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Exploring the biochar contribution in sustainable agriculture through techno-economic assessment and water impact simulations

Master thesis Agritech Engineering

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1 Abstract

In an age shaped by climate change, which is disrupting natural ecosystems' balances and impacting both human and animal health, society must actively attenuate these changes.
From this perspective, innovative and sustainable resources are needed to mitigate water scarcity, ensure food security, and reduce air pollution. Biochar could play a key role in this effort due to its ability to provide benefits for agriculture by reducing water demand, increasing yields, reducing fertilizer use and promoting resistance to stress and diseases.
It also offers environmental benefits by capturing and storing carbon in the soil for extremely long periods, valorizing bio-waste that is currently lost, and generating economic value through the generation of carbon offsets.
Biochar production and its incorporation into soil address twin challenges: supporting farmers and sustaining the environment by transforming waste into a value-added product.
This thesis presents a techno-economic evaluation of biochar production, including its physical and chemical characteristics, certification processes, and application methods. Focus is given to a detailed analysis of existing carbon credit systems, the biochar market, and its key stakeholders, which has the potential to generate significant revenue streams.
Moreover, this work aims to analyze how applied biochar interacts with agricultural soils, examining all the related physical, chemical and biological modifications and effects.
The final section investigates the relationship between biochar-induced soil changes and crop performance, simulating multiple scenarios of soils, environments, and crops, using the FAO AquaCrop software, while maintaining a consistently critical perspective on the environmental benefits such as reducing water demand and improving agricultural efficiency.
This work is grounded in a thorough literature review, critical analysis and data manipulation, complemented by interviews with leading experts in the field, to gain expert know-how.
This work outlines the complexity of the regulatory framework that farmers face when adopting this new resource, which increases skepticism and reduces adoption rates, which in turn promotes economic barriers: this is confirmed by data, showing that 58% of users do not earn income from carbon offsetting. Nevertheless, the sector is continuously growing, with an expected CAGR of 55% and a projected production capacity of 220 t/y for 2025, with Northern European countries leading the EU market.
AquaCrop simulations were run focusing on hydraulic changes extracted from Edeh et al. (2020) "A meta-analysis on biochar's effects on soil water properties". Simulations highlight that in sandy soil results are more relevant, leading up to + 12% of biomass produced and more than 10% in irrigation efficiency, while in clay soil results are quite negligible. However, biochar is considered a great crop stress buffer and enhanced soil water retention. Moreover, the ability to perform multiple simulation runs across diverse environmental conditions, irrigation schedules, and crop types makes it possible to directly investigate the correlation between biochar application and crop biomass production.

Scaling biochar technologies will require harmonized certification frameworks that recognize both agronomic and carbon-sequestration services. Embedding biochar within circular bioeconomy strategies offers a scalable pathway to resilient agriculture and tangible climate action storing 3 kg of CO_{2eq} for 1 kg of biochar buried.

2 Introduction

Climate change, the increasing scarcity of natural resources, and the need for more resilient and sustainable agricultural production are among the most pressing challenges facing the scientific community, policymakers, and the entire agrifood sector today. Agriculture, as a sector deeply linked with the environment, is both a victim and a contributor to climate change: on the one hand, it suffers from the effects of drought, soil degradation, and biodiversity loss; on the other, it significantly contributes to greenhouse gas emissions, fertilizer-related pollution, and suboptimal water resource management. In this complex scenario, it becomes essential to identify and implement innovative, sustainable, and scalable solutions capable of reducing agriculture's environmental impact without compromising the productivity and profitability of farming systems.
This thesis focuses on a topic of growing scientific, social, and industrial interest: the use of biochar as a multifunctional tool to promote sustainable agriculture, mitigate the effects of climate change, and enhance the value of waste and by-products from the agroforestry sector.
Moreover, this works aims to analyze the overall world biochar aspects, through a techno-economic analysis with practical simulations of biochr application in agricultural sector. In the first part, the thesis focuses on the current state of the art of the biochar sector, examining both technical and regulatory aspects. From a technical perspective, it explores the properties of biochar, its uses, advantages and limitations, and the main production technologies. On the legislative and economic side, it analyzes the European and Italian regulatory frameworks, the historical developments that led to the emergence of the carbon market, emission limits and related pollutants, certification bodies, and the operating principles of current carbon credit systems.
All these parts are functional to the development of the economic analysis, made both on the biochar as a material and on the carbon offset credits that biochar generates, with practical focus on agricultural sector, such as biochar combined with fertilizers, and pyrolysis byproducts, such as wood distillate.
After that the business analysis is completed, the focus is put on the agricultural application, exploring the interaction of this sustainable resources with soil and how it changes its properties.
The research problem addresses a critical and in-depth understanding of the role that biochar can play in transforming agricultural systems, particularly through the improvement of soil physical, chemical, and biological properties through time.
Also the agricultural methods to applying it in the field are investigated, analyzing the possible biochar treatment to enhance the agronomic results.
The thesis end with a practical simulation of biochar application in agricultural soil using the FAO software AquaCrop and evaluating how biochar affect yield, water retention and stresses.
This methodology makes it possible not only to analyze the theoretical potential of biochar but also to simulate realistic scenarios and quantitatively evaluate its agronomic performance across different soil types (sandy,

loamy, and clayey), C3 and C4 crops, and varying irrigation regimes and environmental conditions.
The overarching goal of this work is to critically, quantitatively, and interdisciplinary assess the potential contribution of biochar to sustainable agriculture strategies and climate mitigation. The goal is to asses the feasibility and the possible growth of this sector, focusing on the market aspects and than on the technical aspects and real benefit that it can give to agriculture.
It's obtain thanks to a deep analysis of present literature and existing experiments, analysis of business reports, interviews made with firms, associations and professors operating in this sector and with a practical simulation phase.
The original contribution of this thesis lies in the integration of various analytical perspectives (technical, agronomic, regulatory, and economic) within a single evaluative framework. In particular, the use of the AquaCrop model to simulate large-scale, realistic scenarios involving biochar application represents an innovative methodology, enabling a comparative and quantitative assessment of its direct impact on crop yield, irrigation efficiency, water dynamics within the effective root zone, and plant response to drought and related stress conditions.
Another distinctive element is the critical analysis of the regulatory context and the mechanisms for accessing carbon credits, a very complex topic that is generally underexplored by the technical and scientific literature. Finally, the thesis provides an updated overview of the barriers limiting biochar adoption, offering concrete suggestions to overcome economic, logistical, and regulatory challenges.
In summary, this work aims to serve not only the academic world but also agronomists, policymakers, agri-industrial entrepreneurs, and carbon market stakeholders, offering a comprehensive, critical, and practical perspective on the role that biochar can play in the transition toward more resilient and sustainable agroecological systems.

3 The biochar

Biochar is defined by EBC (European Biochar Certification, developed by the Ithaka Institute) as a "porous, carbonaceous material that is produced by pyrolysis of biomass and is applied in such a way that the contained carbon remains stored as a long-term C sink or replaces fossil carbon in industrial manufacturing. It is not made to be burnt for energy generation". Historically, biochar was known as charcoal and played a fundamental role in early civilizations. It was widely used for cooking, heating, slow-burning fires, medicinal purposes, and as a bedding material. However, its use declined with the development of more efficient and user-friendly materials and technologies.
Traditionally, biochar was produced using natural coal pits. The process involved stacking wood in a conical, circular formation with a diameter of 4-6 m. Larger pieces were placed at the core, while smaller ones were used to seal gaps. The entire structure was then covered with a thick layer of leaves (10-12 cm) and soil. Once ignited, the pile was maintained for 4 to 5 days by feeding it through an opening at the top. Small lateral holes were also made to ensure a minimal air supply. The entire process lasted 14-15 days, during which the pile's volume decreased by 40% and its mass by 80%. To stop the pyrolysis process, workers covered the pile with soil and doused the embers with water.
Early evidence of biochar use in agriculture was discovered in Amazonia, notably in the so-called "Terra Preta dos Índios" soils. These soils are easily recognized by their dark brown color, which is due to their high carbon content.
This means that he agricultural benefits of biochar were already well understood at the time, as it was used as a "natural fertilizer" and consistently employed to enhance crop yields.
Today, however, its advantages extend far beyond productivity: under the EU Emissions Trading System (EU ETS), the directives that establish the rules for emissions allowances within the European Union, biochar is now representing one of the most promising techniques for sequestering carbon in the soil and reducing emissions. From an economical point of view, it totally change the market of biochar, rising up the value of this product.

3.1 Biochar general characterization

Biochar is defined by EU legislation as "carbonaceous material obtained from organic matrix that has undergone thermochemical conversion in limited presence of oxygen with a process that ensures a temperature above 180 °C for a minimum of 2 minutes.“
It is included in the EU Regulation 1009:2019 as CMC 14: Pyrolysis and Gasification Materials. It falls under the Product Function Category PFC 3 organic soil improver and PFC 4 cultivation substrate.
Biochar is officially recognized in Italy as an amendment allowed in agriculture (Legislative Decree 75/10, Annex 2, order number 16, as amended by ministerial decrees of June 2015 and June 2016). It includes materials obtained from the carbonization of virgin plant products and residues from agriculture and forestry. Recognized by-products included are olive pomace, grape marc, bran, fruit pits and shells, and untreated wood processing residues. Ministerial Decree of October 10, 2022, includes biochar among fertilizers allowed in organic farming, with stricter limits for Polycyclic Aromatic Hydrocarbons (PAHs) (4 mg/kg dry matter instead of 6 mg/kg).

3.2 Chemical properties

Biochar chemical characteristics are really important in determining its applications.
The conversion of biomass to char is performed thanks to three main reaction:

- Boudouard reaction: $C + CO_2 \longrightarrow 2\,CO$
- Water gas reaction: $C + H_2O \longrightarrow CO + H_2$
- Partial oxidation of carbon: $aC + bO_2 \longrightarrow cCO + dCO_2$

They are surface reactions that require a reactive surface and the reactivity strongly depend on temperature and the concentration.
The carbonization process leads to detachments of functional groups that contains hydrogen and oxygen, increasing the carbon content of the products. This brings to a reduction of H/C and O/C ratios, as possible to see in figure 1 on the following page.
Generally, lower are H/C and O/C of final product, higher thermal stability will have biochar, which makes it more resistant to deterioration and breakdown in the soil, improving the stability through time.
More than that, biochar with low ratios values have higher surface area and cation exchange capacity (CEC), which enhances the biochar's capacity to retain and exchange essential plant nutrients.

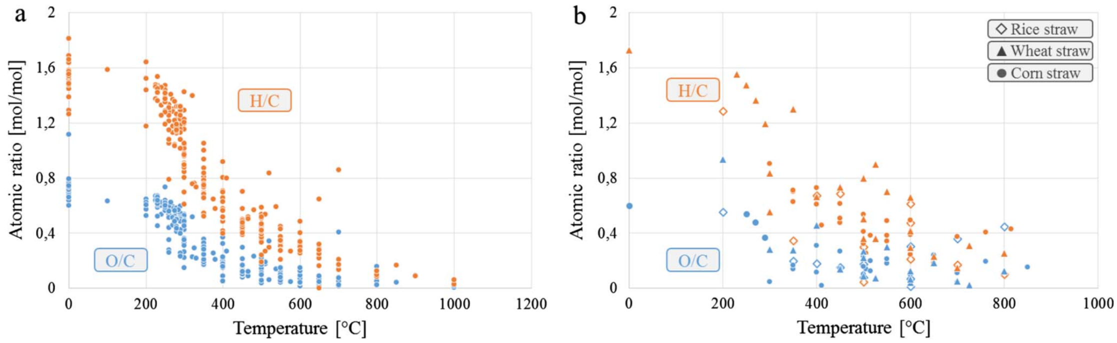

Figure 1: (a) H/C and O/C ratios of carbonized woody biomass, n(H/C) = 290, n(O/C)=289 and own measurements; (b) different carbonized straw types, n(H/C) = 51, n(O/C) = 61. (n is the number of single values displayed in each figure) Extracted from Weber et al. (2016).

Considering as sample wood biomass, the elemental composition changes mostly in the temperature range of 200-400 °C, in which there is the decrease of oxygen concentration and the increase of carbon concentration. At higher temperature (higher than 700°C) it's possible to reach 95% of carbon and oxygen to less than 5%, while hydrogen arrives to 2% during pyrolysis stages. No correlation between temperature and nitrogen content are registered, unless for animal waste and sewage sludge where rising up temperature reduce the nitrogen concentration.
Temperature is not the only operational parameter that should be taken into account, but it should be correlated to the residence time; indeed even at high temperature but with a short residence time, the biochar produced has a low carbon content.

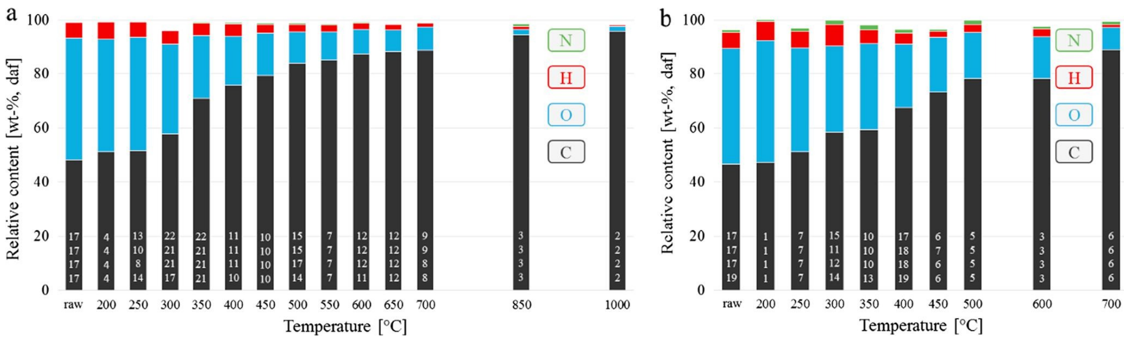

Figure 2: Relative composition of (a) woody and (b) straw-like biomass. Number of values considered (n) is given in each column, arranged according to the elements shown. Relative composition of biochar are based on dry and ash-free matter. Extracted from Weber et al. (2016)

It is really important to underline that the concentration of carbon showed in 2 is rising with temperature, but it doesn't mean that the biochar yield is increasing; indeed at higher temperature, due to molecules cracking reaction, part of that is transformed in gas phase and so the carbon concentration in biochar decrease. This information can be retrieved in figure 3 on the following page, where the amount of biogas produced is increasing with temperature. This aspect will be thoroughly explained in the following chapter.

