC4 (all amendments in a ratio 1:2 (w/w) to soil) were used for the measurement of soil water retention (SWRC). All treatments were filled into sample rings, fully saturated, and later kept at given suction pressure head. For the material characteristics see table 3. Also, 1 L pots were prepared, each filled with 1440 g of soil and composts in a ratio 2:1 (w/w). Further, one-hundred seeds of yard grass (Lollium perenne L.) and arugula (Eruca sativa Mill.) were sown directly into the pots. Four replicates of the following treatments were prepared: Fluvisol without compost, prepared compost (C0), co-composted biochar (C4, C10), and compost with biochar added later (FC4, FC10). The fourth treatment was retail compost (HB) (Agro Zahradnicky Kompost, Agro CS, CZE). HB was included as a control, against which to compare the 'home-made' (biochar added) amendments. Each pot was watered by distilled water up to about field capacity for germination, kept constant over the whole period of the experiment. The growing experiment was conducted under a controlled situation inside a greenhouse, with an average temperature of 20 °C and a 12-h period of light (ensured by high-pressure sodium lamps). Plants were left to be grown for a period of 35 days (Teodoro, et al., 2020).

3.3.1.4.2. Manured biochar experiment

Regosol was chosen in this study, because in this type of agricultural soil, sugar beet production negatively impacted by a high amount of water depletion and leaching of organic matter. Manure, a conventional organic fertilizer, and biochar (the same product as in the previous experiments) were prepared as the soil amendments (table 3). To create an appropriate experimental blend of both biochar and manure, the two amendments were mixed, with 90% manure and 10% biochar (w/w) and left to equilibrate under a controlled condition. After a month, this blended treatment (manured biochar) (MB) together with manure (M) and biochar (B) were dried and sieved (through <2 mm) for their consequent usage.

Seven soil treatments were prepared (control (C), and the soil mixed with the different amendments (Biochar (B), Manure (M) and their combination (MB)) at two different doses (2 and 5 wt%; B2, B5, M2, M5, MB2 and MB5). They were put into 1 L pots, each in five replicates.

Inside of each pot, five seeds of sugar beet were subsequently sown, and plants were randomly reduced to two after germination. An FDR 5TM moisture sensor (Decagon, USA) was installed in each pot, to monitor soil moisture. Three watering phases were set up, during a total sixteen-week: (i) starting with a regular watering during the first nine weeks, with 100 mL poured in each pot twice a week; (ii) drought simulation during the next three weeks, with a reduction of watering to 25 mL; and (iii) re-irrigation during the last four weeks, with an increase of the watering to 75 mL (Lebrun et al., 2022).

3.3.2. Laboratory measurements

3.3.2.1. Bulk density, total porosity, easily available water, and plant available water calculations

In trial 1 and 2, five undisturbed soil samples were collected from each vessel for the estimation of total porosity and bulk density (overall, 5 replicates × 7 treatments = 35 samples for each trial). All the collected samples in trials 3 (total of 60) and 4 (totally 27), were used also to estimate total porosity and bulk density. The same procedure was followed for all trials. Accordingly, total porosity was calculated from the difference in soil weight at maximum possible saturation, which was the slow gradual saturation from the bottom to the top of the samples for a one-week period; and the dry state, the weight after oven dried at 60 °C for 72 h. Subsequently, the bulk density of each sample was calculated from the mass of the soil at dry state divided by volume of the sample (100 cm3; volume of the ring).

Thereafter, available soil water content for plants (AWC) were estimated, which is the difference between volumetric water content at pF 2 and pF 4.18. The easily available water content for plants (EAWC) also calculated from the difference between pF 2 and pF 3.7.

3.3.2.2. Saturated hydraulic conductivity

Sample preparation for Laboratory permeameter

Saturated hydraulic conductivity analysis to determine Ksat, were only used in trial 1 and T2. From each 5%-treatments and control for each soil type, 5 undisturbed soil samples were used (5 replicates × 4 treatments = 20 samples for each soil) to determine the Ksat. For this purpose, a laboratory permeameter (Ejikelkamp, Netherlands) was used utilizing the standard constant head method (Eijkelkamp, 2017).

To eliminate the effects of entrapped air, samples were gradually saturated from the bottom by changing the height of water level in the container of the laboratory permeameter (Jačka et al., 2014). The details of the laboratory permeameter operation is discussed in the next section.

Theory and Operation of the permeameter (the constant head method)

The laboratory permeameter is applicable for measuring the saturated permeability of undisturbed soil samples collected with standard soil sample rings. The permeability coefficient or 'K-factor' can be determined for nearly all types of soils.

The laboratory permeameter operates by creating a difference in water pressure on both ends of a saturated soil sample and measuring the resulting flow of water.

The outside of the sample rings cleaned well to be prepared and placed into the sample holders. A hydrophilic gauze (nylon cloth) with a synthetic O-ring was attached to the blunt side of a sample ring. The sample ring with the cutting edge on top was placed into the ring holder. This causes the water, during measuring, to flow through just like a natural situation of a downward flow of water. By closing and tightening the ring holder, the

ring can be pressed firmly against the O-ring (was sealed to prevent water flow outside the sample ring).
A prepared ring sample was placed in a ring holder. The ring holder was located inside the plastic container.
A siphon creates a difference in water level inside and outside the sample ring. This difference causes a continuous flow of water through the sample. The height of the water column measured by measuring the water level in the container and inside the holder of the sample rings (h = the difference of both measured water levels). When measuring, a constant level difference (h) should be maintained inside and outside of the ring holder (2 mm). By collecting the drained off water in a burette up to a certain point during a fixed period, the K-factor of a sample can be determined. The formula to calculate the K-factor is introduced in the next section.

Ksat factor calculation using the constant head method

To calculate the K-factor when applying the constant head method Darcy's Law was used:

Darcy's Law equation: V = K * i * A * t
(V) is the volume of water flowing through the sample (volume measured in the burette) [cm^3], (K) is K-factor [cm/d], (A) is cross-section surface of the sample [cm2], (t) is the time used for flow through of water volume.
(i) is permeability rise gradient, or: h / L [-], in which (h) is water level difference inside and outside the ring holder [cm], (L) is the length of the soil sample [cm]. L, A, V, t, and h were determined during the measuring.

3.3.2.3. A comprehensive measurements of Water retention curve
3.3.2.3.1. Sand box (Saturation level / field capacity)

Sample preparation

In trial one and two, six undisturbed soil samples were used to measure soil water retention curve (SWRC) in control and all 5%-treatments (6 replicates × 4 treatments = 24 samples for each soil). The 08.01 Sandbox

(Eijkelkamp, NED) was set using the standard method (Eijkelkamp, 2019) to apply a range of pressures from pF 0 (nearly full saturation) to pF 2 (−100 hPa). Value of pF 2 is an estimate of field capacity (FC), which also is defined by Kutilek and Nielsen (1994) for sandy soil.
The same procedure was done on five undisturbed soil samples of consolidated and non-consolidated treatments (4 replicates × 6 treatments = 24 samples for each trial, $T3_1$ and $T3_2$).
Regarding trial four, all 27 undisturbed soil samples (9 replicates × 3 treatments) were prepared to put into the sandbox.

Theory and operation

A hydrophilic gauze (nylon cloth) was fixed to the blunt side of a sample ring (bottom side) with a synthetic O-ring. All samples were placed into the sand box, while a 0.5 cm layer of water is covering the surface of the sand in the sandbox. To saturate the samples, sand box was set to 'Supply' and water level in the container was slowly raised to 1 cm below the top of the sample rings. This process was applied within a period of one week, to avoid air trap and soil structure damage. Sand box was set back to 'Close' when the desire water level was reached. Samples were weighed after a week when they were nearly saturated. This weight (including ring, cloth, and the O-ring) is used to calculate water content at saturation, pF 0. Thereafter, the suction regulator was set to the next level down, so that a greater suction was applied to the centre of the samples. The middle of the soil sample is used as the reference level for zero pressure (in 5cm standard rings). An omega ruler is used to set the zero point on the sliding ruler to the correct height. This process helps to correctly adjust the hight of the suction regulator.

Further, samples were measured at -10.0 cm water (pF 1), - 31.6 cm/ - 63.1 water (pF 1.5 / 1.8; pF 1.8 were only measured in T2) and -100 cm water (pF 2.0).

3.3.2.3.2. Sand/ Kaolin box (pF 2.7)

Sample preparation

Samples of trial 3 and 4 were then moved to 08.02 sand/ kaolin box to be measured at pF 2.7 (Eijkelkamp, 2016).

Theory and operation

In general, 08.02 sand/kaolin box is used to apply a range of pressures from pF 2.0 (-100 hPa) to pF 2.7 (-500 hPa). In this study it was used in trials 3 and 4 to apply a pressure of pF 2.7.

Kaolin covered sand functions to pass the pressure from the vacuum vessel and drainage system to the soil samples. The sand/kaolin box has a drainage system inside it. This box is filled with very fine synthetic sand covered by a layer of kaolin clay (china clay). A Nylon filter cloth was used to keep the kaolin layer clean against fine materials clogging the sand. The sample rings were placed on this filter cloth, which roles as a medium for kaolin suction (creates by a pump in the vacuum vessel) through the samples (similar to sandbox).

3.3.2.3.3. Pressure extractor 5 bar (3 - 3.7 Pf)

Sample preparation

Consequently, all samples were moved to the pressure apparatus. The 5 Bar Ceramic Plate Extractor 1600 (Soil moisture, USA) in pressure head from to −5000 hPa (pF 3 to pF 3.7) were applied using the standard method (Soilmoisture, 2008). It took 3 months for each trial.

Theory and operation

After the porous ceramic plate was completely saturated with water, it was placed in the Pressure Vessel (Fig. 18). Then air pressure of 1 bar, and subsequently after forty-five days 3 bar, applied to extract moisture from the soil samples under controlled conditions.

As soon as air pressure inside the chamber is raised above atmospheric pressure, excess water through the microscopic pores in the ceramic plate starts to be forced out by the higher pressure inside the chamber. Since the pores are filled with water and the surface tension of the water supports the pressure much the same as a flexible rubber diaphragm, the high-pressure air will not flow through the pores in the ceramic plate.

The diameter of the pore in the ceramic plate is the parameter that determines the maximum air pressure that any given wetted porous ceramic plate can stand before letting air pass through the pores. The smaller the pore size, the higher the air pressure needs to be to pass through. Pressure Plate Cells were used at air pressure extraction values below the "Bubbling Pressure" or "Air Entry Value" for the Cell (the pressure value that finally breaks down these water meniscuses).

During each operation at any set of air pressure in the Extractor, soil moisture is flowing from around each of the soil particles and out through the ceramic plate. It continues until the effective curvature of the water films throughout the soil are the same as at the pores in the plate. At this point, an equilibrium is reached, where there is an exact relationship between the air pressure in the Extractor and the soil suction in the samples. Eventually, when equilibrium occurs, the flow of moisture nearly stops. The weights of the samples were recorded at this level and pressure extractor was set to the higher pressure for the next run (5 bar). Next round of measurement was done when the new equilibrium was reached.

Samples were then moved to the 60° oven for 72h to determine bulk density. Thereafter, Soil samples were airdried to be used for permanent wilting point estimation.

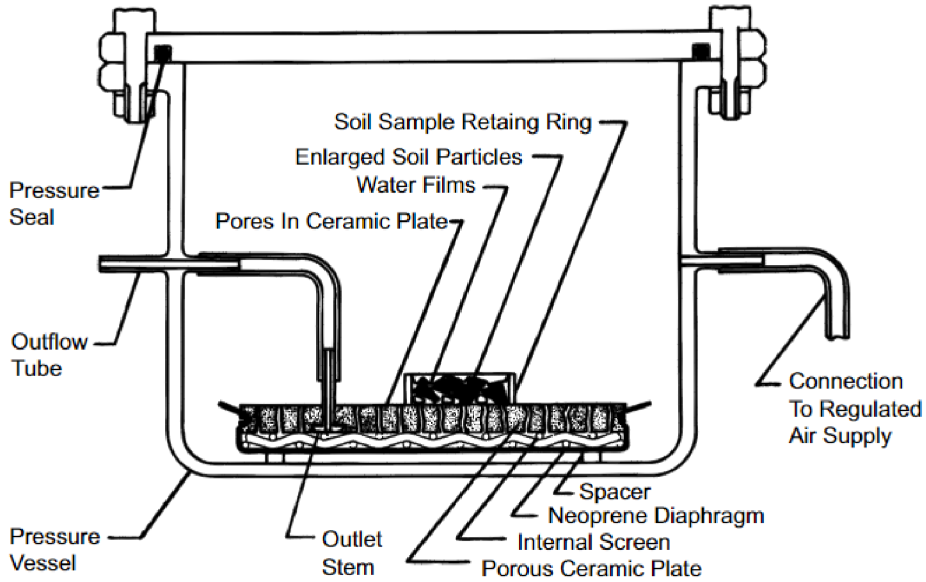

Fig. 18. Cross section of the pressure vessel (Soilmoisture, 2008).