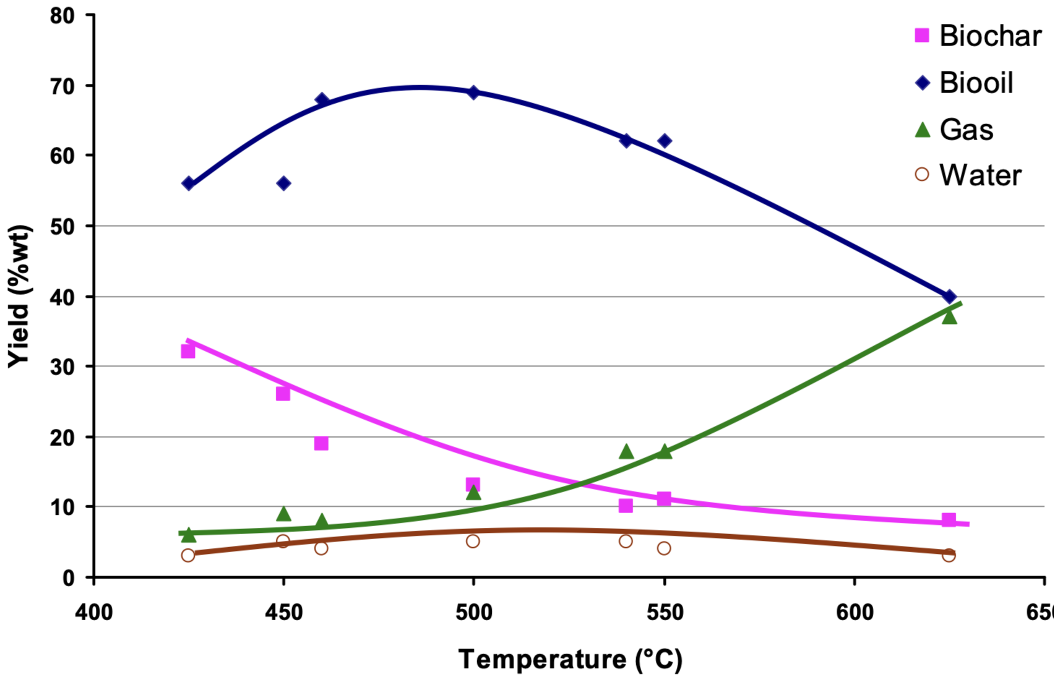

Figure 3: Relative proportions of end products in pyrolysis of biomass. Extracted from Jahirul et al (2012)

One of the most important parameter that should be evaluated to characterize biochar is the fixed carbon concentration. It is defined as "the carbon content that remains in the solid structure after the volatile components are driven off" (Britannica).
In raw biomass, it is in the range of 10-30%, moving to 50-60% in the range temperature of 250-350 °C, arriving at 90% for temperature above 700 °C. Obviously, two important aspects should be underlined: the fixed carbon concentration is changing with feedstock characteristics and those percentages are on dry-ash free bases.
The increasing of fixed carbon concentration is inversely proportional to the volatile matter concentration, that is a direct result of the devolatilization process that is promoted by temperature.
In general, devolatilization process is the transformation in gas phase of the biomass components. Analyzing the derivative thermo-gravimetric analysis of 4 different type of wood biomass can establish that there is a correlation between devolatilization and temperatures:

- In the range 200-300 °C hemicellulose, that is a non-glucose sugars that encase cellulose fibers (20-35 % of wood dry weight) it begins to volatilize. It is the easiest degradable components.

- In the range 300-400 °C cellulose, that is condensed polymer of glucose (40-45 % of wood dry weight), start to volatilize.

- For temperature higher than 400 °C lignin, that is non-sugar polymer, (15-30 % of wood dry weight) finally start to volatilize.

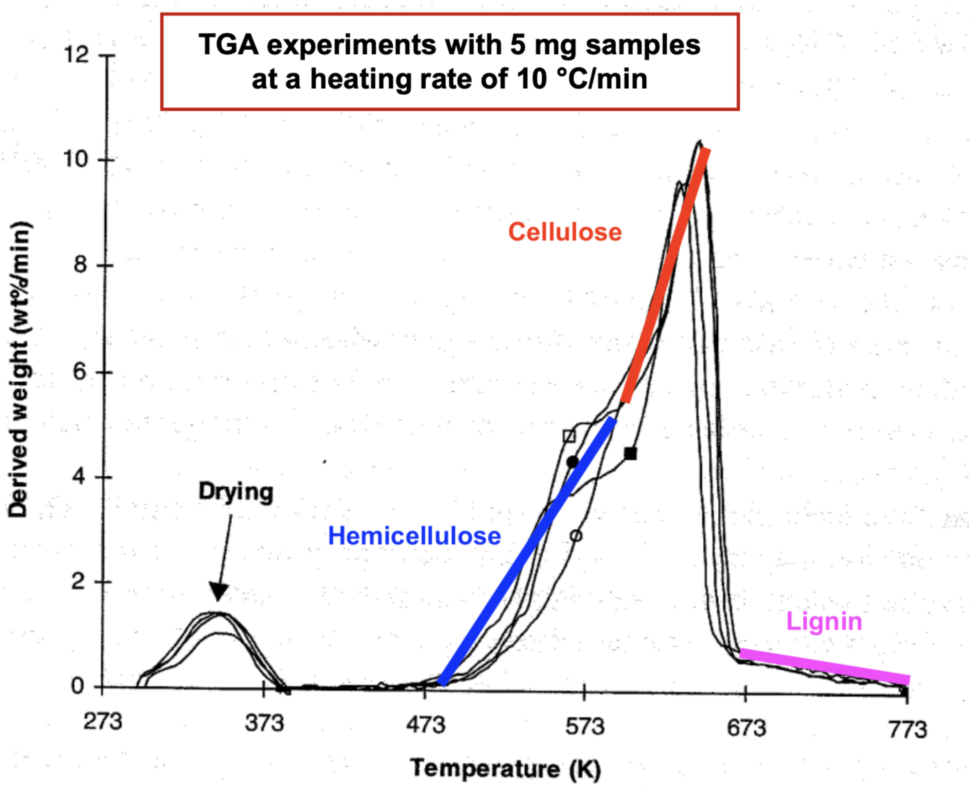

Figure 4: Derivative thermogravimetric analysis of Spruce, Birch, Beech white and Acacia. Extracted from Van Loo et al. (2002)

During the process, the ratio H/C decrease because functional groups leaves the solid structure, but this did not happen for aromatic structures, that are characterized by high thermodynamic stability. Exist, in general, two type of aromatic compounds:

- Randomly organized aromatic rings (amorphous phase).
- Condensed polyaromatic sheets (crystalline phase).

In the range 500-800 °C the probability that the carbon is bounded in the aromatic compound is the highest.
Moreover, if functional groups leaves the biochar, biochar alkalinity change: the detachment of compounds leads to unpaired negative charges and hence the ability to accept protons, such as carboxyl –COOH (–COO) and/or hydroxyl –OH (–O) groups. This means that if the temperature increases, so do the alkalinity and, obviously, the pH.
Unlike other properties, the pH is only slighted affect by residence time and so it means that the acid reacting functional groups are released early during the process (5-10 min).

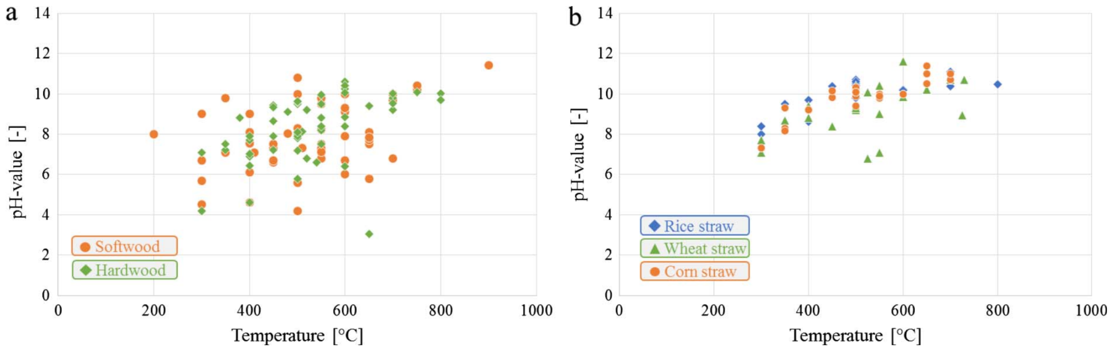

Figure 5: pH value of carbonized wood (a) and straw (b). Extracted from Weber et al. (2016)

Alkalinity also affects the CEC (Cation Exchange Capacity), which measures the material's ability to exchange ions. Commonly, using agricultural waste feedstock, the average biochar CEC is 32.7 $cmol/kg$ for chars produced below 300 °C and less than 5 $cmol/kg$ for char produced at temperature above 800 °C.
Another relevant parameter, also to match the requirement for the applications is the ash content: high ash content may inhibit the use in industrial application and intensify the ash-related problems to the pyro-gasificator. The main components of biomass ash are SiO_2, CaO, and K_2O.
Their presence is due to the decomposition of cellulose, hemicellulose, and lignin, as well as the interaction between volatiles and char.
Not surprisingly, ash content increase with temperature but is strongly affected by the feedstock nature.

3.3 Physical properties

The carbonization process led to degradation of the biomass fibers structure.
Biomass porosity typically ranges from 50% to 55%, but as the temperature increases, so does the porosity of the biochar, reaching a maximum of 72% for woody biomass at 850 °C and exceeding 80% for grass biomass at 700 °C.

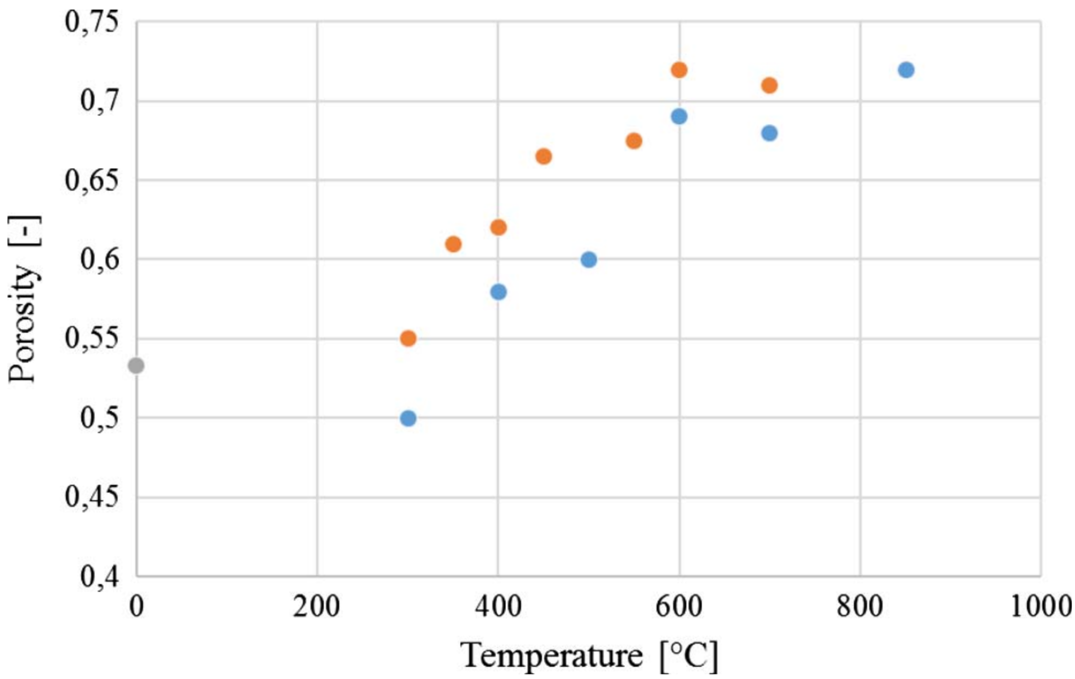

Figure 6: Porosity of woody biochar. (Markers of the same color stem from the same experiment). Extracted from Weber et al. (2016)

The bulk density behaves differently, showing a steep reduction from raw and drying phase, while during pyrolysis it remains more or less constant.
Another important biochar feature is the surface area because it is linked also with CEC, porosity and water holding and absorption capacity. During the process it changes as a result of the volatilization phenomenon, as the porosity.
To assess the total surface area it's possible to use BET analysis, in which the biochar that is analyzed is exposed to a gas with specific volume and pressure.
There are several technologies that differs in the gas used (e.g. N_2, CO_2) and operating temperature, but all of those are shown a lot of difficulties in performing measures.
In conclusion, what is possible to state is that surface area increase primarily with temperature, but is also affected by residence time.