3.3.2.3.4. WP4C Dewpoint Potentiometer (permanent wilting point)

The WP4C Dewpoint PotentiaMeter devise (METER Group, Inc. USA) was used for measurement of soil water content at −15 bar (pF = 4.18, permanent wilting point; PWP) following the standard method (Campbell, 2020).

Theory and operation:

The WP4C instrument applies the chilled-mirror dew point technique for measuring the water potential of a sample (soil sample in this study). Under this technique, the sample is equilibrated (when the water potential of the air in the chamber is the same as the water potential of the sample), with a mirror, located in the headspace of a sealed chamber and a method of detecting condensation on the mirror.

Stainless steel cups were used in the measuring process. Since, stainless steel cups can reach to temperature equilibrium with the sample more quickly than the plastic cups. A quick temperature equilibrium leads the measurement to achieve more accurate results. Samples were put in the sample cup completely covering the bottom of the cup. In this case, the surface of the sample would be larger. It speeds up the reading by shortening the time needed to reach vapor equilibrium. It also proves more stable infrared sample temperature, which increases instrument accuracy. The sample cup was sealed against a sensor block in the WP4C instrument, while a fan speeds equilibration of the sample with the headspace vapor. The fan also controls the boundary layer conductance of the dew point mirror. The dew point temperature of the air, and the sample temperature are measured during a run, from those the WP4C computes the vapor pressure of the air as the saturation vapor pressure at dew point temperature. Eventually, these measurements at the equilibrium of the water potential of the sample and the headspace air, also at the internal equilibrium of the sample itself, gives the water potential of the sample.

Measuring Water Potential and PWP estimation

The resolution of the WP4C instrument is 0.05 MPa, that can be measured reliably through the following procedure (Campbell, 2020). The lower limit or the permanent wilting point (-1.5MPa, -15 bar, pF 4.18), is easily and quickly determined using the WP4C. Since it is much more difficult to prepare a sample at a given water potential, samples were brought to a pre-determined water content first. Therefore, the water content of the samples at -1.5 MPa were measured by the following procedure.

First, samples were prepared at pre-determined water contents, then their water potentials were measured with the WP4C. Further, the -1.5 MPa water potential was found mathematically. To prepare a sample for each trial at approximately the -1.5MPa water potential, 100 g of air-dry soil (M_{ad}) were used. Then the following equation helped to obtain the mass of water needed (M_{wa}) to make the soil samples get to the -1.5MPa of water potential:

$M_{wa} = (w-w_{ad})\ M_{ad}/1+w_{ad}$

The water-added samples were thoroughly mixed and placed in a sealed container overnight to equilibrate. Afterwards, some grams (recorded for the further calculations) of the prepared soil sample were placed in a sample cup and its water potential was determined with the WP4C. The same procedure was done by preparing two or three samples at water contents around the estimated -1.5 MPa value. Finally, by drawing and calculating a linear regression between water potential and volumetric water content of all the estimated values, water content at the PWP was determined for each type of soil sample.

3.3.2.4. Soil and porewater chemical analysis

Rhizon-collected porewater samples were initially examined for electric conductivity (EC) and pH by a multi-meter (Multi 3420, WTW, Germany), conductivity cell (TetraCon 925) and pH meter (pH 3310, WTW, Germany). Afterwards, the porewater major inorganic anions were determined by ion chromatograph Dionex ICS-5000 (Dionex, USA). Also, total (in)organic C concentration was measured using TOC-L CPH Analyser (Shimadzu, Japan) as well as total concentration of selected elements in the solutions using ICP-OES (720 ES, Varian Inc., USA) to detect availability and potential depletion of the nutrients.

3.3.3. Statistical analysis

Normality testing (Shapiro and Wilk, 1965) was made to ensure that datasets can be well-approximated by normal distribution. Thereafter, the one-way analysis of variance (ANOVA) and subsequent Tukey Honest Significant Difference test (Tukey HSD) was conducted to evaluate differences in means between treatments for measured soil properties. The software R (The R Foundation for Statistical Computing 2018; under the GNU General Public License) were used for performing the statistical analyses at 0.05 significance level.

3.3.4. Estimation of van Genuchten parameters

The model chosen in this study simply can be define through two of the most popular functions, Brooks and Corey [1964] (BC-equation; 1) and van Genuchten [1980] (VG-equation; 2).

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (1)$$

Where Se is the effective degree of saturation, also called reduced water content (0 < Se < 1). Further defined by van Genuchten, (1980) relatively by smoother function with attractive properties.

$$S_e = \frac{1}{\left[1 + (\alpha h)^n\right]^m} \qquad (2)$$

Equations (1) and (2) shows that the soil water retention curve θ(h) (h denotes suction) contains 5 parameters, which are the residual water content θr, the saturated water content θs and the shape factors α, n and m. The RETC software evaluates the hydraulic properties of unsaturated soils. In the RETC program the 'retention data only' was chosen as the type of fitting using van Genuchten model, m=1-1/n.
Therefore, parameters of the van Genuchten model were obtained for each treatment by fitting laboratory measured SWRC datasets (table S3). In T1 and T2, 7 volumetric water content points (retention data point) averaged over six replicates, 8 volumetric water content points (for both T3, T4) averaged over five replicates in T3 and nine replicates in T4 at pF 0, 1.0, 1.5/1.8, 2.0/2.7, 3.0, 3.7 and 4.18 using RETC software (Van Genuchten et al., 1991).

3.3.5. ranges of pore sizes, and the equivalent pore diameter
Ranges of pore sizes (equivalent pore diameters) were estimated using the values of the applied suction pressures. The equivalent pore diameter (Fig. S4) was calculated applying the well-known Young-Laplace equation (Kutilek and Nielsen (1994) and Lim et al. (2016), Hillel, 1980).

$$h = \frac{2\gamma \cos\left(a_{contact}\right)}{gr\left(\rho_{water}\right)} \qquad (3)$$

In equation (3) h is the height of rise in the capillary column (in a soil pore) (m), γ is the surface tension of water (equals to 71.97 kg s−2 at 25), $a_{contact}$ is the contact angle (assumed = 0° rad), g is the acceleration due to gravity (9.8 m s−2), ρ is the density of water (999.97 kg m−3), and r is the radius of the pore (m), (Lim et al., 2016).

CHAPTER FOUR

Results

4.1. Impacts of biochar, manure and compost sole or combined amendment

4.1.1. Co-composting process outcomes

Biochars' highly reactive surfaces and porosity as well as carbon purity lends favourably to its additive in co-composting due to its high capacity to retain water from the fresh biomass during the process.

The pH of retail compost (HB) was slightly acidic in comparison to all 'home-made' composts (pH = 7.33–7.67; Table S2). Also, its total nitrogen content was lower in comparison to all home-made composts. Moreover, C content is significantly lower in HB, however, the C content of home-made compost increased far more by the presence of biochar due to its high C content (86.6%).

The presence of 10% biochar enhanced the composting process after one month (the grass almost completely decomposed with no unpleasant smell). Addition of biochar indeed accelerated the composting process. Comparing C4 (4% BC) and C10 (10% BC) to C0 (0% BC) showed that both co-composted products reached a stable state earlier. This acceleration effect could be explained by the high water and nutrients holding capacity of the biochar, which reasonably created better conditions for co-composting process.

The moisture content of the 'home-made' compost was periodically monitored (Fig. S5). Accordingly, moisture content was kept nearly unchanged around 65 and 75% during the first 80 days of co-composting process. After that the moisture content started decreasing (C0 decreased to 25%, C4 to 52% and C10 remained stable at 67% moisture content). After three weeks of composting pH (in the three prepared composts) reached neutral values between 6.9 and 7.6 (slightly higher (alkaline) pH in C10) and remained stable until the end of the process.

4.1.2. Nutrient retention/leaching as measured in soil porewaters

In the pot experiment with manured biochar, after performing a principal component analysis based on soil properties, it was revealed that the additional application of biochar mixed with manure had no effect (no difference between M2 and MB2 and between M5 and MB5). However, nutrient leaching (e.g., NO_3^-, K^+) from manure addition to soil was reduced when biochar was blended in (by ≤86% compared to manure alone).

In the box experiments (T1, T2), the application of biochar in soil (directly) and/or as the additive in manure/compost significantly decreased DOC leaching (reflecting its high stability; Fig. 19) as well as improved nutrient retention such as nitrogen (see also table S4).

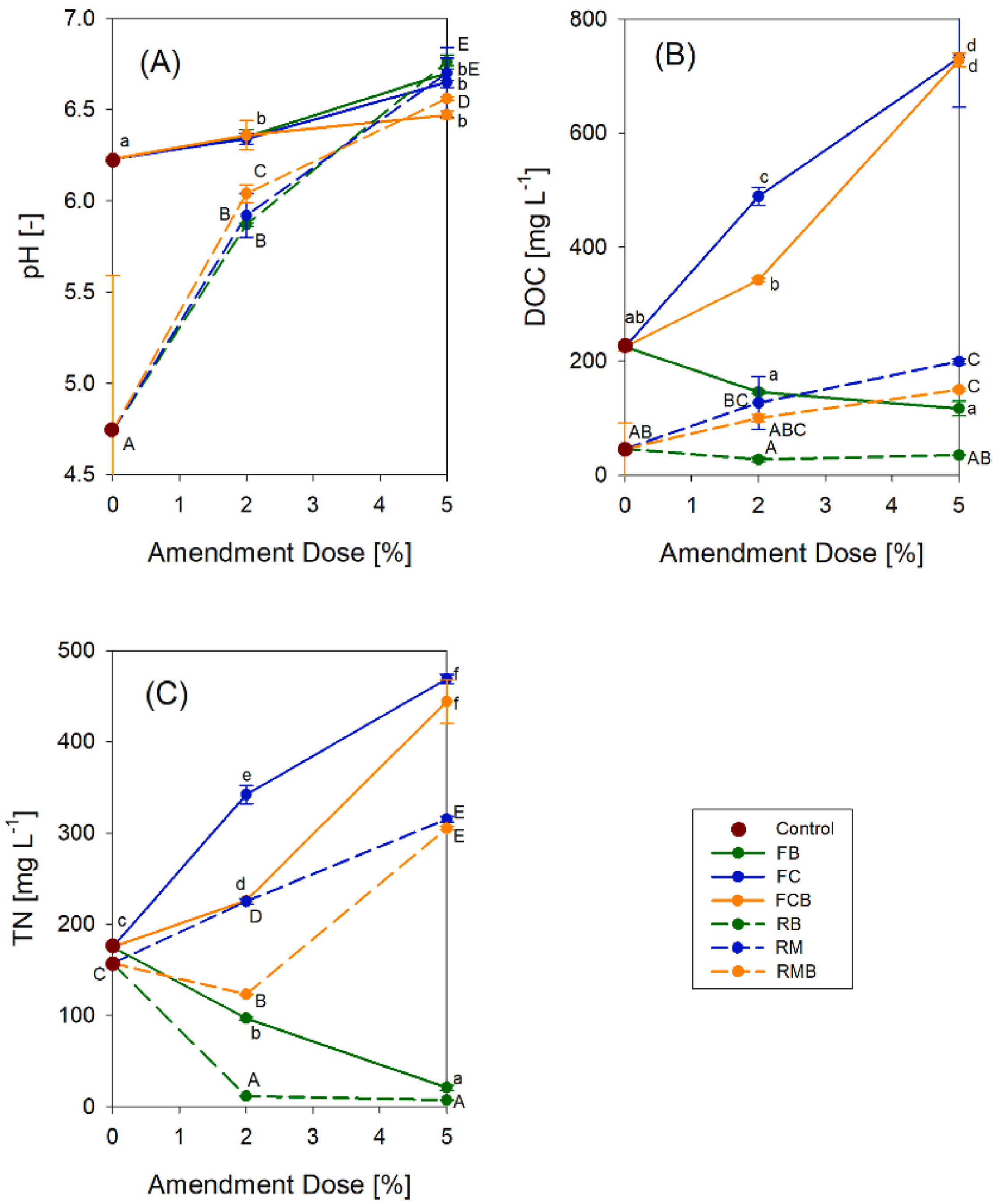

Fig. 19. Value of pH (A), and concentration of dissolved organic carbon (B) and nitrates (C) in porewater of each variant (Seyedsadr et al., 2021).

4.1.3. Plant growth responses to the soil improved by amendments

In co-composting pot experiment, E. sativa did not germinate in the control-contaminated soil, five weeks after germination. In the contrary, application of HB and FC10 produced small cases where necrosis was observed. However, homemade compost application with and without co-composted biochar produced strong plants growth.

A different response was observed for L. perenne. Plants under control established successfully but with poor biomass production. Plants treated by HB developed better, whereas plants with the application of home-made compost produced the greatest biomass.

In general, irrespective to the type of compost or BC addition, the results showed that the addition of compost improved the growth and development of plant considerably (Teodoro et al., 2020).

During pot experiment (manured biochar), the plant physiology parameter measurements were made in the middle of the drought period and showed that amendments affected leaf physiological response to water deficiency. Regarding the biomass weight, biochar, manure and their combination enhanced the fresh biomass production compared to the control soil. Using single manure induced a higher biomass than biochar, which could be related to the higher nutrient content of manure. Similarly, adding the 5% amendments was more efficient than 2%, which again can be due to more nutrients added to the soil. Finally, in the blended biochar-manure, it resulted to a greater biomass increase than the single application of each biochar or manure (Lebrun et al., 2022).

4.2. Biochar with(out) conventional organic matter in the soils

4.2.1. Changes to the physical properties caused by the amendments

In the Fluvisol (T1), changes in bulk density (ρ) showed a significant difference among the control samples (F) compared to all treatments. Especially those where higher rates of the organic amendments were used had a significant reduction (Fig. 20A). accordingly, treatments FCB5, FB5, and FC5 represented the most significant reduction of ρ of 11.0%, 9.4% and 9.2%, respectively. However, no significant difference was seen between individual amendments. The decrease of ρ (and increase of total porosity) related to the rate of the amendments. The changes follow similar trend for enriched compost and co-composted biochar treatments.

The smallest of ρ changes regarding Regosol (T2) occurred in RB2 (6.7%), and the greatest occurred in 5% manure amendment (RM5; 29.5%). The differences between manure treatments with and without biochar (RMB2 and RM2, as well as RMB5 and RM5) were not significant. This represents limited amount of the biochar in the mixture to have any effects on ρ. All treatments in T2 experiment presented substantial increases in porosity compared to the control (R; Fig. 20B). The most significant changes in total porosity were seen between treatments with a high rate of manure with 51.3% (RM5) and 41.0% (RMB5) increases, respectively. Total porosity increased furthest in the T2 (29.7%) compared to the T1 (7.5%) in the case of 5% biochar application.

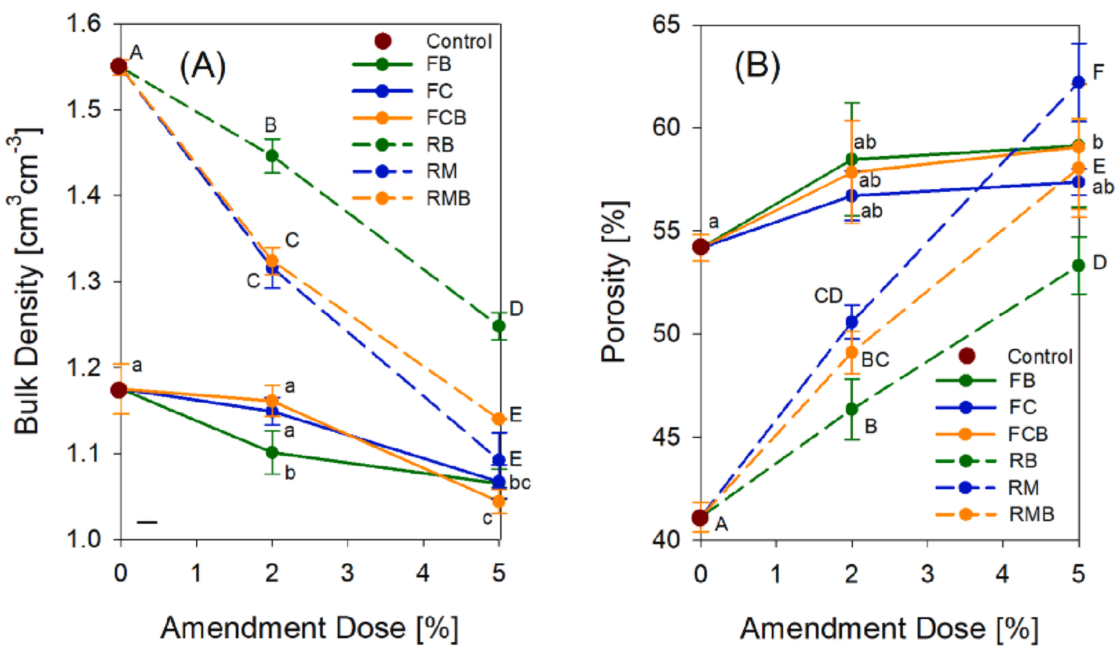

Fig. 20. Bulk density (A) and total porosity (B) of two sets of experimental samples (T1 &T2); Data are in mean values (n = 5). Different letters represent statistical differences between treatments and control by Tukey HSD at $p < 0.05$ (Seyedsadr et al., 2021).

4.2.2. Effect of the amendments on soil water retention curves

In the Fluvisol trial (T1), regarding water retention curve, each amended soil samples (Fig. 21A) starts with an insignificant increase in water content at full saturation (pF 0) compared to the control (Table S3). After each treatment application, the distribution of pores >30 μm (representing "free water"; Fig. S4) significantly decreased, mostly by compost addition. The highest dose of biochar added alone (FB5) showed the highest water content at field capacity (FC; pF 1.8), which was statistically different (by 32.8% higher) in comparison to control F (Table S3). However, FB5 then rapidly depleted the water content than the two remaining organic treatments (FC5, FCB5; Fig. 21A). Treatment FB5 represented the best improvement among other treatments, in terms of both AWC (34.7%) and easily available water content (EAWC; 48.4%) compared to control F (Fig. 21C).

In the Regosol trial (T2), the amendments profoundly changed the shape of SWRC. Consequently, the changes resulted in more gradual decrease of water with decreasing pressure head (Fig. 21B). Both manure treatments (RM5, RMB5) represented the highest saturated water content in comparison to the control R and RB5. This result was also reflected by the increased values of total porosity, especially for both manure variants. All treatments showed an effective increase of water retention (Fig. 21B), in lower pressure heads (lower than field capacity) compared to control. Water at saturation level held more by both of the amendment combinations with manure (e.g., RM5 and RMB5). Although a two-fold increase of this "free water" content was seen when manure is applied (compared with RB5), this water at the saturated level represents non-utilizable water by plants (Hardie et al., 2014). Results reveals that all treatments significantly improved AWC (by RB5 = 83.9%, RM5 = 102.7%, RMB5 = 89.6%) and EAWC (by RB5 = 114.2%, RM5 = 118.7%, RMB5 = 102.2%) in trial 2 (Regosol).

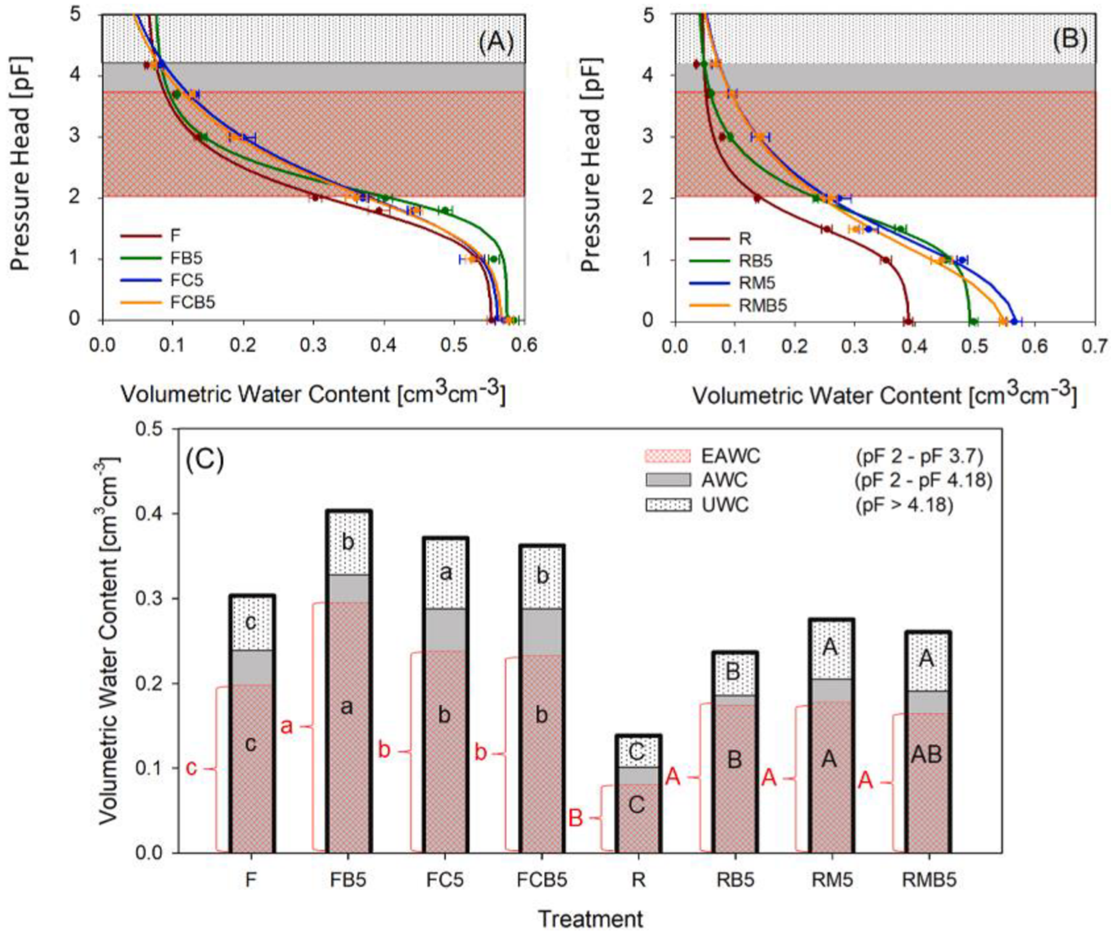

Fig. 21. Water Retention Curves of Fluvisol (A) and Regosol (B) experiments, and division of soil water into unavailable (UWC) and available (AWC). The part of easy-available for plant (EAWC) is red-marked (C). Individual figures (top) show water retention curves of Regosol and Fluvisol samples (non)enriched by organic amendments. Means of 6 replicates are highlighted by bullets. The graphs are supported by the more detailed at Table S3 (standard deviation and letter differences are presented). Different letters in figure (C) represent statistical differences between variants by Tukey HSD for each trial (capitals for trial T2), (Seyedsadr et al., 2021).

4.2.3. Saturated hydraulic conductivity changes

There was an overall decrease in Ksat in both soils. In the Fluvisol, Ksat values of all amendments decreased compared to the control (F), the most pronounced for FC5 (54.7%; Fig. 22). The presence of biochar (FCB5) resulted in a 27.3% decrease compared to the control F. In the T2, Ksat of biochar and the mixture of biochar and manure (RB5 and RMB5) was decreased compared to control R. Contrarily, higher Ksat was measured only on the mixture of soil and manure RM5 (7.11% increase compared to R). Though, the changes among all amendments were statistically insignificant.

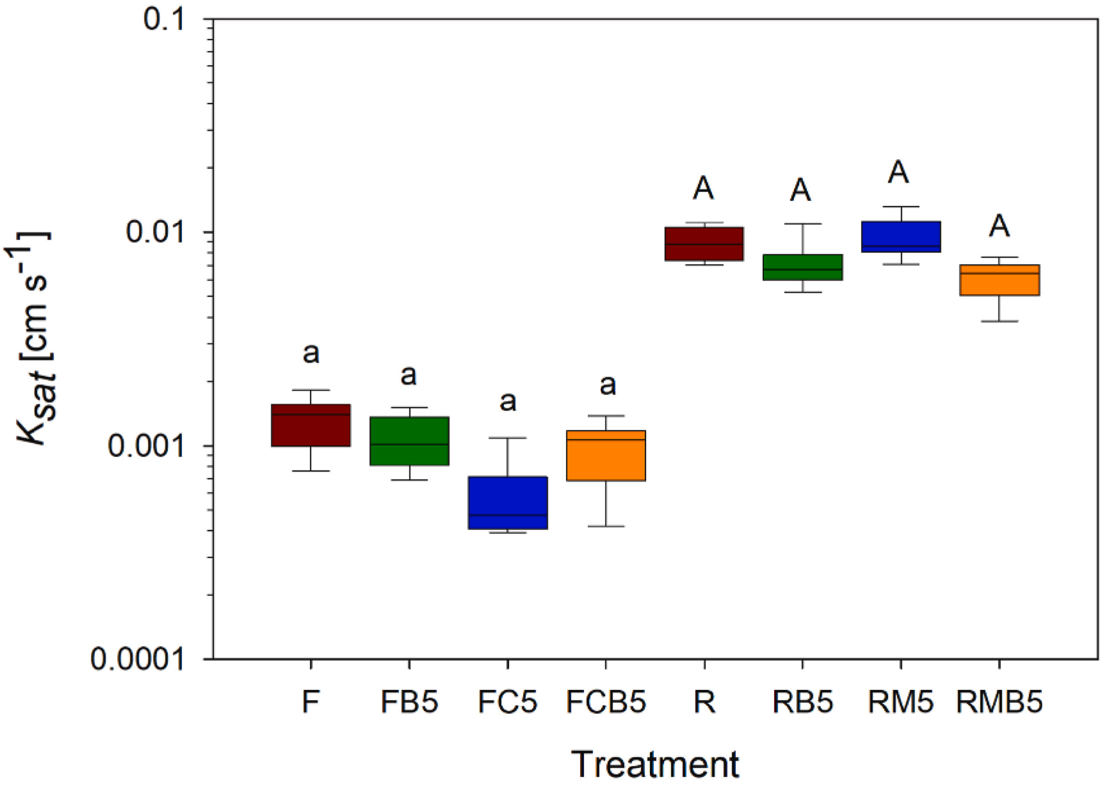

Fig. 22. Laboratory *Ksat* values of the experimental Fluvisol (green) and Regosol (red) treated by the organic amendments; Boxplot represents *Ksat* (sample minimum, first quartile, median, third quartile, maximum, n = 5); Different letters represent statistical differences between treatments by Tukey HSD at $p < 0.05$ (Seyedsadr et al., 2021).