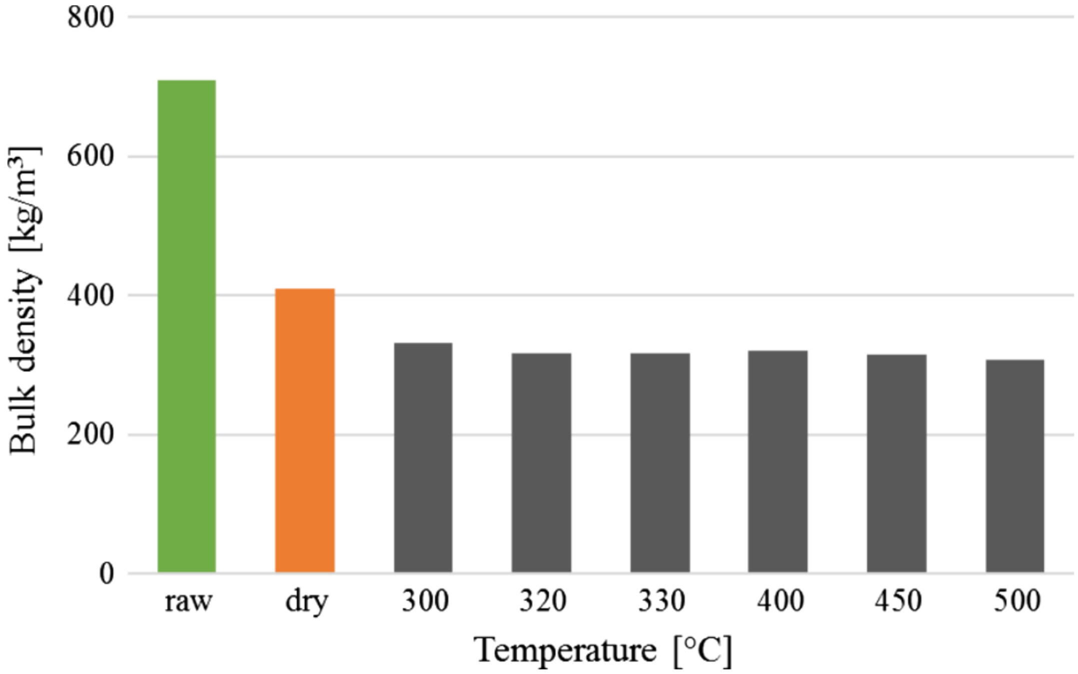

Figure 7: Bulk density of raw, dry and pyrolyzed mallee wood. Extracted from Weber et al. (2016)

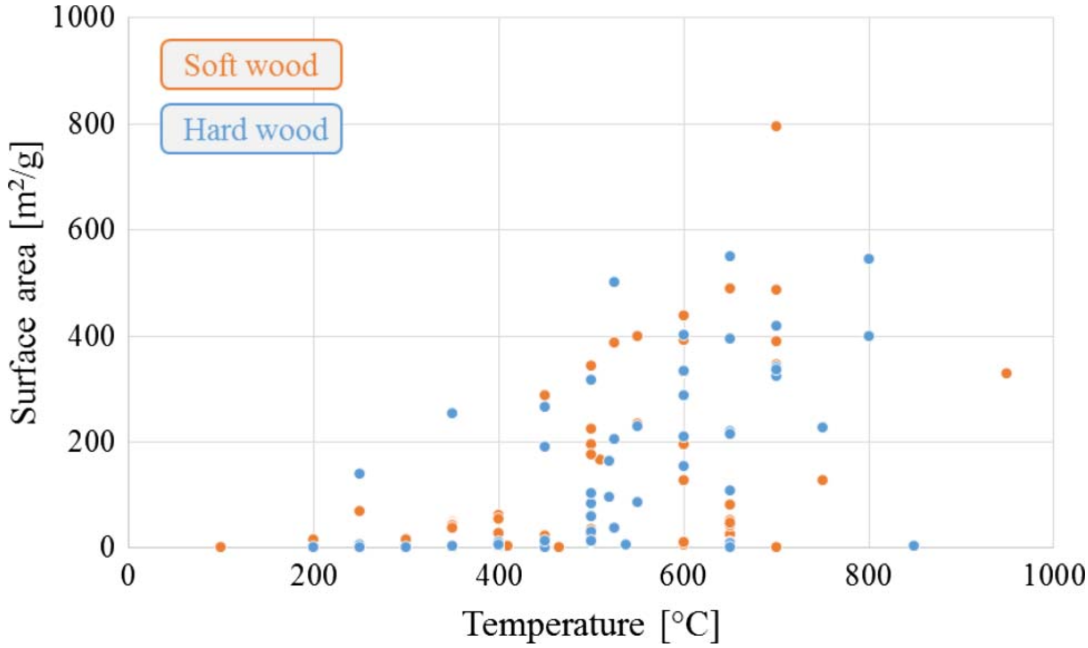

Figure 8: Surface area of woody biochars (N2-measurement). Extracted from Weber et al. (2016)

In relation with surface area is relevant to evaluate the pore volume and pore size distribution to assess the adsorption capability of gases or liquids. For example, is not enough to have high surface area: if the pores are too small gases can't get into and water may be bound too tightly to be extracted by plant roots.

The pore size distribution can be classified using three type of categories: macropores (with a pore diameter of 1000–0,05 μm), mesopores (0,05–0,002 μm), and micropores (0,05–0,0001 μm).
As already seen before for porosity, the total pore volume increases with temperature: the micropores distribution of raw woody biomass is in the order of 10%, while in the final biochar can overcome 80%.
For what concerning the hydrophobicity and water holding capacity there are two mechanism that can show counteracting effects: the amount of surface functional groups (leaving the biomass during the process, they indirectly reduce the hydrophilic behavior) and the porosity of biochar bulk volume (higher porosity means higher water holding capacity).
There is still a lot of irresoluteness: some studies as Chun et al. (2004) and Pimchuai et al. (2010) state that "higher treatment temperature leads to less water being adsorbed onto the chars inner surface" other, indeed, in the studies of Zornoza et al. (2016) and Kinney et al. (2012) low temperature biochars were extremely hydrophobic and the authors characterized chars produced at more than 500 °C as less hydrophobic, some even as hydrophilic. One possible explanation is that the hydrophobicity is due to the presence of aliphatic functional groups that are destroyed in the range of 400 °C - 500 °C. To avoid misleading, should be better to underline that biochar doesn't become hydrophilic, but just "less hydrophobic".
The water holding capacity increase with temperature as does the porosity. In fact, the easiness to penetrate is directly proportional to the pore dimension, that increase with temperature.
Finally, in figure 9 on the next page are graphically summarize main biochar properties.

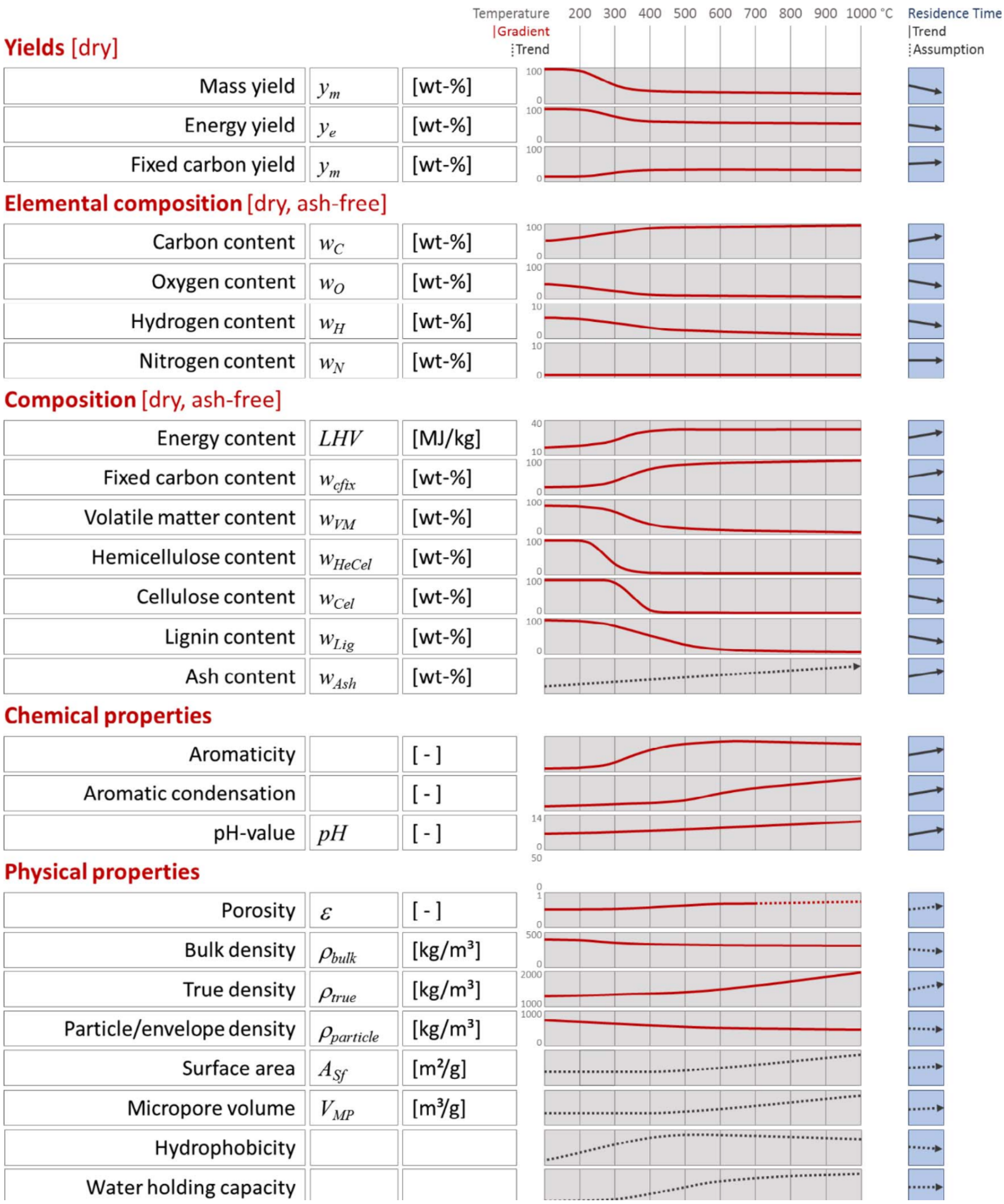

Figure 9: General properties of biochar in function of process temperature and residence time. Extracted from Weber et al. (2016)

3.4 Pros and cons of biochar uses

3.4.1 Advantages

The advantages and applications of biochar should be assessed from two perspectives: the practical properties of the material itself, and the economic/financial benefits it can provide.
Considering the material itself, biochar has historically been used in agriculture to improve crop yields. It can be seen as a carbon-based sponge that maintains its structure over time, remains chemically stable in the soil, and, most importantly, thanks to its porous structure, helps retain water and nutrients in the soil, reducing losses.
Going deeply in details:

- Water retention: biochar is able to maintain water in soils thanks to its pores, so it can be a valid method to improve soil's water holding capacity, reducing the water demand from environment helping a lot in fight against climate change and water scarcity.
  To have an idea how biochar can interact with soil's characteristics, must know that generally a well-structured rich in organic matter soil in the superficial horizon has a porosity of 65-70%, while a soil poor in structure or that suffer compaction has a porosity of 20-25%.
  More than that, it is important also to differentiate the type of porosity:
  - Macroporosity: pores with a diameter > 60 μm are not able to retain water and are therefore important for soil permeability and movement of water and air through the soil.
  - Microporosity: pores with a diameter < 10 μm are capable of retaining water by capillary forces and are therefore important for water retention and resistance to drought.

  In this context, biochar can modify soil porosity structure and increase water holding capacity, especially in coarse textured soil.

- Nutrient availability: the physical and chemical characteristics explained before permit scientific world to assess to biochar the ability to store nutrients in the soils, working as a sponge and avoiding leaching (in particular for Nitrogen (N) and Phosphorus (P), the main nutrients needed by plants and crops).
  Maintaining them in the zone around plants rhizosphere promote the possibility for roots to catch nutrients in the best moment desired.
  Note that this doesn't mean that biochar is a fertilizer; rather, it stores and slowly releases nutrients.
  Most of the time, when the goal is to enhance the yield, biochar is not supplied alone, but it is mixed with some natural fertilizer such as cattle urine biogas slurry, press water from tofu production, compost tea or non-natural commercial liquid fertilizers, in order to give to boost fertilization efficiency.
  More than that, in multiple studies, biochar shown that is increase the fertility promoting the N-cycle and P-cycle occurrence.

- Soil structure: making a rough analysis of biochar composition, it is mainly formed by carbon.
  Putting it in the soil, it will improve the soil organic carbon content (SOC) and so does the organic matter and the strength of micro-organism since that carbon is one of their main building blocks.
  The effect can also be seen just looking at the soils that are treated with it: they change their color becoming more dark brown and this, in agronomy, is directly related to the organic content present inside. As consequence, the soil fertility increase and so does the micro-diversity.

The combination of these advantages indirectly leads to further benefits as increasing crop yield, pH reduction in acid soils, CEC increasing, roots and microbial growth and reduction of nutrient leaching and consequently ground water table pollution.

In recent years, it has gained international recognition due to its significant benefits also in other sectors such as:

- Livestock: animal feeding, aquaculture and bedding.
- Environmental remediation: gas, water, air and odor.
- Building materials: concrete, asphalt and insulation.
- High tech: biosensors, batteries, substitute of graphene.
- Food: to maintain quality through time.
- Industry: waste treatment, odor control, carbon capture, moisture control and steel and silicon production.
- Materials: polymers, bio-plastic, paints and carbon based composite.

Regarding the economic advantages, they are mainly linked to biochar's crucial role in carbon sequestration that directly generate an income through carbon credits generations.
As previously mentioned, biochar is primarily composed of fixed carbon, which does not react with the soil microbiome. This allows to store carbon, originally captured by plants through photosynthesis acivity, in the soil over long time, up to 100 years.

3.4.2 Disadvantages

This new sustainable resource may also have some drawbacks, which are mostly related to incorrect use or unsuitable application contexts. In agriculture and horticulture, for example, the application rate is crucial: when exceeded, biochar can actually have the opposite of the desired effect. High concentrations of biochar in the soil increase water retention, that in some cases can reduce the amount of oxygen available in the rhizosphere, potentially suffocating plant roots.

Another possible issue is that, due to its strong ability to retain nutrients, biochar's strong nutrient-retention may temporarily immobilize N, P, and K in poor soils, reducing short-term availability to crops.

It can also happen, particularly in soils where nitrification is already very active, that biochar unintentionally promotes the growth of weeds more than in untreated soils. This was reported by Bo et al. in "Benefits and limitations of biochar for climate-smart agriculture: a review and case study from China" (2023), where a study showed that in an experimental field treated with 15 t/ha of biochar, the amount of weeds doubled compared to the baseline soil.

Furthermore, its generally alkaline pH means that, when applied to acidic soils, it may raise the soil pH too much. This could interfere with the availability of certain micronutrients and reduce their effectiveness for plants.

Another potential downside lies in contaminated soils. In these contexts, biochar's porous matrix may also attract and retain harmful substances such as heavy metals or organic pollutants, which could then affect plant growth or accumulate over time in the environment.

From a regulatory perspective, one of the biggest challenges is the complexity of the legal framework, which limits demand and slows market development, preventing a reduction in production costs. In Italy, for instance, only a small number of waste materials are currently allowed for biochar production. This not only limits its economic viability but also reduces the potential environmental benefits, as carbon sequestration and potential waste reuse.