4.3. Regosol treatment using biochar mixture under consolidation (T3)

4.3.1. Changes to the physical properties caused by the amendments

Consolidation had no significant impact on bulk density whether in the control or any of the treatments. However, the treatments did have a significant impact on this parameter; RMB10, 20 & 50 decreased bulk density by; 24, 26 and 25%) and manure treatments by 24% (Fig. 23).

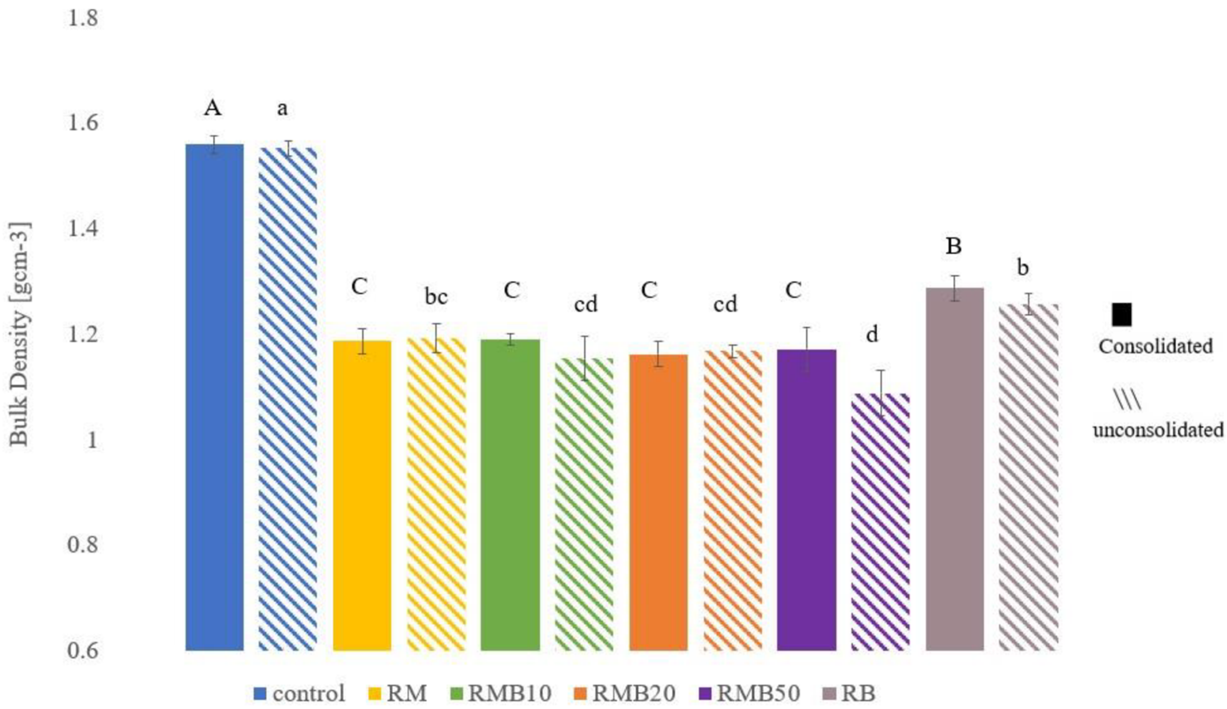

Fig. 23. Bulk density of the consolidated and unconsolidated samples; Data shown as mean values (n = 4). Different letters represent statistical differences between treatments and control by Tukey HSD at $p < 0.05$.

Consolidation had some insignificant impacts on total porosity (determined from saturated water content). However, all treatments significantly improved the total porosity compared to control (Fig. 24); RMB50 were higher in total porosity (30%, respectfully) significantly than biochar (20%) and manure (20%) alone. As a result, the application of RMB50 raised total porosity by more than 10% compared to the control.

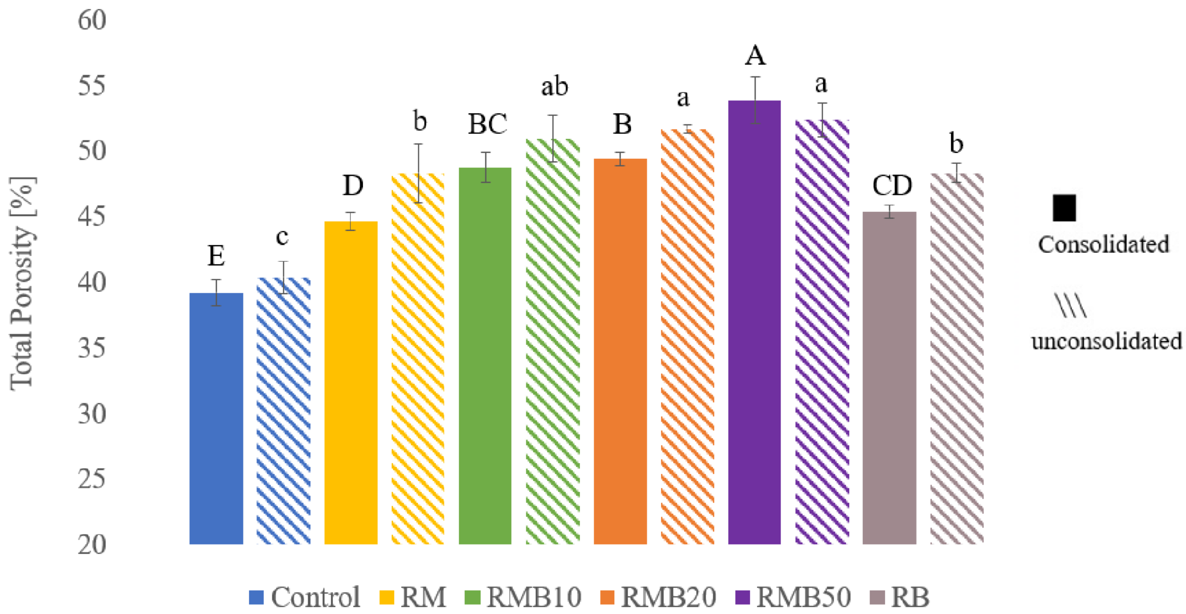

Fig. 24. Total porosity of the consolidated and unconsolidated samples; Data shown as mean values (n = 4). Different letters represent statistical differences between treatments and control by Tukey HSD at $p < 0.05$.

Consolidation had insignificant impact on water retention curves (Fig. S6), but the most profound impact was, once again, due to individual soil treatments (Fig. S6.C).

4.4. Biochar vs. hydrogel in the Cambisol

Changes in bulk density (ρ) showed a significant difference among all treatments (Fig. 25) Biochar represented the most significant reduction of ρ of 14.0 %. In contrast, no significant difference was seen between amendments in total porosity.

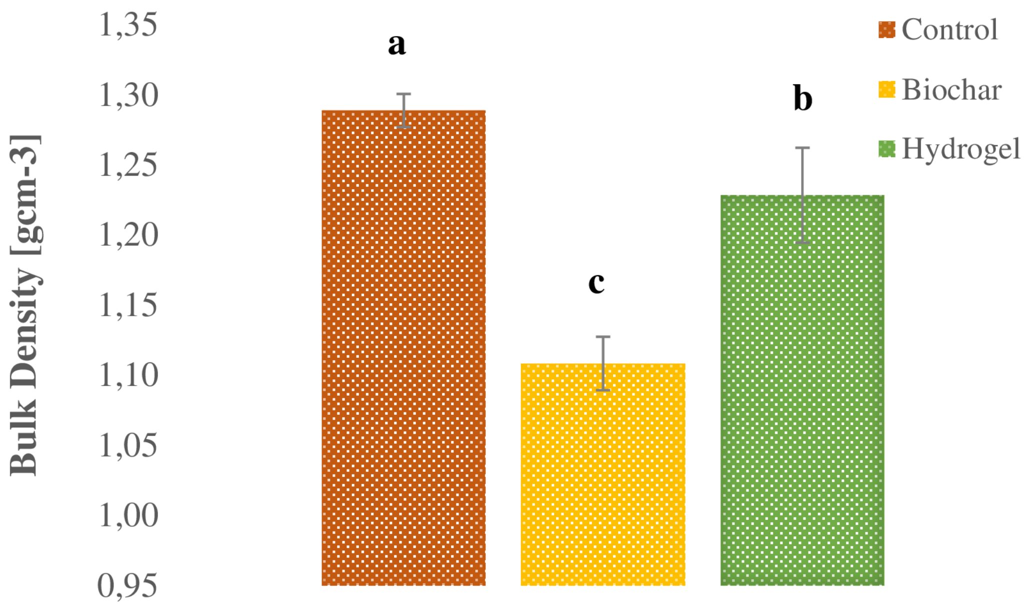

Fig. 25. Bulk density of the control, biochar and hydrogel samples; Data shown as mean values (n = 4). Different letters represent statistical differences between treatments and control by Tukey HSD at $p < 0.05$.

Water retention curve of each amended soil samples (Fig. 26) started with an insignificant increase in water content at full saturation (pF 0) compared to the control soil. Biochar amended soil samples showed a higher water content at field capacity (FC; pF 2) of 35.85 % (32.53 % higher than hydrogel) compared to untreated samples. A better improvement in terms of both AWC and easily available water content (EAWC) represented by biochar (57.43 % and 53.38 % respectively), see figure 26 (right). Hydrogel on the other hand, showed an insignificant increase in terms of EAWC in comparison to control. The only significant improvement that hydrogel made, compared to untreated soil, was regarding AWC (only an increase of 9.5 %).

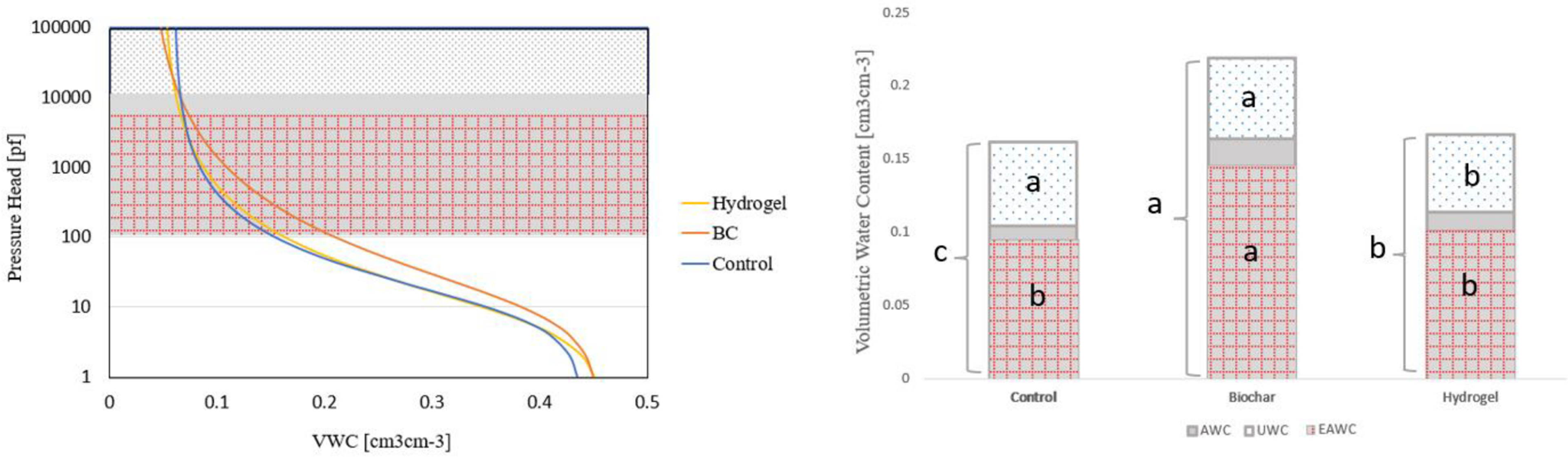

Fig. 26. Water Retention Curves of biochar and hydrogel experiment in Cambisol.

CHAPTER FIVE

Discussion

5.1. Biochar in the soil amendment mix

5.1.1. Characteristics of the co-composted material

The presence of biochar, aspecially at the highest dose (C10) during the composting process hastened the 'finishing' such that the final compost material contained barely any visible vegetation fragments with no unpleasant odourafter one month of composting compared to C0 and C4. These findings are consistent with earlier studies (Lehmann and Joseph, 2012).