That said, these restrictions are not necessarily a bad thing: feedstocks must always be carefully selected to avoid producing contaminated biochar. Poor-quality inputs can result in materials that contain toxic compounds like PAHs (polycyclic aromatic hydrocarbons), PCBs (polychlorinated biphenyls), dioxins, or heavy metals, substances that should absolutely be avoided in any agronomic application.

Although biochar is often reported to enhance soil biodiversity and productivity, it may also alter natural microbial communities: this could disturb the balance of soil ecosystems, especially in areas with already fragile or unique microbial populations.

From an agronomic perspective, many farmers remain cautious about using biochar, mainly because its effects are highly dependent on local conditions. Soil type, climate, crop species, and the characteristics of the biochar itself all influence the outcome, making the results very difficult to predict and, therefore, a proper preliminary analysis should always be conducted.

Economically speaking, the production of biochar is not always financially sustainable, particularly for small or medium-sized operations. The initial investment in equipment can be high, and transportation of the feedstock is another major cost, especially since these materials have often high volume and weight. For this reason, the Italian Biochar Association (ICHAR) recommends creating short supply chains with transportation distances under 40 km, to keep both economic and environmental costs under control. This aspect implies that, without carbon credit certification or public incentives, the cost of biochar for farmers can be too high.

Aspect	Advantages	Disadvantages
Economic	- Valorization of agricultural residues (savings on fertilizers and waste management). - Possibility of accessing carbon credits.	- High costs for facilities, production, and transport. - Uncertain profitability without public incentives.
Technical	- Advanced technologies improve efficiency (microwave, flash pyrolysis, etc.).	- Wide technological variability with trade-offs in cost, yield, and impact. - Lack of standardization: biochar quality is not homogeneous.
Agricultural / Productive	- Increases fertility in poor or acidic soils. - Can reduce fertilizer use by up to 50% and increase yields by up to 30%.	- Effects on yields are highly variable (depend on soil, climate, and crop). - In fertile soils: may have no effect or even negative (e.g. nutrient imbalances).
Social	- Job creation in biochar production and management. - Potential improvement in food security.	- Low adoption among smallholder farmers due to lack of training and capital.
Ecological	- Long-term carbon sequestration in soils. - Improves soil structure and water retention. - Potential reduction in GHG emissions (CO_2, CH_4, N_2O).	- Possible soil contamination by PAHs, dioxins, heavy metals. - Alteration of soil microflora and risk of invasive species. - Risk of increased N_2O emissions in nitrifying soils.
Regulatory	- Presence of voluntary standards (e.g. EBC) and integration into EU regulations.	- Lack of a global, binding regulatory framework. - Legal uncertainty hinders trust and investment in the sector - High complexity levels of standard and regulatory framework

Table 1: Advantages and disadvantages of biochar across different areas of application. Extracted from Zhang et al. (2023), Islam et al. (2024), Schmidt et al. (2021), Keiluweit et al. (2022), Ahmad et al. (2022), Lehmann & Joseph (2015), EBC (2023), CO_2RE (2024), Shackley et al. (2015), Shackley et al. (2016), EcoHedge (2023).

4 Technology state of the art

According to the biochar definition, these technologies can be used to produce biochar are defined as "thermochemical conversion of organic matrix in limited presence of oxygen with a process that ensures a temperature above 180 °C for a minimum of 2 minutes".
Thermochemical technologies involve the use of elevated temperatures to sustain the process, and the required energy can be supplied either from external sources or through the combustion of a portion of the feedstock itself.
These thermochemical processes are: torrefaction, pyrolysis (fast, intermediate, slow and microwave), gasification, hydrothermal carbonization and flash carbonization.

4.1 Types of biochar

Depending on the type of technology used, the solid product can be categorized as:

- Biochar: can be produced from dry feedstock (moisture content less than 10%) through all the pyrolysis technologies and also in gasification with proper process parameters selection. If the initial biomass has moisture level higher than 10%, a drying pretreatment phase must be implemented.
  Obviously, this initial phase require high level of heat that can be partially recovered, but this however strongly affect the energetic balance: in Bridgwater et al. (2012) "Review of Fast Pyrolysis of Biomass" paper, the authors affirms that the drying phase accounts for 20-40% of the total energy required for the entire process.

- Hydrochar: to avoid problem related to the drying phase, hydrothermal carbonization (HTC) is the main solution.
  The initial biomass can have high levels of moisture and the solid product obtained is called hydrochar. To perform it, elevated pressure (till 10 MPa) are necessary.
  In this process, the feedstock is heated to trigger a series of simultaneous reactions in the liquid phase, including hydrolysis, dehydration, decarboxylation, aromatization and recondensation. In this way, the oxygen and hydrogen content decrease sharply.

- Charcoal: it is the generic product of a thermal decomposition process highly porous, low density and brittleness that is produced by torrefaction or carbonization of biomass.
  The general uses are in metallurgical smelting applications or as fuel.

Biochar and hydrochar are generally lumped together and improperly defined as biochar, that is because they are derived from feedstock with similar chemical composition (cellulose, hemicellulose, and lignin), but their final physical and chemical characteristics differ considerably and this affects obviously also the application fields.

In the table 2 are reported some differences of the two, but it's definitely been weighing to underline that the final characteristics of the product strongly depend on feedstock and operating parameters, so the table just give an idea of what in average can be expected by these processes.
In addition to solid products, the thermochemical process produces also bio-oil and bio-gas.

- Bio-oil, sometimes called pyrolysis oil or bio-crude, is defined by USDA (United Stade Department of Agriculture) as "a dark, viscous liquid and is comprised of hundreds of oxygenated organic compounds (carboxylic acids, ketones, aldehydes, furans, sugars) and water." It is highly oxygenated and so its energy content is only 50 - 70% of petroleum fuels.
  It is formed by a high number of different compounds, generally more than 200, so it's not easy to classify it from chemical and physical point of view. The final product is strongly affected by initial feedstock and the conditions used.
  Some common features can be that it contains up to $40\%_{dm}$ oxygen by weight, approximately 30–40% water and pH values in the range of 2,8-3,8 that create more than one problems for transportations. It is not miscible with Diesel, so generally it is upgraded with the idea to remove oxygen thanks to process such as full hydrotreating or zeolite cracking.

- Biogas or pyro-gas is the gaseous part obtained during thermochemical reactions and it is mainly form of carbon monoxide, hydrogen, methane, carbon dioxide and nitrogen, with a calorific value (LHV) ranging from 15 to 22 MJ/Nm.
  It is produced in order to transfer the chemical energy of solid biomass into chemical energyof a gaseous form to produce gaseous fuel, e.g. using Fischer tropsch process to obtain Diesel.
  If it is rich in TARs, that is a generic term describing a complex range of oxygenated organic aromatics compounds that are produced by the partial reaction of the biomass feedstock, it can not be upgraded to produce fuel so it is burned to recover heat.

Characteristics	**Biochar**	**Hydrochar**
Feedstock moisture accepted	$< 10\%$	Also $> 10\%$
H:C and O:C	Lower	Higher
Ash production	Higher	Lower
Porosity	Lower	Higher
C stability	Highest	Lower
C concentration	Highest	Low, rich in nutrients
Drying phase for wet biomass	Necessary	Unnecessary

Table 2: Biochar and Hydrochar: Key Comparisons. Data extracted from Safarian et al. (2023)

4.2 Production methods

4.2.1 Slow pyrolysis

Slow pyrolysis is called in this way because the residence time is really long, from minutes to days, depending on the technology and feedstock. The process temperature fluctuates in the range of 300-700 °C, with absence of oxygen and with a slow heating rate, less than 30 °C/min generally 5–10 °C/min.
The long residence time influences the product yields due to two main factors: biochar and temperature catalyze the cracking of long condensable molecules. In fact, biochar promotes cracking, significantly reducing the bio-oil yield while increasing gas production. Moreover, heat also contributes to the cracking reactions, making residence time a key parameter in the process.
In general, high pyrolysis temperature, low heating rate and long vapor residence time gives us the possibility to produce high quality biochar, that is characterized by high fixed carbon content (generally biochar is considered of high quality if fixed carbon content is higher than 70%) and low concentration of pollutants.
If the goal is to maximize yield, moderate temperature are the best option, because there is less reduction of losses of volatile matter.
Moreover, for agricultural or soil remediation applications, another important feature of the final product is its structure: at high temperatures, the original biomass structure is destroyed, significantly reducing adsorption capability as the pores lose their integrity. Conversely, with gentle heating, the pore structure is preserved.
The temperature is also responsible for the reduction of volatile matter and thus the increasing of the fixed carbon content.
Obviously the initial feedstock, the dimension and the humidity must always be taken into account to asses the potential yield of products, with the general rule that smaller particle size are more suitable for biochar production.

4.2.2 Fast pyrolysis

The main characteristics of fast pyrolysis are the opposite of the slow pyrolysis: high temperature, high heating rate (around 1000 °C/s) and very short residence time (less than 2 s) and these operating parameters are translated in a maximization of bio-oil yield at the expense of the char production.
The higher temperature and high heating rate promotes the decompositions of biomass that release vapors: they are composed of long chain of molecules that can condensate and transformed in liquid phase.
The best operating temperature is 500 °C: for lower temperatures there is not enough heat to promote the extraction of long chain molecules that remain stuck in the biochar, while at higher temperatures molecules cracked, losing the ability to condensate and remaining in gas phase also at ambient temperature.
For the same reason the residence time is really short, in fact, higher is the residence time, higher will be the probability that molecules cracks.
Moreover, also the presence of the biochar reduce the gas yield because it

acts as a catalyzer promoting chain breaking.
To have an idea of how strongly the process parameters affects the products yields, a change in heating rate from 10 to 50 °C/min can reduce the biochar yield by 3-8 wt%.
The effects of heating rate and temperature are not linear (data exposed are related to rapeseed stem):

- Temperature: from 200 to 300 °C the biochar yield can sharply reduce from 80% to 36%, but when it increase from 300 to 700 °C the yield reduce much slower.

- Heating rate: from 1 to 5 °C/min yield increase, but decrease from 5 to 20 °C/min and this is due to the velocity in which biomass decompose: with high heating rate it decompose fast and parts of the carbon is removed and transformed in gaseous or liquid phase. The maximum yield is obtained for 5 °C/min.

In addition to that, also pressure has a role: if it grows, also does the quality and the yields due to the increase of the retention time in the chamber and so promoting molecular depositions.
On the opposite side, working at higher temperature the biochar quality increases due to volatilization of pollutants and other undesired molecules. For pine sawdust if pyrolysis temperature increase from 550 to 750 °C the carbon content increase as well from 70,68% to 78,75%.

4.2.3 Intermediate pyrolysis

As it's name says, intermediate pyrolysis works with parameters in the middle between the two previous methods already explained operating at moderate temperature 300-500 °C, moderate heating rate (1–10 °C/s), short vapor residence time (a few seconds) and moderate feedstock residence time (1 to 15 min).
Given these characteristics, the process is still designed to maximize bio-oil production; however, compared to fast pyrolysis, the yield is generally lower. In contrast, gas and biochar yields may increase, although this strongly depends on the operating parameters and the type of feedstock used.
In general, with these operational parameters the yields of the three products are more or less similar, as can be observed in table 3 on page 34

4.2.4 Microwave assisted pyrolysis (MAP)

Microwave-assisted pyrolysis (MAP) offers a more efficient and controllable approach to biochar production.
Thanks to its rapid heating rates, reactions are significantly accelerated, often resulting in higher yields within shorter times compared to traditional methods. MAP is particularly well-suited also for feedstock with high moisture content, as its heating mechanism relies on molecular motion, making it more effective than with dry materials. Moreover, it allows for better selectivity of target products in a single-stage process.

However, the system is more complex and presents challenges in monitoring, especially due to the uneven heat distribution, which makes temperature control difficult.
There are also safety concerns related to potential microwave leakage, requiring strict health precautions.
Additionally, when it comes to biochar yield, conventional pyrolysis techniques still tend to outperform MAP.
One significant advantage of this technology is that the heating is not applied directly to the biomass. Instead, microwaves typically heat the chamber surrounding the biomass, resulting in a more gentle heat transfer.
This helps preserve the structural integrity of the biomass during processing, which translates into more defined pore structures and consequentiality improved adsorption capacity.

4.2.5 Flash carbonization

A flash carbonization process is a partially combustion of packed biomass that works using high levels of pressure (in the order of 1 MPa) in a pressurized chamber with specific amount of air/oxygen injected. Using this technology, the conversion of biomass into char is really fast.
Temperature rising involves an increase in the fixed carbon in the solid product improving the quality of the char.
However, as previously mentioned, this comes at the cost of reduced yield and increased ash content.

4.2.6 Hydrothermal carbonization

Hydrothermal carbonization is a method that uses wet feedstock and can be particularly advantageous, as it avoids the energy consumption associated with the drying phase. It is also the only method in which the solid yield can reach up to 80 wt%.
The main operational parameters are temperature in the range 100-300 °C, elevated pressure (2–10 MPa) and residence time in the order of hours. The presence of water offers the advantage of accelerating the carbonization process, as it acts both as a medium and as a reactant. Being an oxidizing substance, it facilitates the reaction. On the other side, it has negative impact on the energy demand, because part of the energy is loss just for the evaporation of water.
To maximize solid production, the reaction is generally carried out at low temperatures (150–200 °C), with maximum yield for 180 °C with a residence time of 30 min. As the temperature and residence time increase, the solid yield decrease while the gas yield increases; however, the carbon content in the solid also increases.
When comparing the solid products to assess the best possible application, hydrochar, despite its lower carbon content and higher level of contamination, is suitable for nutrient-poor soils, whereas biochar is optimal for stable carbon sequestration and contaminant reduction thanks to its higher surface area, although its production process generates more ash.

4.2.7 Gasification

Gasification process can be explained considering it as a pyrolysis process but with a added step: char oxidation reaction that forms gas molecules. The idea of the process is to transform the chemical energy present in solid biomass into chemical energy in gaseous form.
It differs from all the other already explain mainly for two reasons: the operating temperature are generally much higher (700-1600 °C) and there is an higher amount of air equivalence ratio (ER) supplied during the process. It is defined by Science Direct (2022) as actual air to biomass weight ratio divided by stoichiometric air to biomass weight ratio needed for complete combustion. In gasification process it is in range between 0,2 and 0,4.
As with the other technologies previously discussed, the three resulting products are char, gas, and liquid, but, as the name suggests, this process is optimized to maximize gas production and biochar is, generally, an unwanted by-product.
The reason why it is mentioned as a technology used to produce biochar is because its quality is really high, with an high fraction of fixed carbon. The cons of this technology are the reduced amount of solid yield that are generated (in the order of 10 wt%).
Obviously, quality is influenced by all factors already explained for the other technologies but here also the air equivalence ratio (ER):
Higher value of ER leads to biomass combustion and an increasing of gasification temperature which affects the solid carbon yield and quality. Multiple studies (e.g. Tauqir et al. (2019) and Muvhiiwa et al. (2019)) asses negative impact of ER:

- Increase ER from 0,1 to 0,45 reduce the biochar yield from 4,3 kg/h to 1,3 kg/h at operating temperature of 500 °C.
- ER increasing from 0,15 to 0,6 reduce carbon content from 89% to 80% at 700 °C and from 93% to 86% at 900 °C.

Generally the most used gasifying agent are CO_2, H_2O with external heat supply, while O_2 or air with internal heat generation.

4.2.8 Torrefaction

An easy way to produce char is the torrefaction; it requires low temperature (200 °C - 300 °C) in inert atmosphere with low heating rate (20 °C/min) and residence time that varies with respect to the feedstock, but that is in the range of 10 to 180 min.
The main goal of this technology is the production of solid char (60-80%) that generally is used as fuel.
The other product is the syngas (40-20%) that is generally burned in combustion chamber for recover the required heat needed by the process. Liquid byproducts are not commonly produced.
Considering the end-use of the char, calorific value, energy yield and energy density are critical indicators such that the initial biomass loose only 10 wt% of the initial energy content reaching more or less 22 MJ/kg.
Looking at the temperature range in which this technology works, the initial

moisture content of biomass plays a crucial role to asses the energy efficiency of the process: if the feedstock has high amount of water, the process in not energetically sustainable. Natural drying phase could be a solution.
In general, as before, temperature is the main parameter and as it increase, across different biomass types, the resulting char exhibits a higher carbon content.

4.2.9 Final considerations on the technological overview

As highlighted several time, feedstock, operational parameters and technology used strongly affects the final product, but some common features and general considerations can be outlined:

- Biochar should be always produce starting from dry biomass (moisture content lower than 10 wt%) because if it were not, most of the energy will be used to remove water instead of heating the biomass and the process could not be energetically sustainable.

- Aquatic biomass, such as herbaceous crops or grass, can be naturally dried thanks to solar heating or can be used to fed gasification or hydrothermal carbonization process.

- Temperature is the most critical parameter: as it increases, the carbon content rises while the solid yield decreases. Closely related to temperature, the heating rate also plays a key role, influencing the speed of heat transfer as well as the structure of the biochar and the decomposition of volatile matter.

- The second most important operational parameter is the residence time, higher it is, higher will be the formation of solid product.

- Best technological method to balance quality and quantity of solid yield is slow pyrolysis, with 25-50 wt% of total yield and carbon content generally higher than 70%.
  If, for some reason, the goal becomes biochar with very high carbon content (more than 85%) the temperature must rise up and this means that gasification become the best possible technology.
  Obviously quality and quantity are inversely related, and slow pyrolysis is the actual best possible solution to balance both.

- If biochar is produced with gasification methods, ER becomes the most important factor: higher it is (always in the range of 0,2 - 0,5), higher will be the biomass combustion and so the reduction of solid yield.

Table 3: Operating conditions and product/byproduct yields of different technologies. Data extracted from Safarian et al. (2023)

Technology	**Temperature**	**Residence time**	**Heating rate**	**Biochar**	**Bio-oil**	**Syngas**
Slow pyrolysis	300–700 °C	Long (from minutes to days)	Slow, <30 °C/min (generally 5–10 °C/min)	21–80% (generally 35%)	30%	35%
Fast pyrolysis	300–1000 °C	Very short (<2 s)	Very fast, 1000 °C/s	5–38% (generally 12%)	50–75%	13%
Intermediate pyrolysis	300–500 °C	Moderate (1–15 min)	Moderate, 1–10 °C/s	30–40%	35–50%	20–30%
Flash carbonization	300–600 °C	Moderate (<30 min)	Very fast	50% (charcoal)	0%	50%
Gasification	600–1500 °C	Short (10–20 s)	Moderate to very fast	10%	5%	85%
Torrefaction	200–300 °C	Relatively long (10–120 min)	Slow, <20 °C/min	60–80% (charcoal)	0%	40–20%
Hydrothermal carbonization	100–300 °C	Long (1–16 h)	Slow	45–95% (hydrochar)	5–20%	0–5%
Microwave	350–650 °C (400–2700 W)	Moderate (1–60 min)	Fast (25–50 °C/min)	15–80%	8–70%	12–60%

5 European and Italian Legislation on biochar production and uses

Biochar production and use are obviously controlled by authorities, mainly to avoid contamination in soil, environment or in food. In particular, all the regulatory framework focuses on three main pillars:

- Technology adopted.
- Type of feedstock accepted.
- Pollutant presence inside final product.

5.1 European Legislation

Biochar is included in the EU Regulation 1009:2019 as CMC 14: Pyrolysis and Gasification Materials (legally, no longer referred to as “biochar”).
It can be produce with from agricultural and silvicultural waste material but also with organic waste from separate collection, animal by-products, living or dead organisms, waste from food industry, residues from the production of bioethanol and biodiesel and other additives (up to 25%).
The only other regulated use of biochar is as an additive in animal feed, and it is permitted under EU Regulation 68/2013, which classifies it as a product derived from the carbonization of plant biomass.
Its use must comply with Directive 2002/32/EC on contaminants and Regulation 178/2002 on feed safety, allowing only clean and uncontaminated plant-based feedstock, such as untreated wood, crop residues, or biomass from sustainable agriculture.
The use of waste-derived or chemically treated materials is strictly prohibited.
In Italy, as in many other European countries, there is currently no specific national regulation governing the use of biochar for animal feeding.
As a result, most producers rely on voluntary certifications, such as EBC Feed, to ensure compliance with EU safety standards and to guarantee product quality.

5.2 Italian Legislation

Italy was one of the first European countries to regulate the use of biochar in agriculture with Legislative Decree 75/2010.
Biochar is officially recognized in Italy as a soil organic improver allowed in agriculture (Legislative Decree 75/10, Annex 2, order number 16, as amended by ministerial decrees of June 2015 and June 2016).
It includes materials obtained from the carbonization of virgin plant products and residues from agriculture and forestry.
Recognized by-products included are olive pomace, grape marc, bran, fruit pits and shells, and untreated wood processing residues. Energy recovery must take place (following Industrial Emissions Directive (IED)) rules and using Best Available Technology (BAT)): re-using gasses or heat generated during the process.
Ministerial Decree of October 10, 2022, includes biochar among fertilizers

allowed in organic farming, with stricter limits for Polycyclic Aromatic Hydrocarbons (PAHs) (4 mg/kg dry matter instead of 6 mg/kg).
In order to produce and sell biochar in Italian market, is not enough to be strict with all the regulatory frame work, but it is also mandatory to register with SIAN.
The National Agricultural Information System (SIAN), established by Law No. 194 of June 4, 1984 (Article 15), is a structured and interdisciplinary service system available to agricultural producers and various institutional stakeholders in the agricultural, forestry, and agri-food sectors to support functions of guidance, coordination, and management.
It provides a centralized database through which producers can submit documentation, notify products, and obtain legal authorization for marketing biochar and, doing so, it ensures products meet legal compliance for commercialization.
Unfortunately, in Italy, the national regulation is still in force, as the European regulation has not yet been adopted.
The main issue concerns the types of biomass accepted in Italy, which are strictly limited to waste biomass, whereas at the European level there is a broader acceptance of different biomass types.
The failure to adopt the European regulation remains one of the most significant limiting factors for the national biochar market growth.

5.3 Certifications and standards - biochar production and use

To help producer and customer to comply with regulatory framework and better understand how to manage properly biochar,multiple associations have emerged in recent year, with the scope of support the growing of this sector in a safety and sustainable environment.
The idea is that they follows and monitor all the supply chain and give the possibility to use a logo that guarantees the quality and conformity of that specific product.
Obviously, they create guidelines based on general national or international regulatory framework.

5.3.1 EBC - European Biochar Certificate

The EBC is the European association for biochar production and "it was developed to limit the risks of biochar usage to the best of our scientific knowledge and to help the users and producers of biochar to prevent or at least to reduce any hazard for the health and for the environment while producing and using biochar" (EBC, 2023).
The certification approach born thanks to a partnership with CSI (Carbon Standard International), that develops standards and system solutions for climate-positive agriculture, forestry and industry and upstream, and downstream sectors, offering a wide range of services with quality and reliability.
One of the main prerogatives imposed by EBC certifications is the sustainability of the process. It establishes three pillars:

- Reuse pyrolysis gasses generated during the process.
- Any emissions must comply with the national regulations in which biochar is produced.
- At least 70% of the heat must be reused (for heating the chamber or for drying biomass, if necessary).

EBC establish specific limits and characteristics for feedstock, processing methods and biochar parameters, grouped into seven distinct categories:

- EBC-feedPlus: this is the most comprehensive certification. It meets all the requirements of other categories and complies with EU and EFTA (European Free Trade Association) regulations for both animal feed and agricultural soil applications.
  Biochar with this certification can be used with all types of livestock and applied to soils.
  However, producers must also be officially approved as feed suppliers under national regulations.
- EBC-feed: complies with EU regulations for animal feed, but not with those for fertilizers, which are more stringent. As a result, it can be used in animal feed but not for soil amendment under current EU fertilizer laws.
- EBC-Agro/EBC-AgroOrganic: these certifications are valid for agricultural use of biochar.
  They comply with the EU Fertilizing Products Regulation, and in the case of EBC-AgroOrganic, also with the regulation for organic farming. Some EU countries have additional national requirements (e.g., Switzerland, Germany, Sweden), but these certifications allow for cross-border use within the EU.
- EBC-Urban: designed for urban uses such as tree planting, parks, drainage systems, and ornamental plants.
  It focuses on environmental and occupational safety, especially to prevent water contamination. It cannot be used for soils involved in food or feed production.
- EBC-ConsumerMaterials: applies to products that may come into contact with skin or food-related items (e.g., takeaway cups, textiles, plastic goods).
  Biochar must be embedded in materials to prevent dust release. Does not include medical or direct food uses.
- EBC-BasicMaterials: intended for use in basic industries (e.g., construction, asphalt, industrial components).
  Requires safety measures for handling and prohibits agricultural or urban use. Certified biochar can only be traded B2B (not to private consumers).
  Any material that exceeds the limits of this certification is considered potentially hazardous waste and must be disposed off accordingly.

The definition of a certification class is a statement of admissibility of biochar for a given purpose regarding applicable laws, regulations, and relevant industry standards.
These categories are arranged in order of strictness, from the most stringent to the least: indeed EBC-feed is the category related to the use of biochar as feed additive, so it must comply with stricter rules for safety reasons.

5.3.2 IBI - International Biocchar Initiative

IBI was formed in July 2006 at a side meeting held at the World Soil Science Congress (WSSC) in Philadelphia with the interest to promote the research, development, demonstration, deployment and commercialization of the promising technology of biochar production.
"IBI's mission is to scale biochar to reach its full potential and achieve global net zero targets by empowering communities and industries.
Through strategic partnerships, innovation, education and advocacy, we aim to accelerate and scale the adoption of biochar technologies worldwide, fostering sustainable business models, and facilitate community-based action that combats climate change and create a resilient future for generations to come" (IBI, 2024).
In 2009, IBI started to work on standards, with the goal to define what biochar is and what is not and give to consumer a certifications of conformity and safety.
In 2024, IBI and Carbon Standards International (CSI) announced a new partnership to create stronger standards and certifications to meet the needs of a rapidly scaling biochar industry.
More than all the others, IBI takes from the beginning the role of informatory reference body, with the idea of spread knowledge, support research and continuously pushing for market growing. It has a world relevance, working also for developing country growth through educational programs.
To obtain IBI certification, which is valid for one year, producers must adhere to the guidelines set by the IBI.
These guidelines focus on toxicity assessments and the soil enhancement properties of biochar, and require that the feedstock be certified by specific bodies approved by the IBI.

5.3.3 ICHAR - Associazione Italiana Biochar

"The Italian Biochar Association (ICHAR) is a non-profit organization founded in 2009 to promote, through collaboration between the research community and the private sector, solutions, technologies, advanced studies, demonstration activities, and educational projects focused on the application of biochar in agriculture as an innovative strategy to enhance global soil fertility and mitigate greenhouse gas emissions" (ICHAR, 2024).
It is the no-profit national center that helps Italian producers to be compliant with Italian regulations and/or with EBC standard and more than that it has the role of information authority, to transfer to producer and farmers all the knowledge needed.

They following the EBC and IBI strategies with the goal to establish a strong national Biochar market, that at the moment, is really just at the beginning.
Looking at the the D.lgs 75/2010, Ichar has founded two certifications that lasts two years: MVVB ICHAR and MVVB ICHAR PLUS that differs for quality parameters, as it is possible to see in table 4.