Reaching a stable finished compost in a faster time whilst retaining the quality of the material, practically and economically, is desirable. It has previously been found that the addition of food waste-derived biochar to biodegradable plastic polylactic acid improved its degradation rate under composting conditions (Kane and Ryan, 2022).

Regarding the end-product quality enhancement, including biochar in the process of composting, can induce stability earlier in the composting process than composting without biochar, resulting in several desirable effects to amended soils, such as increased water holding capacity of the biochar. For example, Teodoro et al (2020), added 4 to 10 % wt. of the wood-based biochar is recommended to cause favourable results of plant growth due to promotion of water and nutrients retention after compost-char was added to soil. However, according to Agegnehu et al. (2016), co-composting of chicken manure, for instance, requires a larger amount of biochar (20%) to see favourable results, like decreased nitrogen loss by 52%.

In the experiment using rice- and sugarcane-based biochar (Farid et.al., 2022) the benefits of compost and biochar were found when using co-composted biochar (the plant residues + 10% biochar + 15% manure + 5% mineral fertilizer, by weight), which presented improved results of zucchini growth parameters and the sandy soil C balance, compared to biochar or compost alone. Co-composted biochar decreased considerably

C emissions, and, hence, lessened GHGs, since this amendment presented positive carbon cycle values.

5.1.2. Leaching nutrient status resulting soil amendments

In trial 1, compost and co-composted biochar samples (FC5 and FCB5) exhibited the greatest leaching of DOC, TN, K, Ca, and Mg. On the contrary, the application of biochar alone to the same soil (FB2, FB5) decreased DOC leaching compared to control. Results from trial 1, suggest the possible stabilisation of soluble humic substances by biochar. Biochar in combination with compost and/or manure can function as an ion exchange matrix. This property of biochar can bind leached elements from other organic matrices (Seyedsadr et al., 2021).

Lawrinenko and Laird (2015) considered three possible sources for the origin of anion exchange capacity in biochar (depends on the feedstock and pyrolysis and the significant amounts of C, O, and some N), which are responsible for the possible leaching reduction of anionic nutrients. Sources includes Pyridinium groups, Oxonium groups, and Protonated aromatic rings. Oxygen (O) containing alcohol, carbonyl, and carboxylate functional groups are also claimed to contribute to biochar cation exchange capacity (CEC) due to their negative charge that serves as Lewis bases for the sorption of cations. Heteroatom comprising chemical functional groups in biochar that are polar and provide sites for hydrogen bonding, ion–dipole and dipole–dipole interactions, also influence surface properties of biochars.

When comparing the single amendment application in the pot experiment with manure (Lebrun et al., 2022), manure caused a higher biomass production than biochar, which could be related to the higher nutrient content of manure. Also, adding 5% of the amendments was more efficient than 2%, which again can be explained due to more nutrients added to the soil. Further, when biochar was added to manure, it induced a greater biomass growth than the application of biochar or manure alone. Therefore, biochar stability and capacity to hold nutrients are fundamentally more effective than those of other organic matter in soil.

Also, even a much greater nutrient retention can occur when it is in combination with a specific chemical structure (manure / fertilizers) due to its high charge density (Lehmann and Joseph, 2012). Lehmann and Joseph (2012) also introduced retention of P in liquid manures as the main motivation for applying biochar in combination with liquid manures or slurries.

Similarly, the experiment on agricultural sandy loam soil highlighted the positive interactions between biochar and farmyard manure on wheat growth and yield when 2% of the mixture applied to the soil. The higher crop growth and grain yield can be explained due to nutrient retention (Bashir et al., 2020) induced by biochar due to its sorption capacity that could have retained manure nutrients and further released them slowly during plant growth (Lebrun 2022). In contrast, the application of manure without biochar released its nutrients more quickly (Lebrun et al., 2022), with potential leaching (Lebrun et al., 2022; Seyedsadr et al., 2021).

Therefore, biochar being in contact with organic fertilizers in soil, practically reduces the nutrient being leached out of the soil matrix to proximal waters and thus, increases the longevity of organic fertilisers to soils (El-Naggar et al., 2019; Razzaghi et al., 2020; Xiao and Meng et al., 2022; Zainul et al., 2017). Biochar effects on nitrogen retention in trial 1 and 2 is also in agreement with Li et al. (2018) study, in which 2% w/w biochar addition to a silty clay soil reduced N leaching. Moreover, El-Naggar et al (2019) discussed that activating, coating, composting, and co-composting biochar with other organic matters can be promising methods to enhance the effectiveness of biochar for promoting soil fertility.

5.1.3. The effect on plant growth

Teodoro et al., (2020) clearly suggests that different source material for biochar variously affects the physiological response of the plants: the biochar used for the present study be found to be suitable amendment supporting plant growth in metal-contaminated soils (Fluvisol).

Biochar increased soil water content while single use of biochar and manure and combined improved soil and plant nutrient content. Such observations showed that biochar and manure amendment, due to their effects on soil moisture and nutrient status, could alleviate drought stress to the photosynthetic system of sugar beet plants. drought stress affects plant growth that is due to the reduction of photosynthesis. The addition of manure and biochar increased biomass production (Lebrun et al., 2022). Other studies have stated similar results with faba bean under drought stress (Abd El-Mageed et al., 2021).

Briefly, the mechanisms that is involved in the positive effects of biochar on crops can be discussed as follows:

(i) biochar reduces soil bulk density through its high porosity, which consequently reduce soil resistance to root penetration (ii) its high porosity improves soil moisture retention; and (iii) biochar can improve nutrient availability due to nutrient retention and modification of soil physicochemical properties. Although soil pore water analysis in pot experiment showed that biochar retained nutrients, this could still be available for plants.

Similarly, manure effectiveness on soil moisture and soil nutrient contents could explain the improvement of sugar beet biomass. Moreover, addition of easily degradable organic matters like biochar and manure/compost amendments to soil is beneficial for soil micro- and meso-fauna, which in return have a great role in organic matter and nutrient cycling as well as soil structure (Sizmur et al., 2016; Lebrun et al., 2022).

Some biochars are reported as having wide C:N ratios suggesting that their addition to soils can adjust nutrient stoichiometry unfavourably and render N unavailable for plant uptake. However, this could be mitigated by compost which has a higher N content. Therefore, co-composted biochar could be suggested to keep the C:N ratio in a favourable rate for plants (Sizmur et al., 2016).

5.2. The Effects of biochar alone and the biochar mixtures on selected soil properties

5.2.1. Changes of bulk density and porosity

Comparing the Fluvisol and Regosol, it appears that the influence of biochar on bulk density *(ρ)* reduction is more apparent in coarse-textured soils, which is along with Blanco-Canqui (2017) and Razzaghi et al. (2020) results. The very low ρ of all the applied amendments in trial 1 (T1) and 2 (T2) is lower than 1 g cm^{-3} (Table 3), showing the extent of their impact on soil ρ are comparable to the range of biochar impacts that have been reported in meta-analysis studies (Omondi et al., 2016; Edeh et al., 2020; Razzaghi et al., 2020), in which biochar application has reduced ρ by ~11% in the coarse-textured (sand and loamy sand) and ~7% in medium-textured soils (sandy loam, loam, silt loam, sandy clay).

A decrease of ρ similar to the results of T1 and T2 has been reported in a column experiment using maize- and beechwood-based biochar into sandy soil (Abel et al., 2013). A linear character of the ρ reduction has been shown in another study (Omondi et al., 2016; Edeh et al., 2020), which could be negatively correlated to the changes in porosity. Also, Hardie et al. (2014) reported that biochar may cause greater total porosity and/or lower bulk density.

The following mechanisms can explain biochar influence on soil porosity in general: (1) direct influence of biochar inter-pores, (2) packing or accommodation pores formation between biochar and the surrounding soil aggregates (Blanco-Canqui, 2017), and (3) via improved soil pores persistency due to increased aggregate stability (Hardie et al., 2014). An increase in SOM and aggregate stability induced by the soil amendments can also cause this effect (El-Naggar et al., 2019; Liu et al., 2012).

In more details, biochar impacts the soil bulk density reduction through the following possible mechanisms (Blanco-Canqui, 2017; Horak et al., 2019; Blanco-Canqui, 2021): 1) According to the fact that the bulk density of biochar is much lower than the average bulk density (1.25 Mg m -3) of the soil, therefore, having a higher porosity than soil mineral particles, the overall bulk density of the soil reduces after biochar addition through the dilution effect. Also, it has been suggested that swelling effects may cause a decrease in ρ in sandy soils (Jacka et al., 2018). 2) An increase in organic carbon concentration after biochar application to soil, particularly labile carbon, can boost the biological activity, soil aggregation, and increase macro-porosity, and consequently reducing soil bulk density. 3) Also, the high ion exchange capacity and high specific surface area of biochar can alter the pore-size distribution in the soil due to the easy bonding organic matter with clay particles by the biochar presence (Horak et al., 2019).

5.2.2. Soil water retention curves modifications

Biochar in Fluvisol represented the best improvement in terms of field capacity and of both available water (AWC) and easily available water content (EAWC) compared to the rest of the treatments in T1. Although there was no sign of a positive effect of biochar in combination with compost in the T1 and T2, it results in a greater likelihood of long-lasting positive effects of biochar in combination with compost due to the longevity of biochar. Biochar made water to be released more slowly in the RMB5 compared to RM5, although in both cases they held more water at saturation level. The water content at saturation level (doubled when manure was applied compared to RB5) demonstrates “free water”, which represents non-utilizable water by plants (Hardie et al., 2014). In the T1 and T2, a rapid loss of water (between pF 2 and pF 3.0) was induced by adding biochar alone to the Regosol, which could lead to more easily available water content (EAWC). These findings agree with the review of Razzaghi et al. (2020), where biochar increased easily available water content by 21% in coarse-textured soils regarding lab-based studies. The field capacity of the coarse-textured amended soil significantly increased by 51%. It is increased by 13% in the medium-textured soils compared to the fine-textured soils (FC = < 1%) after biochar application. In greenhouse and pot experiment results, the coarse-textured soil field capacity reached a higher percentage (by 71%) compared to the field and lab-based experiments (37% and 10%, respectively; Razzaghi et al., 2020).

Wilting point in the treated coarse-textured soils increased by 47%, and 9% for the medium-textured soils. however, for the fine-textured soils, WP was reduced by 5%. For the studies, which were conducted in the greenhouse & pot, WP for the coarse-textured soils was increased by 85%, while in the field studies by increased by 16%. The results of WP in the lab-based studies demonstrated a decrease of ~2% (Razzaghi et al., 2020).

Biochar application to coarse-textured soils significantly increased available water by 45% compared to the medium- and fine-textured soils (21% and 14%, respectively). Plant available water for coarse-textured soils was increased by a larger percentage (76%) among studies conducted in the Greenhouse & pot experiments. The field- and the lab-based studies exhibited 27% and 21% of the increase in available water in the treated coarse-textured soils, respectively. Available water in the medium-textured soils showed an increase in field-based studies (33%) compared to the GH & pot (8%) and lab studies (18%). The same variable in the amended fine-textured soils was increased by 19% in the field and lab studies, and 13% in the GH & pot studies. Razzaghi et al., 2020).

A report by another study shows that Biochar mostly altered the water retention curves of the sandy soil, while only a few changes were observed in sandy loam and clay loam. Biochar increased the water holding capacity by 62% in the sandy soil, 38% in the Sandy Loam, and 18% in the Clay loam (Santos et al., 2022). An increase by 28.5% of AWC of biochar amended sandy soils has been observed in a meta-analysis compared to unamended controls (Ibrahimi et al., 2022). This is also comparable to 24.3% increase reported by Omondi et al. (2016) and Blanco-Canqui (2017), who also presumed that increased water retention did not necessarily lead to increased AWC.

Studies reporting biochar mixed with compost (Al-Omran et al., 2019; Zainul et al., 2017) and/or co-composted biochar (El-Naggar et al., 2019; Teodoro et al., 2020) have generally shown a significant greater water retention in comparison to using compost alone. A field study demonstrated a synergistic positive outcome of compost-biochar mixtures on water-storage capacity of a sandy soil, in which a constant amount of

32.5 tons ha-1 and biochar at (5, 10, and 20 tons per ha) were mixed (Liu et al., 2012). The improvement of the aggregate's stability explains the increased water retention in manure-amended soils (Nyamangara et al., 2001; Gautam et al., 2021) as it is confirmed by previous studies of soil macroaggregate formation after manure application (for example Chen et al. (2020)).

Four mechanisms can explain the influence of biochar on soil water retention: (1) the direct influence of inner pores within the biochar (2) the size reduction of soil pores by their clogging with smaller biochar particles (Liu et al., 2017), (3) through improved persistence of soil pores due to increased aggregate stability (Hardie et al., 2014), and finally (4) the interaction of water directly with the surface of biochar due to the tension (π) interaction to the carbon surface, hydrogen bonds on carboxyl groups (Conte et al., 2013) or hydration interaction with cations (such as Na^+, K^+, Ca^{2+} and Mg^{2+}) represented by the cation exchange capacity (CEC) (Kutílek and Nielsen, 1994; Jacka et al., 2018).