Parameter	**MVVB**	**MVVB PLUS**	**Method**
C_{org} (% d.m.)	≥ 75	≥ 70	Legislative Decree 7276 of 31/05/2016, Suppl. 13 no. 2
Stability of C_{org} (%)	> 50	> 50	Appendix I, Method 1 – Biochar Quality Mandate v.1.0 – 2014
Ash content at 550°C (% d.m.)	< 15	< 25	UNI EN 13039
Electrical conductivity (mS/m)	≤ 150	≤ 500	UNI EN 13038
$O:C_{org}$	≤ 0.4	≤ 0.4	Legislative Decree 7276 of 31/05/2016, Suppl. 13 no. 2
$H:C_{org}$	≤ 0.4	≤ 0.4	Legislative Decree 7276 of 31/05/2016, Suppl. 13 no. 2
Particle size fraction $<$ 0.5 mm (%)	≤ 30	≤ 50	UNI EN 15428

Table 4: Restrictions imposed by MVVB and MVVB PLUS

5.4 Concentration limits and pollutants

For all regulations, the concentration of some elements or the pH and presence of pollutants inside biochar represents the main issue related to its use.
In general, all the regulatory frameworks have set some limitations in order to guarantee that the product is safe the for environment, animals and humans.
In the table 5 on the next page are shown all the limits for the compound accepted in the final products.
As can be easily to observed, Italian legislation as the strictest regulations, that grantee maximum safety.
One of the most important pollutants that is always monitored is the Σ 16 PAHs (Polycyclic Aromatic Hydrocarbons): they are persistent organic carcinogens with two or more aromatic rings without alkyl groups or hetero-atoms.
For European law, the maximum in Σ 16 PAHs concentration must not exceed 6 mg/kg of dry matter, but must be lower than 4 mg/kg in case of organic agriculture biochar use.
The process operating parameters are crucial to controlling the biochar toxicity:

- High pyrolysis temperature (over 750 °C) produces biochar with a significant high amount of Σ 16 PAHs compared to biochar produced in the range temperature of 450–600 °C.

- Σ 16 PAHs concentrations are generally higher in biochars obtained with gaseous shorter residence times because they don't have time to escape and condensate on solid product. For this aspect, slow pyrolysis represents the best solution.

- During gasification there is an higher production of Σ 16 PAHs due to the higher frequency of forming reaction that is promoted by higher temperature and presence of oxidizing agents.

Parameters	**IBI**	**EBC Agro Bio / Agro**	**EU Reg. 1009/2019 CMC 14**	**Italy D.Lgs. 75/2010**
C_{org} (% d.m.)	>10–30–60	—	—	>20–30–60
H:C_{org}	$\leq$ 0.7	$<$ 0.7	$<$ 0.7	$\leq$ 0.7
O:C_{org}	—	$\leq$ 0.4	—	—
Humidity (%)	—	—	$\leq$ 80	$\geq$ 20
PAHs (mg/kg d.m.)	$<$ 6–300	$<$ 4–6	$\leq$ 6	$<$ 6
PCBs (mg/kg d.m.)	$<$ 0.2–1.0	$<$ 0.2	$\leq$ 0.8	$<$ 0.5
PCDD/PCDF (ng/kg) WHO eq.	$<$ 9	$<$ 20	$\leq$ 20	$<$ 9
As (mg/kg d.m.)	$\leq$ 13–100	13	$\leq$ 40	—
Cd (mg/kg d.m.)	$\leq$ 1.4–3.9	$\leq$ 0.7 / 1.5	$\leq$ 2	$\leq$ 1.5
Cr VI (mg/kg d.m.)	—	—	$\leq$ 2	$\leq$ 0.5
Cr tot (mg/kg d.m.)	$\leq$ 93–1200	$\leq$ 70 / 90	—	—
Cu (mg/kg d.m.)	$\leq$ 143–1600	$\leq$ 70 / 100	$\leq$ 200–300	$\leq$ 230
Hg (mg/kg d.m.)	$\leq$ 1–17	$\leq$ 0.4 / 1	$\leq$ 1	$\leq$ 1.5
Mo (mg/kg d.m.)	5–75	—	—	—
Ni (mg/kg d.m.)	$\leq$ 47–600	$\leq$ 25 / 50	$\leq$ 50	$\leq$ 100
Pb (mg/kg d.m.)	$\leq$ 121–300	$\leq$ 45 / 150	$\leq$ 120	$\leq$ 140
Zn (mg/kg d.m.)	$\leq$ 416–7400	$\leq$ 200 / 400	$\leq$ 500–800	$\leq$ 500
Cl^- (g/kg d.m.)	—	—	—	—

Table 5: Comparison of regulatory thresholds for biochar: IBI, EBC, EU, and Italian legislation

In table 6 on the following page are shown some other limitations that are not present at European level, but that are in force only in the Italian regulatory framework.

Properties	Values	Notes
C_{tot} of biological origin (C_{org} % d.m.)	$\geq$ 20	>60 CL 1 / 30–60 CL 2
Ashes 550°C (% d.m.)	$\leq$ 60	<10 CL 1 / 10–40 CL 2
pH	4–12	—
Electrical conductivity (mS/m)	$\leq$ 1000	$\leq$ 100 in cultivation substrates
Humidity (%)	$\geq$ 20	For powdery products
Growth rate	Suitable	For spring barley or Chinese cabbage

Table 6: Biochar technical operational parameters and classification notes

6 Biochar in carbon credits market

6.1 Historical pillars on European legislation

The creation of a carbon market stems from regulations and directives issued by the European Union, which recognized the need to actively engage in the fight against climate change.
As a result, it set itself the primary goal of reducing CO_2 emissions and, where this is not possible, offsetting them. The main historical pillars on European legislation are:

- United Nations Framework Convention on Climate Change(UNFCCC): approved in New York on 9 May 1992, is the first international treaty specifically referring to climate change.
- Kyoto Protocol: signed in Japan in December 1997 is the implementing instrument of the Convention (2008-2012) and then extend with Doha amendment (2013-2020).
- Paris Agreement: adopted in Paris on 12 December 2015, entered into force on 4 November 2016.

The UNFCCC, signed by 197 countries, represents the United Nations' first commitment to stabilizing greenhouse gas concentrations in the atmosphere at levels that would prevent dangerous anthropogenic interference with the climate system.
It also gave signatory members the possibility of adopting specific protocols, following dedicated conferences, to introduce mandatory limits on emissions.
The three main objectives, stated in Article 3, were:

- Fighting climate change.
- Protecting and supporting developing countries, where climate change could have particularly harmful effects.
- Recognizing that a partial lack of scientific information existed, but that it was not sufficient to postpone preventive and mitigation measures concerning this problem.

Article 4 outlines the obligations of the signatory countries, divided between industrialized and non-industrialized nations: the former have stricter obligations and play a leading role in the fight against climate

change.
Some of these obligations include:

- Preparing an annual report on the policies and measures adopted to reduce emissions.

- Monitoring emissions data not covered by the Montreal Protocol (which relates CFCs, HCFCs, and halons to the formation of the ozone hole).

The first binding targets for emission reductions were only achieved with the Kyoto Protocol, signed in 1997 by 192 countries and entering into force on February 16, 2005.
The main goal set by the Kyoto Protocol was to achieve "an overall reduction of greenhouse gas emissions by 5% compared to 1990 levels during the period 2008–2012 by industrialized countries."
The member states decided to further tighten these commitments, aiming for an 8% reduction in emissions.
The so-called Doha Amendment established a second commitment period (2013–2020), setting the following targets:

- Reducing emissions by 18%.

- Adding nitrogen trifluoride (NF_3) to the list of gases covered by the Kyoto Protocol.

- Continuing the use of carbon market mechanisms, such as the Clean Development Mechanism (CDM) and the Emissions Trading System (ETS)

As before, the European countries involved decided to impose even stricter conditions, aiming to achieve a 20% reduction in emissions and increasing the share of renewable energy in the energy mix to 20%.
Finally, in 2015, the first universal and legally binding global climate agreement was signed.
The agreement defines a global action plan to:

- Mitigation:
  - Limit global temperature rise well below 2 °C above pre-industrial levels and strive to keep it below 1,5 °C.
  - Reduce greenhouse gas emissions to achieve carbon neutrality by 2050.
  - Try to reach goals as soon as possible, knowing that it is tough for developing countries.

- Adaptation: enhancing the ability to adapt to the impacts of change.

- Finance: financial flows aligned with the path towards climate-resilient and low-emission development.

6.2 Carbon Credits and Carbon Offset

Thanks to all the steps outlined earlier, carbon credits were established in 2015 as a measure to mitigate climate change caused by greenhouse gases emissions.
The idea behind that is based on the principles of "polluters pay": all the businesses that emit greenhouse gases must first minimize their emissions and then compensate for any unavoidable remainder.
To compensate the emissions they can buy carbon credits or carbon offset that are a financial unit that represents the removal of one ton of CO_2 equivalent (CO_{2eq}) from the atmosphere.
Through purchases on the market, companies can finance projects that actively remove greenhouse gases from the environment.
To generate these credits two other actors are needed: green project developer, the one that works to actually compensate the emissions, and global platform entities, that verify, certifies and accredits projects for the durable removal of CO_{2eq}.
Carbon credits are divided into two main categories:

- Regulated carbon credits (or emission allowances): these are managed in official emissions trading systems, such as the EU ETS.
  It's based on "cap and trade" systems: governments assign emission limits to companies or countries, and those that emit more than allowed can buy credits from those who emit less.
  This creates a financial incentive to reduce emissions, since staying below the limit allows entities to sell their surplus and make profit.
  For the most polluting companies, such as those operating in the energy or transportation sectors, must stay within emission limits or purchase carbon credits, so it's mandatory.
  If a company or a country exceed limits and does not compensate, EU impose heavy fines.

- Voluntary carbon credits(VCM): these credits, called "Carbon offsets" are part of a separate market, where companies or individuals, without legal obligations, can choose to buy credits to support climate initiatives and "be more green".
  These credits come from certified projects that remove greenhouse gases from the atmosphere or prevent them from being emitted.

Carbon Offsets	**Carbon Credits**
Can be purchased by individuals, small and large companies	Can only be traded by companies and governments
Represent projects that remove greenhouse gases from the atmosphere	Represent the right to emit one ton of carbon dioxide
Used in the voluntary carbon market	Used in government-regulated cap-and-trade systems

Table 7: Differences between Carbon Offsets and Carbon Credits

The value of the carbon credits and carbon offsets is related to their quality and it is measured evaluating consider five parameters:

- Additionality: this is a key criterion for assessing the quality of an offset project. Credits are considered additional only if they represent actual emission reductions that wouldn't have occurred otherwise. Assessing additionality requires estimating what the emissions would have been in the absence of the project, which can be complex.

- Accuracy in assessment: emissions reductions must be accurately measured.
This is easier in some cases (e.g. methane capture at landfills) and more complex in others (e.g. estimating emissions from power grids or solar energy projects).
To ensure reliability, ongoing monitoring and post-implementation verification are essential.

- Permanence: offset credits must reflect permanent greenhouse gas removals or reductions.
Temporary storage is not sufficient, and once credits are issued, the claimed reductions cannot be revised.
The ease of ensuring permanence varies by project type.

- Exclusive claim to avoided or removed emissions: offset credits must correspond to unique and exclusive claims of emission reductions.
Problems arise when different programs double-count the same reduction or issue multiple credits for the same activity.
To prevent this, credits must be promptly retired once used, and registries must maintain full transparency. Fraudulent resale of already-retired credits has occurred in the past, so all retirement actions must be clearly recorded, including on whose behalf the credits are retired.
Double claiming can also occur when multiple entities claim the same reductions for different projects.

- Avoiding social and environmental harm: projects must not harm local communities or cause environmental damage.
Credits must comply with all legal requirements of the jurisdiction where the project is implemented preserving the natural ecosystem.

6.3 Voluntary Carbon Market

Going deeply in VCM, the first big characterization that must be done is related to the type of projects that can be considered acceptable in this market.
They are divided into avoidance projects and removal projects: the first focus on preventing emissions from occurring, while the second actively remove or sequester existing CO_2 from the atmosphere.

- Avoidance: "avoidance based credits are generated by projects that prevent or avoid the release of greenhouse gas (GHG) emissions that would have occurred in the absence of the project". (Carbon Direct,

2023)
The idea is to work on technologies, energy efficiency measures, or adopting sustainable practices in order to reduce or, in the best case, avoid emissions. Generally, these project are managed by firms operating in renewable energy sector, waste management sector and transportation sector.
An example can be the implementation of a wind farm or a photovoltaic system that generate green energy and avoidance the use of fossil fuel-based power plants.

- Removal: "removal based credits are generated by projects that actively remove or sequester CO_2 from the atmosphere, thereby reducing the concentration of greenhouse gases". (Carbon Direct, 2023)
  These activities are often realized by nature based solution, direct air capture (DAC) facilities, Enhanced Rock Weathering (ERW).
  An example can be a reforestation project in an area where entire trees from the forest were swept away.
  Thanks to photosynthesis activity performs by trees, there is an absorption of CO_2 that is stocked inside wood structure and an emission of pure oxygen.

VOLUNTARY CARBON MARKET	
Reduction/Avoidance Credits	**Removal Credits**
Carbon credits that represent reduced or avoided emissions	Carbon credits that represent captured/removed emissions
Technology Based	**Technology Based**
• Renewable Energy • Methane Collection • Industrial Pollutant • Household Devices	• Direct Air Capture • Mineralisation • Carbon Capture and Storage
Nature Based	**Nature Based**
• Avoided Deforestation • Wetland Management • No-till Farming • Methane from Livestock	• Reforestation • Afforestation • Soil Sequestration • Wetland Restoration

Table 8: Classification of Carbon Credits in the VCM

In conclusion, the differences between the two types of credits significantly impact their quality: removal credits are generally considered to have a greater environmental impact with a longer-term fights against climate change and, for this reason, are typically more expensive.

6.4 Actual role of biochar in Voluntary Carbon Credit Market

In the carbon-market world, biochar credits are seen as a removal technology, where CO_2 is taken out of the atmosphere thanks to photosynthesis activity performed by plants.
The concept behind using biochar as a CO_2 removal agent is simple: it is obtained through a process that starts from woody biomass and results in a material primarily composed of carbon that was originally captured from the environment through photosynthesis activity.
Thanks to the pyrolysis process, most of this carbon is converted into fixed carbon, which does not react with the atmosphere or soil. Therefore, burying it in the ground allows to store the CO_2 removed from the environment for over 100 years.
In fact, one of the main characteristics, in comparison with all the other carbon removal methods, is its durability, as it remains stable in the soil over time, indeed main achievement of biochar production is the stabilization of carbon. Without this process, the biomass would naturally decompose or be burned, usually without any energy recovery, simply as a means of disposal, as is often the case with crop residues
This would release CH_4 and CO_2 into the atmosphere, effectively nullifying all the carbon sequestration previously carried out through photosynthesis by the plants.
For this reason, biochar is considered one of the most promising methods for carbon removal, generally more effective than reforestation, which stops to store carbon once plants die.
By contrast, once biochar is incorporated into the soil, it remains there, stable for centuries.
Considering average values, 1 kg of biochar can remove 3 kg of CO_{2eq}.

6.5 Certifications and Standard - Carbon Credits

Not all biochar produced generates financial credits. In Italy, for example, none of the producers currently earn revenue from it.
This is because producers must be certified by external bodies that ensure the entire supply chain complies with required standards to produce biochar capable of delivering a truly environmental benefit.
Around the world the current status is much better, as state by the EBI (European Biochar Industry) in 2023 market report: "75% of the production capacity is certified for carbon removal".
In Europe, this fraction is significantly lower due to producers' skepticism towards voluntary carbon trading systems and in particular to the fact that it is on voluntary base and biochar is not included in the regulated market (the mandatory one).

The certification bodies are the link between the biochar producer and company that buy the allowance.
They create rules that biochar producer and user must follow in order to truly generate a carbon sink. All the platforms have they own guidelines and rules that take into considerations, obviously, also the national and/or international laws.
There are three or four actors: the biochar producer, the biochar user (that sometimes can be also the producer), the platform that emits certifications and the carbon credit buyer.

- The biochar producer are the ones that collect waste residues and transform it in biochar. They must be compliant with all the national regulations imposed for the production, but also with the rules that the certification body impose.

- The user, that generally are farmers, need to follow the regulations imposed by national law, but, in particular, it's really important that they are compliant with the rules imposed by the platform to generate the C-removal credits, because they are the one that actually remove and stock carbon in soil.

- The platform or certification body is responsible for verifying that all steps are properly completed, thereby ensuring the legitimacy of the carbon sink creation.
  Those platform perform measurement and controls to guarantee the reliability and clearness of the entire chain: they check feedstock, quality of the biochar, the energy balance, all the contaminants and also the application in soil.
  Is not easy for biochar, but generally they perform scientific measurements through time in order to asses monitor the evolutions of the project.

- Carbon removal buyers rely on platforms to compensate for their emissions.
  The price of one ton of CO_{2eq} removed is determined by the overall quality of the project, as assessed by the platform considering all the factors explained before in section 6.2 ("Carbon Credits and Carbon offset"). Once the certifications are purchased, companies can showcase sustainability and green credentials, enhancing their brand reputation and goodwill.
  The money earned by the platform is partly used to support its operations, while the majority is allocated to actual carbon sequestration efforts. These funds are directed either to the project developers or the end users, depending on the specific case.

There are several certification entity but the main important are Verra, Gold Standard and Puro.earth.

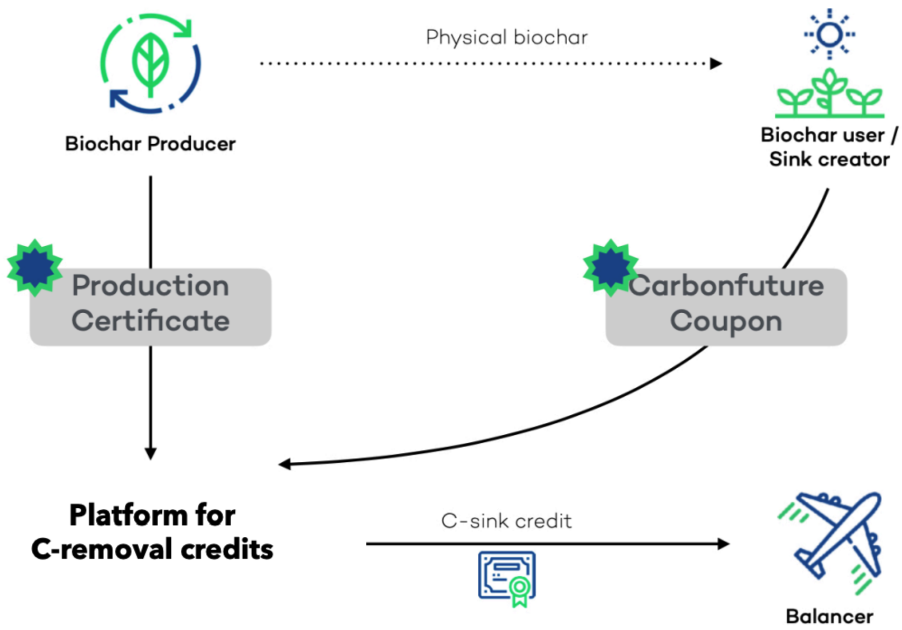

Figure 10: Carbon credit certification supply chain. Extracted from Carbonfuture Guidelines (2022)

6.5.1 Verified Carbon Standard - Verra

The Verified Carbon Standard (VCS) program, created by the non-profit company Verra, is the world's most widely used greenhouse gas crediting program with highest market volumes.
Biochar production falls under the category of "Agriculture, Forestry and Other Land Use (AFOLU) projects". Specifically, it belongs to the "Improved Cropland Management (ICM)" group, as its application as an agricultural soil amendment.
It requires that biomass must comes only from waste sources of that specific country.
The feedstock accepted are:

- Agricultural waste biomass: harvest residue, fruit and vegetables residues, vine pruning, straw, husk, pomace, kernels and leaves.
- Food processing residues: material from washing, cleaning, peeling, centrifugation and separation process, expired food residue and residues from processing in the food industry.
- Forestry and other wood processing: sawdust, off-cuts, forest management residues and by-product, thinning generated from forest wildfire fuel reduction activities or area designated by state, provincial, or federal authorities as overstock, bund woody biomass and disease trees felled during plantation or woodland management.
- Recycling economy: urban/rural green cutting, non-hazardous municipal green waste, biosoilids from WWTP (Waste Water Treatment Plant) and paper mill sludge.

- Aquaculture plants: seaweed, algae waste products, aquatic invasive species.
- Animal manure: waste from swine, cattle, horse and poultry farms.
- High-carbon fly ash from biomass: by product of cogeneration facilities.

The supply chain allows a maximum transport distance of 200 km for all modes. For distances over 200 km, only road transport is permitted.
Biochar must be used in the first year after its production to generate a carbon reduction and also requires a minimum of 50% carbon retention in the biochar over period of 20 years.
It can be applied on the top soil or in the subsoil but in both cases it must follow the qualitative standard to avoid pollution (e.g. heavy metals, PAHs, Furans).
The ratio H:C_{org} must be equal or lower than 0,7.
It is open to a variety of biochar production and use projects such as bricks, asphalt, concrete in which it is guarantee a long term stock carbon storage through laboratory analysis, research and articles.
VERRA Biochar Certification requires stakeholder consultation as part of the project development process.

6.5.2 Gold Standard

Gold Standard is another non-profit company founded under a WWF initiative that certificate biochar project for carbon sequestration.
It is generally compared to Verra because it works in a very similar way.
Some characteristic features are:

- Gold standard strongly focuses on projects' impacts on co-benefits: social and environmental factors, including biodiversity, ecosystem services, and local community engagement. More than that, they require a identification and quantification of those.
- They shrink the types of project accepted to the one that are testable and recordable in renewable energy sector and energy efficiency sector.
- One of the requirements needed is the minimum of 30% carbon retention in biochar over a period of 20 years.
- To assess the carbon credits value they consider also the co-benefits that the biochar application can give to farmers, such as improved soil fertility and reduced emissions from other sources.
- Gold standard wrote down regulations based on the Sustainable Development Goals (SDGs).
- For what concern the conditionality of the projects, they consider also the co-benefit, as improved soil health, reduced air and water pollution, and increased biodiversity.

- They accept only project that plays a significant role in the agricultural and agro-forestry sector, but always looking at the carbon sequestration capacity.

- As for Verra, participation of stakeholder is mandatory, but here the engagement is different and they require more extensive and participatory process.

6.5.3 Puro.earth

Puro.earth certification added biochar to its projects portfolio only in 2019.
To be part of their projects, it must ensure permanent carbon sequestration, so they require that:

- Biochar must be used in applications that preserve its carbon storage properties, such as greenhouse substrates, animal feed additives or insulation materials.

- Biochar must be produced from sustainable biomass or biomass waste sources, similar as the one considered by others.

- The producer must demonstrate net negativity through a LCA (Life Cycle Assessment) or carbon footprint analysis that covers the production, biomass supply, and use of biochar.

- In the production of biochar, the use of fossil fuels (e.g., coal, oil and natural gas) for ignition, preheating, or heating of the pyrolysis reactor is allowed. However, co-combustion of fossil fuels and biomass in the same reaction chamber is not permitted, as fossil carbon may contaminate the biochar product.

- In biochar production processes, pyrolysis gases must be either combusted or recovered through engineered systems that eliminate or significantly reduce methane emissions to the atmosphere.
  Bio-oil and pyrolysis gases may be stored for future use as renewable energy or raw materials.

- The resulting biochar must have a H/C_{org} of 0,2 with a stability over 100 years.

- The produced biochar must meet all applicable quality standards in the jurisdiction where it is used, including legal thresholds for heavy metals, PAHs, and other organic contaminants.

- Measures must be implemented to ensure a safe working environment, clean production, and safe transport of biochar.

- Every year must prepare a report based on data acquire thanks to continuously monitoring activity that confirm the project correctness.

7 Biochar market analysis

Biochar production and market are continuously growing and in some parts of the world, it is becoming a real business opportunity.
The reason behind the growth of the biochar market lies in the double positive impact it intrinsically offers to those who choose to use it:

- From a material point of view, it represents a great opportunity to improve agricultural practices, livestock management, and many other possible applications as seen in the introduction.

- From a financial perspective, applying biochar in soil generates credits and significantly reduces user's costs.

Moreover, during the production process, it is also possible to obtain what is known as wood or vegetal distillate, scientifically called pyroligneous acid or pyroligneous liquor. This plant extract is classified as a corroborant for agricultural use.
It represents a real market opportunity because its production can be easily carried out using already used waste agricultural biomass feedstock and technology employed for biochar: it just needs some easy upgrading phases. It also constitutes a valuable achievement from a circular economy perspective.

7.1 Biochar market analysis

To explain biochar market the sources of information used are the EBI market report, the IBI global market report, CDR.fyi review, SIAN data and multiple interviews with leading experts in the field, to gain expert know-how. Following data and analysis refers to market report of year 2023 and 2024.
Starting the analysis from Europe context can be easily understand how important is becoming this market: in 2023, 41 new production plants were installed, with 5 additional projects initially planned for 2023 but postponed to 2024. In 2022 the number of new installed plant was 28, in 2021 25 and in 2020 only 16.
For 2024 the data are not yet confirmed by the EBI, but from the first estimation it rises to 54 new plants.

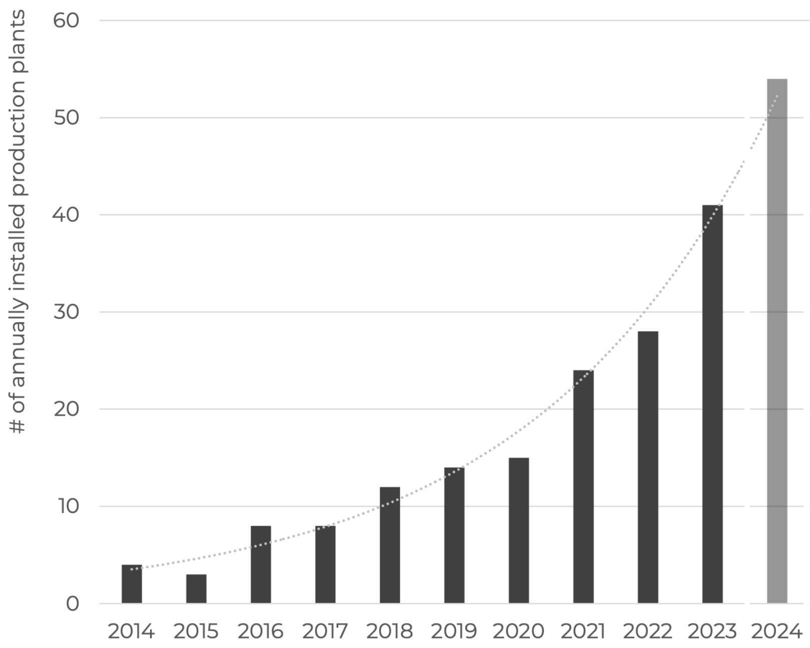

Figure 11: Number of annually new installed production plants in EU. Image extracted from European Biochar Market Report 2023

The number of cumulative production plants is growing exponentially as the number of new platns: in 2021 the total number of plants was 103, that rise to 132 in 2022 and 171 in 2023. Considering plants that will shut down and new projects, the expected number of total installation in 2024 in Europe should be 220.
For 2025 the projects that are in advanced planning and/or in the permitting process are more than 40 and all of that with a overall production capacity over 35000 tons/year.

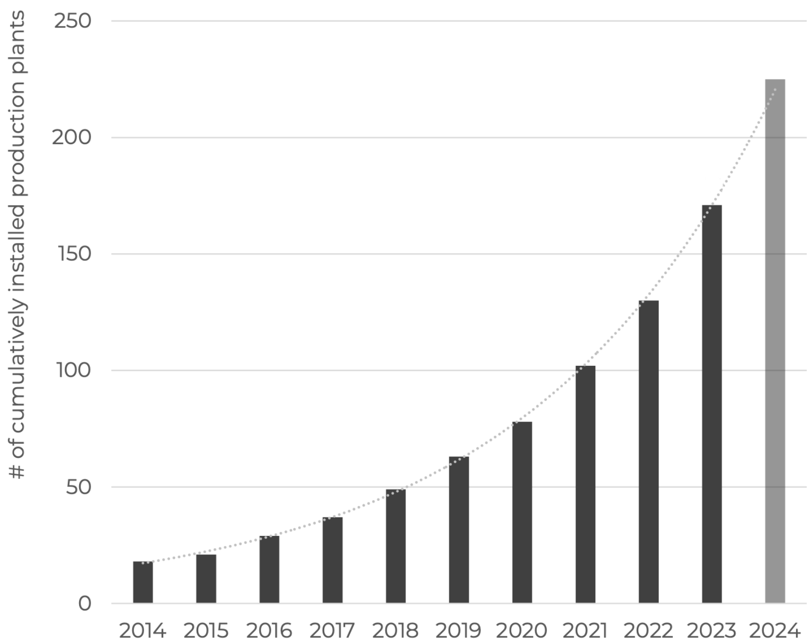

Figure 12: Number of cumulative plants working in EU. Image extracted from European Biochar Market Report 2023

Moving to the production capacity, the trend is really clear: the new plants are always bigger and bigger.
The European production capacity move from 37000 t/y in 2021, to 54000 t/y in 2022 and reaching 75000 t/y in 2023. The data for 2024 estimate 115000 t/y.
Analyzing these data:

- The production capacity from 2022 to 2023 grew of 41%.
- The 3 year CAGR (Compound Annual Growth Rate) in the period 2020-2023 was 54%. CAGR, as reported by "investopedia.com", is defined as: "the compound annual growth rate is the rate of return that an investment would need to have every year in order to grow from its beginning balance to its ending balance, over a given time interval. The CAGR assumes that any profits were reinvested at the end of each period of the investment's life span."
  It is evaluated using:

$$\text{CAGR} = \left(\frac{V_f}{V_i}\right)^{\frac{1}{n}} - 1 \tag{1}$$

  Where:

  - V_f = Final value
  - V_i = Initial value
  - n = Numbers of year

- Based on project pipeline and all the data, for 2025 growth rate is expected to be at 55%.