In summary, the combination of biochar with other organic amendments (composts, manure etc) can add advantages regarding hydraulic properties to soils, which supports previous findings (Lentz et al., 2019; Haynes and Naidu, 1998; Verheijen et al., 2010; Blanco-Canqui, 2017; Brynda et al., 2020; Razzaghi et al., 2020). The long-lasting and the most effective amendment on a silt loam were introduced to be the biochar and manure combination (1% biochar + 2% manure w/w), which produced the greatest PAWC in a long-term study (Lentz et al., 2019).

5.2.3. Saturated hydraulic conductivity changes

In an overall view, Ksat in both soils in T1 and T2, reduced in amended soils, however insignificant compared to controls. Although, the Ksat has decreased after the amendment of biochar, manure and compost or its mixture, these changes had only a limited extent in both examined soils (Regosol & Fluvisol). Increased water retention resulting from Trials 1&2 underpins the fact that the benefits of biochar and other organic matter application for increased water availability not affecting the risk of surface runoff formation.

The decrease in Ksat values in sandy soils has been already reported in literature (Lim et al., 2016; Edeh et al., 2020). The differences in the magnitude of the reduction can be explained by the textural differences or type of clay particles present. Bot and Benites (2005) relates the increase of organic matter to the enhancing rainwater infiltration. Increased level of OM in soil leads to improved soil aggregation and porosity, and consequently an increase in the number of macropores, which thus lead to greater infiltration rates. However, the decrease in Ksat, in the presence of biochar, can be attributed to the clogging of effective soil pores that biochar may cause (Barnes et al., 2014; Wang et al., 2013). Furthermore, the Ksat can also be affected by slow or no flow in intra-pores (of small biochar particles), (Hardie et al., 2014). water flow can also be blocked in effective soil pores by biochar particles (Barnes et al., 2014) or by decreasing the volume of effective pores by water that sorbed on biochar surfaces (Jeffery et al., 2015).

Lim et al., (2016) linked the effect of four different woody biochar (1%, 2% and 5% w/w) on Ksat to biochar particle sizes. The rate, type of biochar, as well as the original particle size of soil influenced the Ksat of the treated soil samples. With larger particles sizes (60%; >1 mm), biochar decreased Ksat to a larger degree than the smaller particle size biochar (60%; <1 mm) in the two sandy (coarse and fine) textured soils. He also stated that increasing in tortuosity in the biochar amended sandy soil could explain the decrease in Ksat. However, 1% and 2% biochar additions to the clay loam soil increased the Ksat. Higher biochar amounts (5%) provided no further changes (Lim et al., 2016).

A review of 37 articles between 2010 to 2019 providing biochar-soil moisture effects was performed by Edeh et al., (2020). It shows that biochar enhanced not only soil water retention (discussed in the previous part) but also decreased Ksat in sandy soils, while it decreased runoff in clayey soils, due to Ksat increase. Results, regardless of soil type, exhibited that biochar application increased AWC, FC, PWP, and total porosity. Ksat and bulk density on the other hand, reduced by 38.7% and 0.8%, respectively.

Omondi et al., (2016) on the other hand, reported an increase in Ksat by 25.2% after biochar application, which was not correspond to the biochar rate application. However, greater effect has been observed in coarser soil texture compared to fine and medium textures. Biochar improvement of macro-porosity and aggregation can enhance the Ksat and soil drainage (Abel et al., 2013; Liu et al., 2012; Hardie et al., 2014; Omondi, 2016) by assisting bioturbation in some soils (Laird et al., 2017; Lei and Zhang, 2013).

The duration of just six weeks of our study limited the assessment of whether the bioturbation occurred. By investigating the saturated hydraulic conductivity in a sandy loam soil (Jacka et al., 2018), Ksat were significantly decreasing over time among control samples, due to particle transport within the pores, which becoming continuously clogged by finer particles. Whereas this temporal variability supressed by the use of biochar (2% and 5%). Samples by 5% biochar reduced the Ksat significantly compared to control samples and the temporal variability modified not only compared to control bu also compared to 2% biochar samples as well. Temporal variability of Ksat values (Jacka et al., 2018), therefore, suggests longer-term monitoring to gain better insight into this aspect of soil hydraulic influence (Omondi et al., 2016).

The crucial limitation of the experiments is that the laboratory experiments are conducted in a controlled condition, which neglect various external factors and variables in world life setting such as rainfall, temperature, existence of biota and root network in the soil profile etc., which can have significant influences on infiltration rate, soil moisture and so on.

5.3. The effect of consolidation on soil physical properties

5.3.1. Implications of biochar and manure on bulk density

The consolidation experiment was designed to test whether amendment with biochar could reduce susceptibility to compaction. In previous studies, changes in physical properties could be immediately observed in compacted, fine- and coarse-textured soils, after mixing compost and biochar to soil, which suggested the influence of the less dense materials on the improvement of the physical soil properties (Glab et al., 2018). Similarly, Glab et al., (2018) study also showed the amendments rates correlation to the changes.

The overview of similar studies by Blanco-Canqui (2021) indicates that biochar application can reliably enhance soil's resistance against compacting forces and potentially improve the overall resilience and strength of the soil. In the same study a comparison has been made, in which bulk density was investigated in different soil amended by biochar as one of the soil compaction parameters. It has been shown that the bulk density decrease was twice larger in fine- and coarse-textured soils (6%) than in medium-textured soils (3%). In the present study only one soil was used, and consolidation failed to have any significant impact on bulk density regardless of whether soil was amended or not.

Significant impacts on bulk density were measured as a result of individual soil amendments in the present work. Biochar high porosity and its high C content are factors that can alleviate the compactability and compression of soils (Blanco-Canqui, 2021; Lima et al., 2022). Therefore, the organic C in biochar could have promoted the elasticity or rebounding capacity of the soil matrix and consequently, can reduce the soil compatibility (Soane, 1990). Even a small change in C content can make a positive change to compactablity of soil (Soane, 1990), it would then explain the significant decrease in bulk density and increase in total porosity by organic matter compared to control. Further work on soil compaction in a range of variously textured biochar amended soils would confirm whether the limited results observed in the present study are representative.

5.3.2. Implications of biochar and manure on water retention

The increase in soil water retention in T3 at FC, EAWC and AWC by all treatments compared to control is attributed to the great water adsorptive capacity of biochar and higher organic C in all treatments that can improve the water aggregation structure of the soil. Regarding AWC, the greatest increase is caused by biochar credited by its high porosity with high C concentration and, also due to its high specific surface area, which increases the ability of biochar to adsorb water.

Previous studies (Garg et al., 2021; Wong et al., 2017) claimed that the amendment of biochar can improve the water retention of dense soil e.g., with over 90% degree of compaction. A column study for the purpose of investigating biochar potential application in bioengineered structures has been conducted by Hussain and Ravi (2021). For that reason, the influences of biochar amendment on the water retention of compacted soils have been measured. As a result, the amendment of 5% to 10% (w/w) biochar increased the optimum moisture content of the silty sand. Also, the lower compressibility during compaction was achieved due to the internal porous structure of biochar, which increased the porosity and entrapment of air in the soil after biochar amendment. Soil water retention was observed to be increased by an average of 30–150% in both silty sand and pure sand after the biochar amendment (Hussain and Ravi, 2021).

Our study only tested ρ, total porosity and SWRC in T3, nevertheless, biochar has been shown to increase Ksat in silty sand, whereas to decrease Ksat in compacted pure sand due to biochar addition. After an investigation of the effect of mesquite biochar on the hydro-physical properties, the amendment of 5%, 10% and 15% (w/w) biochar to the compacted silty sand and pure sand increased water absorption capacity and decreased infiltration rate and Ksat. The results suggested the application of biochar amended soil in bioengineered structures (Hussain et al., 2021).

The study of Liu et al., (2017) indicated that biochar could increase wheat vegetative growth, along with soil compaction stress alleviation. The crop growth was favourably impacted after amendment application, but the reasons are complex, including physical, biological, and chemical aspects. Our study only tested physical aspects; nonetheless, biochars and manures have been shown to be efficacious in soil chemical and biological improvement (Agbede and Oyewumi, 2022), which is potential because of improved aeration of soils, and moisture holding due to the soil physical properties improvement such as soil bulk density reduction, and soil porosity increase (Kang et al., 2022). These improved soil physical properties were possibly benefit wheat tillering and root elongation, and thus boosted the wheat vegetative growth with higher straw weight, which represents good production (Liu et al., 2017).

The obvious limitation is that only one soil was used here; further work should now consider different textured soils. This study also only used one biochar; biochars of different origin materials have been shown to have vastly different surface areas (Nzediegwu, et al., 2022), and thus would impact soil bulk density when added to soils, and also moisture retention. Moreover, in most cases when variables under normal and consolidated conditions were compared in T3, both control samples had insignificant differences. That indicates a limit of compaction influence.

5.4. Efficacy of biochar compared to synthetic soil moisture retention additive (hydrogel)

Summary of the trial 4 results showed that bulk density was reduced significantly in amended samples with both biochar and hydrogel compared to control samples. However, the total porosity in the T4 was not shown significant differences between all samples. Biochar showed a better improvement in case of FC, AWC and EAWC compared to control and hydrogel samples. It should be noted that although biochar was used in higher dose than hydrogel, both were in their optimal dose that was suggested for field application.

Although hydrogel water holding capacity at different suction pressure stayed similar to control samples in our study, results of a lab experiment using 10 different concentrations (0.02% – 33%) of hydrogel in sandy and silty clay loam soils, revealed that hydrogel can improve soil physical properties while also increasing water use efficiency and plant development parameters in agricultural dry and semi-arid fields (Albalasmeh et al., 2022). Mohawesh and Durner (2016), associated the decrease of bulk density of both biochar (1.0%, 2.5%, and 5.0%) and hydrogel (0.10%, 0.25%, and 0.50%) effects to the enhancement of macro-porosity of a sandy soil.

Contrasting results to our study were reported in literature (Mohawesh and Durner, 2016) that the soil amendments, biochar and hydrogel, altered the total porosity and pore size distribution. The same results also have been observed (Womack, et.al., 2022) when 0.4% w/w rate hydrogel were applied to three different soil textures (sandy, sandy loam and clay).

The influence of higher dose has not investigated in our study, though Mohawesh and Duner (2016) reported a significant enhancement of water retention in amended soils by both biochar and hydrogel with positive correlation to the increasing rates. Similar to our result that hydrogel improved the AWC, according to literature hydrogel improved the water retention in clay and sandy loam soils when 1% applied (Saruchi et al., 2019). In the same study (Saruchi et al., 2019), the increase of the water in both soil samples reached the equilibrium after 36 h. The moisture content of clay soil increased better compared to sandy loam soil. The study claimed that the synthesized biodegraded hydrogel-IPN could improves the water holding capacity of the soil, and therefore, it can be used effectively in dry soil conditions for a longer release of water. However, it is stated that a complete degradation occurred after 77 days.

In our study, only the changes in water retention affected by biochar and hydrogel were examined in the forest sandy soil, however, studies (Qin et al., 2022) claimed a significant enhancement in the germination percentage and the average leaves number of wheat plants by 21.88% and 100% after 21 days and an improvement of the water uptake value of wheat plants by 94.7% with Gel-glycerol as the loamy soil amendment. Their findings offered that Gel-glycerol are an excellent applicable agent in the agriculture ecosystem, as well as an alternative solution for solving the conflicts of harsh environmental conditions.

Biochar and hydrogel both are recommended to be used in soils specifically in agricultural soils to enhance water retention, germination, and plant growth etc (Ekebafe et al., 2013). However, some studies showed hydrogel swelling sensitivity to temperature, pH and salt concentrations (Dehkordi and Shamsnia, 2020), and its degradability (Saruchi et al., 2019), while biochar can retain longer in time after application with no harmful trace. Biochar on the other hand, is hard to be applied in the field in large scales and mostly not economically feasible compared to hydrogel application.

5.5. Practical utilization of biochar in drought-prone soils

The primary motivation of our study was to enhance the ability of the coarse-textured agricultural soils to retain more water to mitigate agricultural drought. Such soils are especially vulnerable to various drought-related issues such as increased soil erosion, high salinity, low pH and low nutrients retention and consequent uptake by plants with attendant consequences to sustainable food and agriculture production. This research was therefore oriented towards the investigation of biochar and more commonly used 'traditional' organic amendments and their single or combined influence on soil water retention, which could be directly beneficial for farmers and other land managers.

Our study indicated that biochar amendment can significantly increase plant available water capacity in coarse-textured soils with a more pronounced effect in the tested Regosol (very sandy agricultural soil). This increase in water retention was not accompanied by a significant reduction of K_{sat} which implies an unchanged propensity for surface runoff. This is a favourable finding as an increase in surface runoff leads to an increased risk of erosion, especially on highly trafficked agricultural soils. The documented increase in plant available water content and the reduction in nutrient leaching out of the soil could be beneficial to reduce excess fertilizer leaching and consequent nitrate leaching to underground waters.

Compared to traditional organic amendments, biochar application is expected to have longer-lasting effects which may support higher agricultural production in a less favourable climate. The combination of biochar with compost and/or manure can last longer in soil than when those materials are applied singly, compared to other fertilizers e.g., nitrate itself or other SOM applications alone which would renew input in each cultivation season (Basalirwa et al., 2019). Due to all the previously mentioned positive effects of the chosen biochar alone as well as in the mixture with compost and manure, an increased crop yield may be achievable in such treated soils. Consequently, the expected higher crop yield would bring significant economic benefits to the farmers. Hydrogel on the other hand, due to its high absorbent capacity, is mainly suggested to be used in forest areas, around the root zones of trees. They are also degradable and can be benefits from seasonal application. However, biochar can be widely used and alleviate the harsh and stress conditions in favourable to wide variety of plants.

Furthermore, long term study (Wang et al., 2022), on an agricultural field (Spring Maize) demonstrated that biochar had a great potential for improving soil carbon sequestration (over 80% C sequestration efficiencies) to agricultural soils due to dramatic enhancement of C storage, although biochar addition enhanced soil respiration and enzyme activities. These effects of Soil CO_2 emissions and enzyme activities in biochar treatments decreased further with time. Aging of biochar that leads to a promotion effect on soil emissions proved also through Feng et al., (2022) study by showing the reduction of NH_3 volatilization, N_2O and CH_4 emissions from agricultural soils that highlights the biochar potential role to mitigate global warming (Feng et al., 2022).

CHAPTER SIX

Conclusions and limitations of this work

The scope of this study was to investigate soil hydraulic properties as influenced by biochar addition to low organic matter agricultural and forest soil(s). Biochar was added alone and in combination with manure, compost, or as co-composted biochar to two soils (Fluvisol and Regosol), for the purpose of improving soil water retention and reducing nutrient leaching. Biochar was further added to a Cambisol in comparison to a synthetic soil moisture retention additive (hydrogel) to evaluate their performance concerning water retention. The practical value of the results are as follows: 1) biochar enhanced the proportion of available water content (AWC), especially that to which plants can easily access (EAWC). 2) Ksat results showed insignificant changes among all treatments represented no influence of SWRC on infiltration, which means an unchanged propensity for surface runoff, which is favourable to mitigate against soil erosion, especially on highly trafficked agricultural soils. 3) As biochar also favourably impacted nutrient retention in soils when added to other amendments then biochar represents an effective intervention for low-organic soils impacted by drought and where excess nutrient leaching could be expected as a result of the application of more traditional fertilisers. 4) Biochar was effective to somewhat mitigate against the leaching of DOC and nutrients resulting from manure/compost addition to soils. 5) The application of biochar hastened the maturing of compost made of woody and green material. 6) Using the higher dose of biochar (>10%) in the biochar mixtures to gain a better-quality product is suggested through consolidation experiment results. 7) The comparison biochar (2%) versus hydrogel (0.1%) application to a Cambisol (forest soil), revealed favourable water retention where biochar was applied.

Several limitations of the work presented here remain for future exploration;

1) All of the studies presented were conducted under controlled situations, e.g., in boxes or pot tests. Field experimentation is

recommended for further research to study the long-term effects and larger scale feasibility, with more focus on the longevity of biochar impacts on nutrient retention and whether/ when repeat applications of biochar to soils would be appropriate.

2) A wider range of variously textured soils should be tested with more range of amendments dosage that can benefit a reliable conclusion. This is especially the case where soil compaction is concerned; the consolidation experiment presented here failed to adequately explore this important soil physical parameter, possibly because only one soil was utilised. and the selected static load was not enough. Possibly spending a longer time on this experiment could help to analyse and explore more e.g., investigating higher static load and measuring Ksat
3) Further studies on investigating the hydrogel degradation in different soils and ecosystem (forest, agricultural lands etc.) is highly recommended as biochars are likely to be in competition with commercial products for purchase and utilisation by land manager

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Supplements

Table S1. Typical range of biochar properties produced by GP750 (Brynda et al., 2020).

Parameter	Unit	Typical range
Bulk density	*[kg/m³]* → $[kg/m^3]$	120–250
Ash, A^d (550 °C)	*wt%*	5–25
Volatile matter, V^d	*wt%*	3–8
Fixed carbon, FC^d	*wt%*	65–90
Lower heating value, Qi^d	$[MJkg^{-1}]$	25–28
H/C	$[molmol^{-1}]$	0.005–0.010
O/C	$[molmol^{-1}]$	0.025–0.05
pH	*[–]*	11.7–12.6
Specific surface area, S_{BET}	m^2g^{-1}	350–700
Mesopore surface area, S_{meso}	m^2g^{-1}	200–350
Volume of micropores, V_{micro}	$mm^3{}_{liq}g^{-1}$	100–250
Total pore volume, V_{tot}	$mm^3{}_{liq}g^{-1}$	300–550

Fig. S1. Three 200-L spinning plastic drums were placed in the greenhouse (CZU university) at approximately 20 °C, to prepare compost and co-composted biochar.

Table S2. Pristine characteristics of the soil and all used amendments (Teodoro et al., 2020)

Property	**Unit**	**Litavka**	**Biochar**	**HB**	**C0**	**C4**	**C10**
Clay	%	8.7[a]	/	/	/	/	/
Silt	%	34.8[a]	/	/	/	/	/
Sand	%	56.5[a]	/	/	/	/	/
pH	*[–]*	5.9	11.4	6.66	7.59	7.33	7.67
C	$[g\ kg^{-1}]$	2.87	868	197	377	451	503
N	$[g\ kg^{-1}]$	0.2	5.8	11.7	17.5	19	17
K	$[g\ kg^{-1}]$	6.58	3.15	9.84	14.5	11.8	10.6
Mg	$[g\ kg^{-1}]$	0.68	2.82	3.62	2.91	2.43	2.27
Fe	$[g\ kg^{-1}]$	37.4	/	8.47	2.47	1.28	2.01
Mn	$[g\ kg^{-1}]$	4.28	/	0.26	0.32	0.22	0.35
Cu	$[g\ kg^{-1}]$	71.9	6.86	27.3	14.1	11.8	12.3
Zn	$[g\ kg^{-1}]$	4002	651	167	133	110	249
Pb	$[g\ kg^{-1}]$	3539	12.9	25.87	9.12	13.31	22.6
Cd	$[g\ kg^{-1}]$	39	0.13	0.63	0.25	0.12	0.21

[a] Values obtained from Jacka et al. (2018)

Table S3. Parameters of Van Genuchten equation and hydrolimits of the retention curves which were fitted with measured average volumetric water content to minimize RMSE. Data shown are means ± standard deviation (n = 5).

	Θ_r	**Θ_s**	**α**	**n**	**RMSE**	**Measured average volumetric water content [$cm^3.cm^{-3}$] with standard deviation pF**						
	[cm^3 cm^{-3}]	*[cm^3 cm^{-3}]*	*[-]*	*[-]*	*[cm^3 cm^{-3}]*	**0**	**1**	**1.8**	**2**	**3**	**3.7**	**4.18**
F	0.062	0.553	0.027	1.588	0.011	$^{b}0.553\pm0.007$	$^{ab}0.531\pm0.007$	$^{c}0.393\pm0.016$	$^{c}0.302\pm0.009$	$^{b}0.136\pm0.005$	$^{b}0.104\pm0.002$	$^{c}0.063\pm0.001$
FB5	0.075	0.575	0.013	1.769	0.011	$^{a}0.585\pm0.007$	$^{a}0.557\pm0.008$	$^{a}0.487\pm0.010$	$^{a}0.402\pm0.010$	$^{b}0.145\pm0.004$	$^{b}0.107\pm0.001$	$^{b}0.074\pm0.001$
FC5	<0.001	0.564	0.031	1.301	0.012	$^{a}0.571\pm0.007$	$^{b}0.526\pm0.10$	$^{b}0.443\pm0.008$	$^{b}0.37\pm0.015$	$^{a}0.2\pm0.011$	$^{a}0.132\pm0.004$	$^{a}0.082\pm0.001$
FCB5	<0.001	0.568	0.031	1.315	0.015	$^{a}0.577\pm0.013$	$^{b}0.526\pm0.018$	$^{b}0.446\pm0.009$	$^{b}0.361\pm0.008$	$^{a}0.188\pm0.018$	$^{a}0.128\pm0.005$	$^{b}0.073\pm0.002$

	Θ_r	**Θ_s**	**α**	**n**	**RMSE**	**Measured average volumetric water content [$cm^3.cm^{-3}$] with standard deviation pF**						
	[cm^3 cm^{-3}]	*[cm^3 cm^{-3}]*	*[-]*	*[-]*	*[cm^3 cm^{-3}]*	**0**	**1**	**1.5**	**2**	**3**	**3.7**	**4.18**
R	0.046	0.391	0.053	1.735	0.008	$^{d}0.389\pm0.008$	$^{c}0.352\pm0.010$	$^{c}0.253\pm0.009$	$^{c}0.137\pm0.002$	$^{bc}0.079\pm0.003$	$^{b}0.056\pm0.001$	$^{c}0.036\pm0.0003$
RB5	0.038	0.493	0.038	1.584	0.005	$^{c}0.498\pm0.007$	$^{b}0.451\pm0.008$	$^{a}0.376\pm0.010$	$^{b}0.235\pm0.004$	$^{b}0.092\pm0.002$	$^{b}0.061\pm0.001$	$^{b}0.049\pm0.001$
RM5	0.026	0.580	0.153	1.316	0.015	$^{a}0.565\pm0.013$	$^{a}0.479\pm0.009$	$^{b}0.323\pm0.016$	$^{a}0.274\pm0.015$	$^{a}0.143\pm0.015$	$^{a}0.096\pm0.007$	$^{a}0.069\pm0.001$
RMB5	0.020	0.565	0.211	1.288	0.013	$^{b}0.548\pm0.007$	$^{b}0.445\pm0.018$	$^{b}0.302\pm0.012$	$^{a}0.259\pm0.006$	$^{a}0.142\pm0.006$	$^{a}0.095\pm0.009$	$^{a}0.068\pm0.0007$

Table S4. Chemical analysis of collected porewater representing the leakage potentially coming out of the soils, (means ± SD, n= 3). Different letters represent statistical differences between treatments by Tukey HSD at $p < 0.05$ (Seyedsadr et al., 2021).

Property		**T1 - Fluvisol**							**T2 - Regosol**							
		F	**FB2**	**FB5**	**FC2**	**FC5**	**FCB2**	**FCB5**	**R**	**RB2**	**RB5**	**RM2**	**RM5**	**RMB2**	**RMB5**
pH	*[-]*	^{b}6.23 ± 0.01	^{a}6.35 ± 0.04	^{a}6.70 ± 0.04	^{a}6.34 ± 0.03	^{a}6.65 ± 0.19	^{a}6.36 ± 0.08	^{a}6.47 ± 0.02	^{e}4.74 ± 0.85	^{d}5.87 ± 0.01	^{a}6.76 ± 0.04	^{d}5.92 ± 0.12	^{a}6.70 ± 0.08	^{c}6.04 ± 0.05	^{b}6.56 ± 0.01
EC	*[$\mu S\ cm^{-1}$]*	^{c}83.3 ± 4.6	^{c}87.5 ± 3.53	^{b}146 ± 5.66	^{b}126 ± 1	^{a}196 ± 13	^{b}133 ± 113	^{a}203 ± 2	^{d}54.3 ± 2.5	^{d}66.0 ± 1.4	^{cd}84.5 ± 6.4	^{c}102 ± 1	^{a}263 ± 9	^{b}155 ± 10	^{a}282 ± 18
IC	*[$mg\ L^{-1}$]*	^{b}34.5 ± 4.3	^{b}19.2 ± 2.3	^{b}38.1 ± 1.2	^{b}41.7 ± 0.7	^{a}98.9 ± 20.2	^{b}23.8 ± 1.1	^{a}77.1 ± 5.2	^{b}8.48 ± 1.87	^{b}8.39 ± 1.52	^{b}7.17 ± 2.62	^{ab}13.4 ± 2.56	^{a}18.9 ± 1.98	^{ab}9.67 ± 0.78	^{ab}13.5 ± 0.9
DOC	*[mg L-1]*	^{cd}225 ± 8	^{d}146 ± 3	^{d}117 ± 13	^{b}489 ± 16	^{a}732 ± 87	^{c}342 ± 3	^{a}728 ± 12	^{bc}46.1 ± 2.8	^{c}27.3 ± 3.7	^{bc}35.2 ± 0.3	^{ab}127 ± 46	^{a}199 ± 5	^{abc}100 ± 6	^{a}150 ± 2
TN	*[$mg\ L^{-1}$]*	^{d}175 ± 1	^{e}96.7 ± 1.5	^{f}20.8 ± 3	^{b}342 ± 10	^{a}469 ± 5	^{c}226 ± 2	^{a}444 ± 24	^{c}157 ± 0.3	^{e}11.4 ± 0.3	^{e}7.10 ± 0.10	^{b}225 ± 3	^{a}315 ± 3	^{d}123 ± 1	^{a}305 ± 2
K	*[$mg\ L^{-1}$]*	^{e}18.7 ± 0.2	^{e}23.0 ± 0.01	^{c}66.2 ± 0.7	^{c}61.4 ± 0.5	^{a}147 ± 3	^{d}45.0 ± 0.6	^{b}121 ± 3	^{e}42.0 ± 0.6	^{e}20.7± 0.4	^{e}32.2 ± 0.8	^{d}211± 2	^{b}670 ± 18	^{c}373 ± 9	^{a}694 ± 6
Ca	*[$mg\ L^{-1}$]*	^{d}33.2 ± 0.1	^{d}29.6 ± 0.8	^{b}69.9 ± 0.5	^{b}73.3 ± 0.3	^{a}101 ± 2	^{c}50.5 ± 0.3	^{a}102 ± 2	^{a}150 ± 1	^{f}11.4 ± 0.2	^{g}8.09 ± 0.13	^{e}70.3 ± 0.8	^{c}105 ± 2	^{b}112 ± 1	^{d}87.9 ± 0.6
Mg	*[mg L-1]*	^{f}7.03 ± 0.1	^{f}6.59 ± 0.05	^{d}17.3 ±0.2	^{c}19.0 ± 0.1	^{a}31.5 ± 0.5	^{e}12.6 ± 0.1	^{b}27.5 ± 0.7	^{d}21.4 ± 0.4	^{f}1.99 ± 0.11	^{g}1.49 ± 0.15	^{d}20.3 ± 0.4	^{a}41.0 ± 0.5	^{c}32.1 ± 0.8	^{b}33.7 ± 0.3

Fig. S2. Graphs of Fluvisol (A, B) and Regosol (C, D) showing the pressure head data collected with tensiometer (T5) and volumetric water contents measured with FDR probs (Seyedsadr et al., 2021).

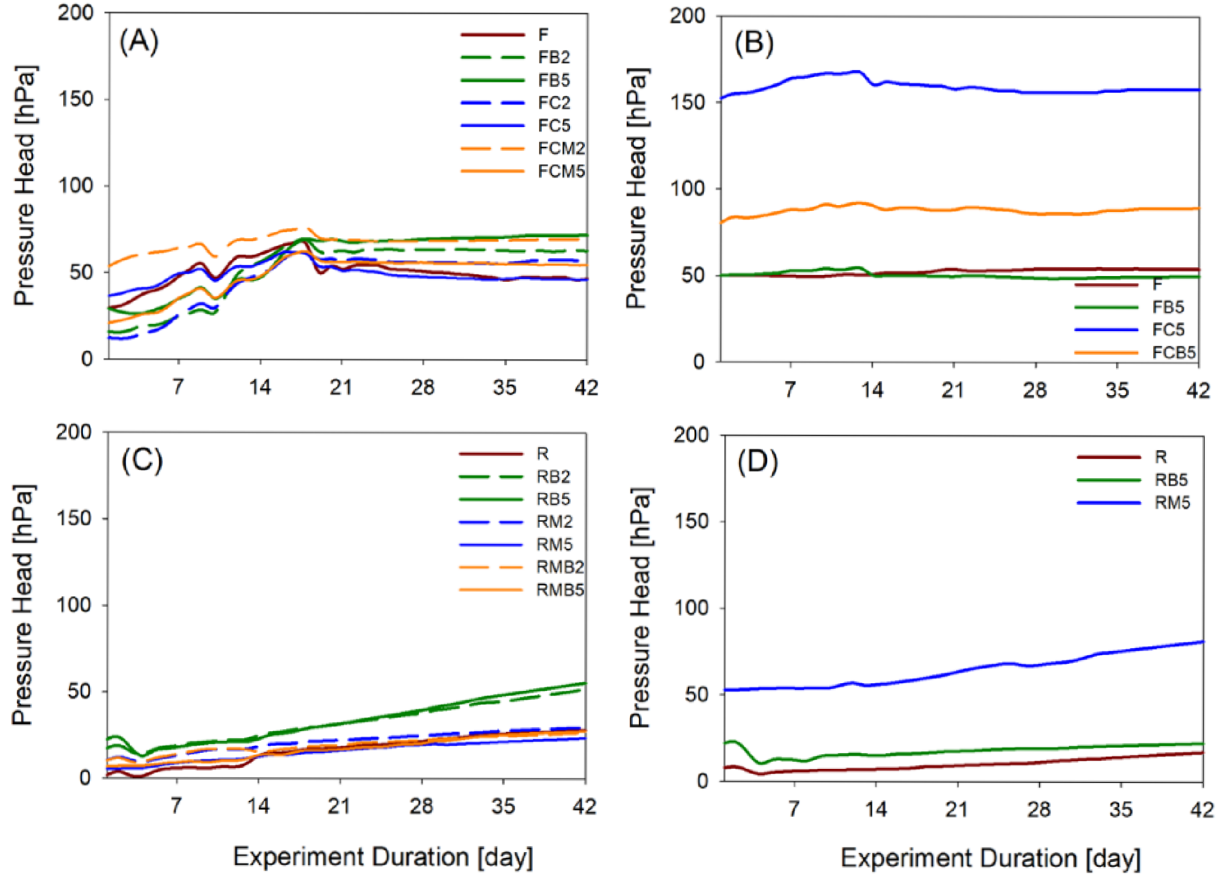

Fig. S3. Undisturbed soil samples collected from the upper 10 cm thick layer of each box using standard stainless-steel soil sample rings.

Fig. S4. An illustration of the equivalent pore size ranges of each pressure head, calculated using Young–Laplace equation. The legend shows equivalent pore size ranges. Data are means (n = 6), (Seyedsadr et al., 2021).

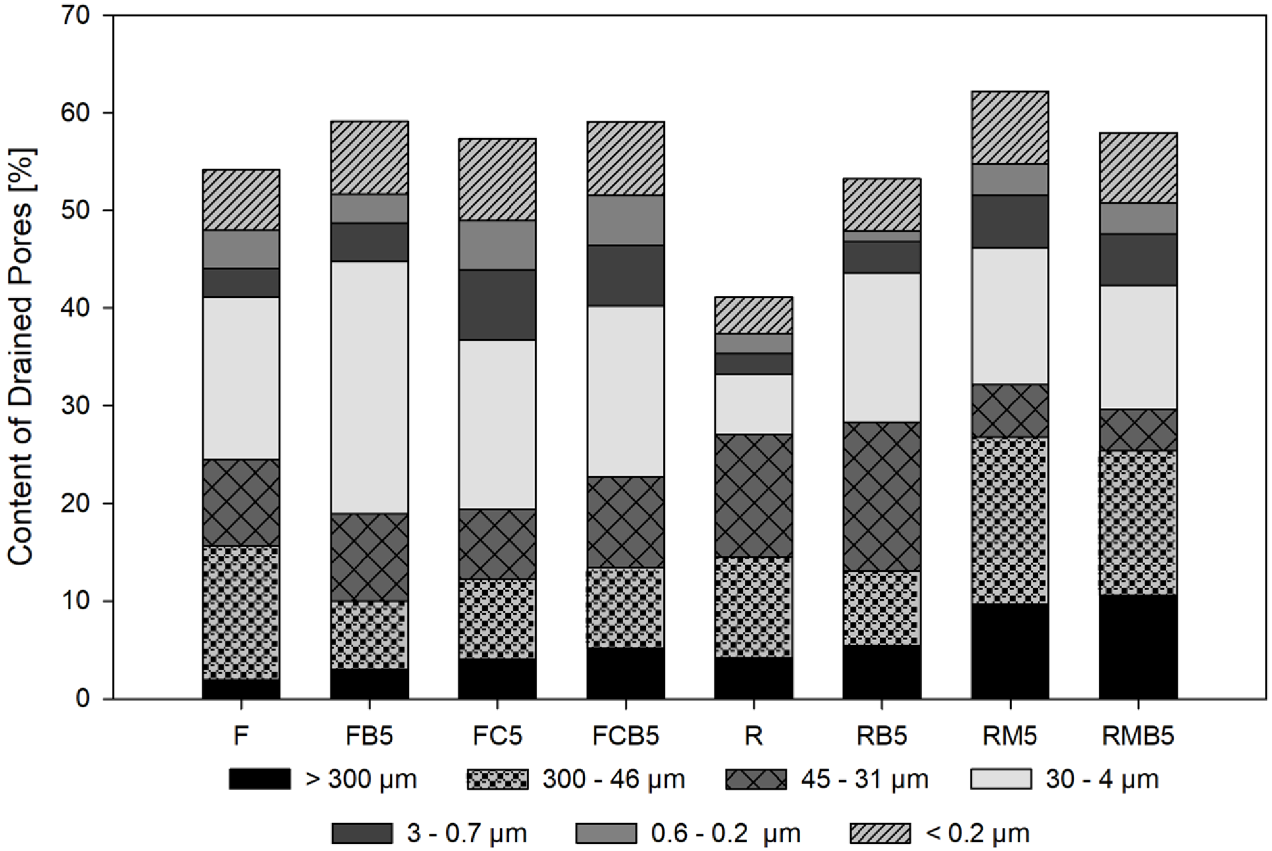

Fig. S5. Variation in time of pH and moisture content during the composting process of compost (C0) and co-composting with 4 and 10 % of biochar (C4) vs. (C10).

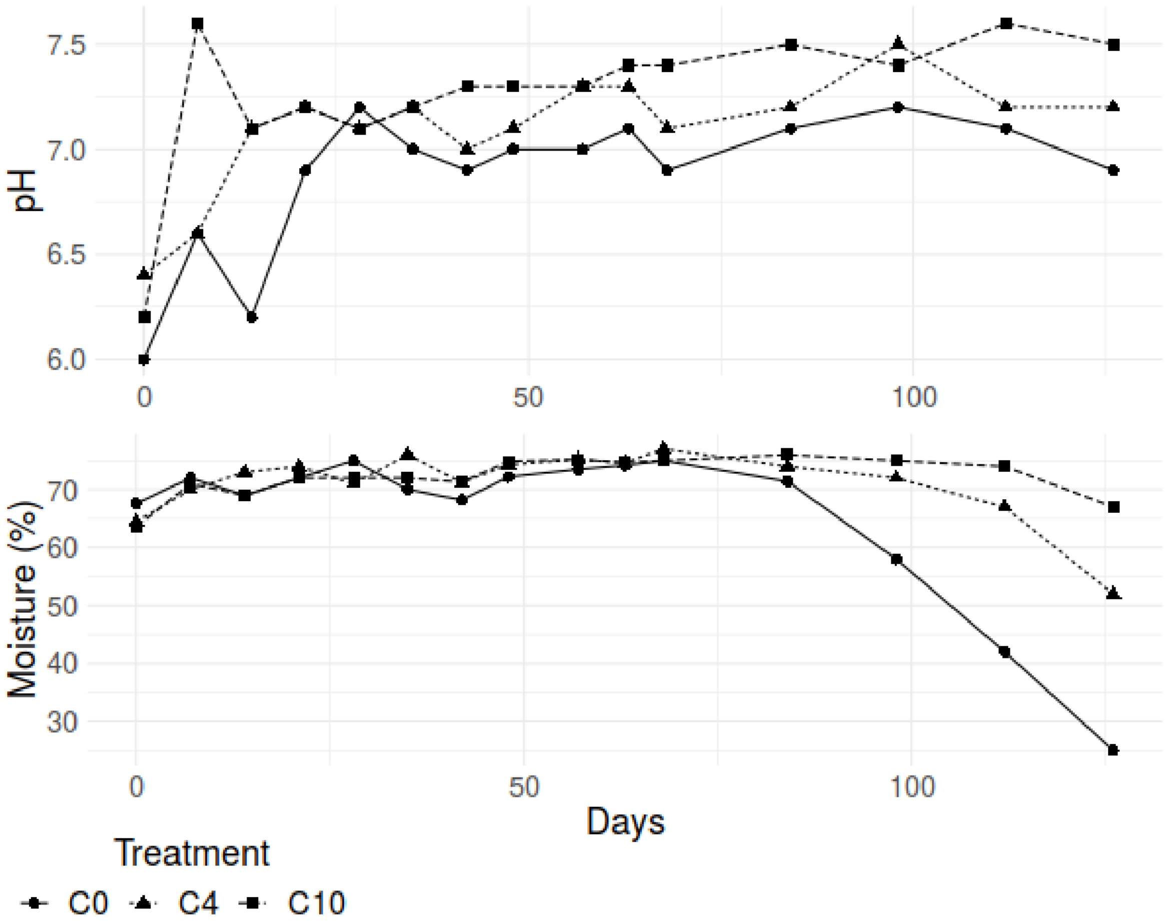

Fig. S6. Water Retention Curves of Regosol under two conditions (un/consolidated), and division of soil water into unavailable (UWC) and available (AWC). The part of easy-available for plant (EAWC) is red-marked (C). Different letters in figure (C) represent statistical differences (for AWC marked in grey) between variants by Tukey HSD for each trial