Unfortunately, the biochar production capacity does not match the real one, so for estimate it, EBI assume that:

- 6 months operation and 60% up-time in the commissioning year.
- 12 months operation and 80% up-time in following years.

With these assumption, the 2023 biochar production reduce decrease from 75000 t/y to 49000 t/y while for 2024 the expected one is higher than 70000. Moving to the production facilities, almost 80% of the production capacity of 2023 is in the equipment categories medium, large and very large and the remaining part is subdivided for small and industrial size equipment.

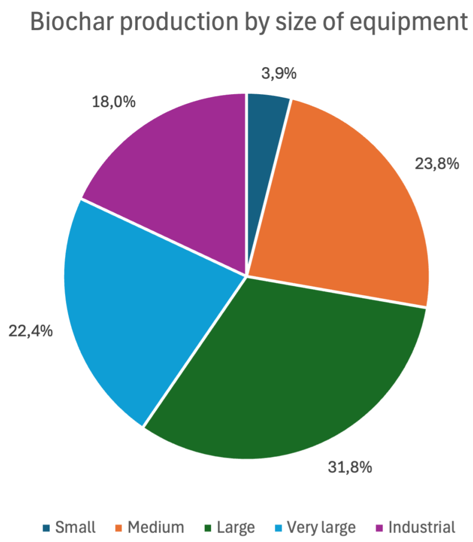

Figure 13: Equipment subdivision by size for EU biochar producers. Data extracted from European Biochar Market Report 2023

Equipment Category	**Capacity (t)**
Small	100 – 199
Medium	200 – 499
Large	500 – 1,999
Very large	2000 – 4999
Industrial	$\geq$ 5000

Table 9: Equipment categories defined by capacity. Data extracted from European Biochar Market Report 2023

In Europe the production distribution is not homogeneous, but it is much higher in Nordic countries and Germany, followed by Switzerland and Austria lumped together.
The Nordic region has become the most significant in terms of activity, particularly in Sweden, Denmark, and Finland, which lead in developments. In these counties there are the first cases of municipal incinerator there were substitute with pyrolyzers or gassificators producing biochar and leading cities to net zero emissions.

At the same time, the contribution from "other countries" is gradually rising, especially with growing activity observed in Spain, France and United Kingdom.

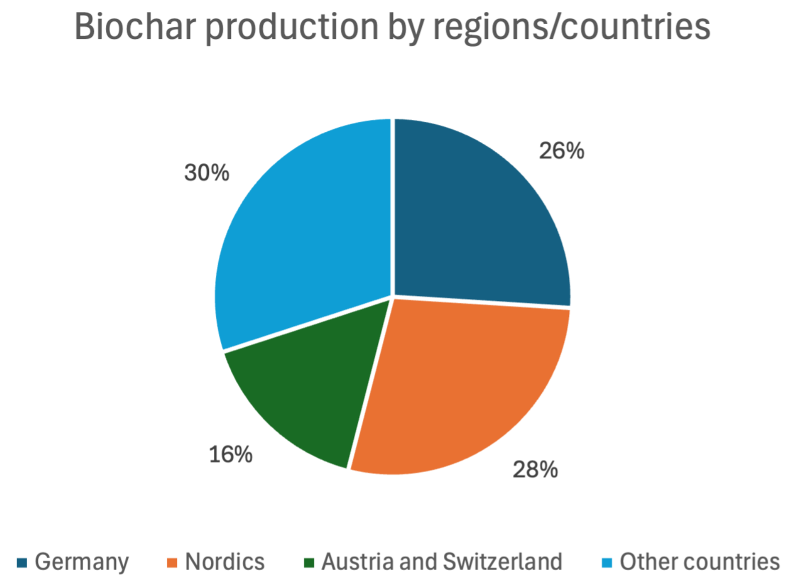

Figure 14: Cumulative biochar production capacity in EU divided by regions/countries. Data extracted from European Biochar Market Report 2023

Looking now at the world production, North america is the leading country, but Asia is growing much faster than all the others.
Some common global trends in the sector include:

- A continuous influx of new industrial players entering the market, highlighting the growing interest and perceived potential of the sector.
- The widespread use of in-forest and agricultural residues as primary feedstock, due to their availability and cost-effectiveness in a circular economy perspective.
- The economic necessity of valorizing surplus energy (heat) generated during production processes that can be used for drying biomass or to supply heat to the chamber.

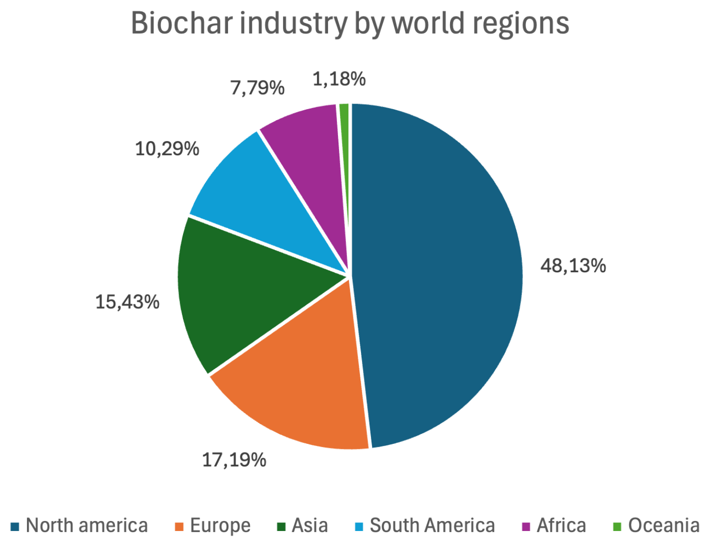

Figure 15: Cumulative biochar production subdivide by world regions. Data extracted from European Biochar Market Report 2023

Th biochar production is growing a lot and it is pushed by the financial leverage that carbon credits gives to them.
However, also for credits, biochar must be used some where.
The figures 16 and 17 on the following page represent the end use market share considering all the world production.
The end use market is the final market for a product or service, where the individual or organization that consumes or uses the product/service makes the purchase.

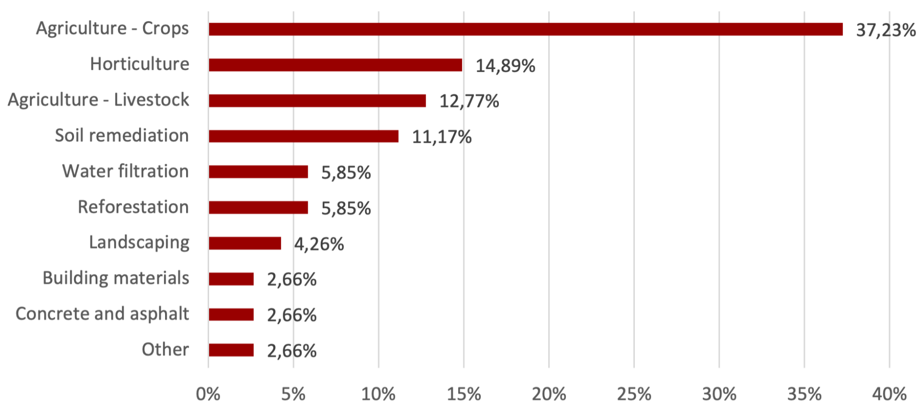

Figure 16: General biochar world end use market. Data extracted from Global Biochar Market Report 2024 by IBI

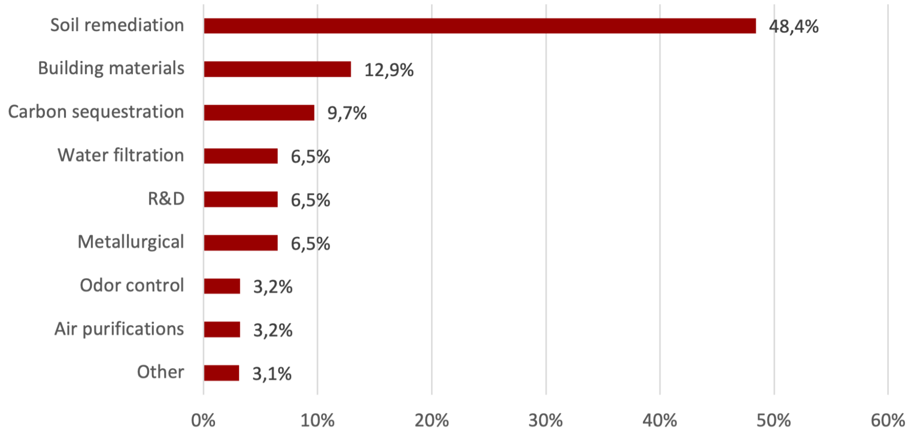

Figure 17: Non agricultural biochar world end use market. Data extracted from Global Biochar Market Report 2024 by IBI

As expected, the agricultural sector is the biggest, sharing the 64,89% of the market (considering "crops", "horticulture management" and "livestock"): one big reason behind that is due to the fact that these sectors are the only ones regulated by laws. At the moment, for all the other sectors there is not a specific regulations.
For what concerning the non-agricultural end use market, the most interesting sector that will show a great expansions in future will be:

- Application in concrete.
- Urban soil application.
- Substitute fossil carbon in metallurgy (not Carbon Removal).

The first two applications are particularly interesting because they enable the production of biochar that, can be effectively applied to reduce the emissions associated with the construction sector, that at the moment are, from an environmental point of view, a huge problem.
Analyzing the IBI global market report is possible to extract data in order to evaluate global biochar market prices:

- Range prices: from 209 to 970 €/m^3.
- Average price: 464 €/m^3.
- Median price: 473 €/m^3.
- Market trend: 33% of producer sold in the range of 451 – 500 €/m^3 followed by 16% in the range of 301 - 350 €/m^3.

7.2 Voluntary carbon credits biochar market analysis

As anticipated, biochar credit market currently works on a voluntary basis, as it has not yet been integrated into mandatory carbon credit systems, like those governing reforestation.
In 10 years, from 2013 to 2023 EU ETS, that is a regulated carbon credits

market, generates profit for more than 152 billions of euros, while voluntary markets, in same period, generate 2 billions of euros.
According to Global Market Insight (GMI), "the entire market was valued at 87,9 billion of dollars in 2022 and is expected to grow at a CAGR of 14.2% during the period from 2023 to 2032".
From these data, it is clear that the dimension of the regulated market is much bigger and this is strictly linked to the intrinsic obligation nature of the market.
However, in 2022, the global Carbon Dioxide Removal (CDR) portfolio expanded the projects accepted and include a broader range of approaches. Among the most prominent methods were biochar, which accounted now account for 40% of the market, followed by concrete mineralization at 27%, and direct air capture at 20%.

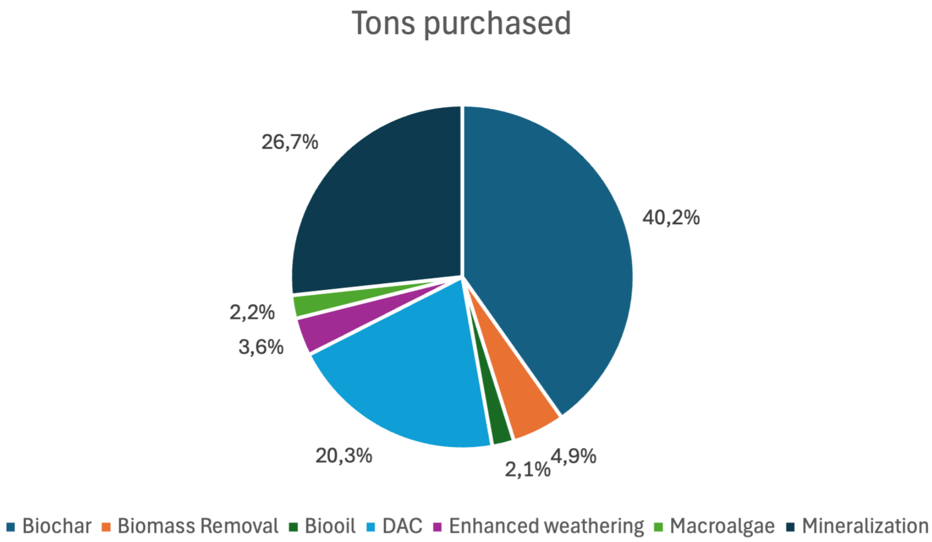

Figure 18: Tons CO_2 voluntary emission certificates purchased in 2022. Data processed from CDR.fyi 2022 review

The number of companies engaging with high-permanence CDR is growing steadily. In 2023, 115 companies are known to have made purchases in this field. The yearly breakdown shows a clear upward trend: 9 companies made purchases in 2020, increasing to 48 in 2021, and reaching 86 in 2022.
Analyzing global market production, the 350000 metric tonnes of biochar produced in 2023 shows a great increasing from the 2021 production, with 91% CAGR. This lead to an increasing in revenues, as seen in table 10 on the next page, with a CAGR of 97% between 2021 and 2023.
Data expert said that the revenues projected for 2025 should arrive to 3,3 billion of dollars.

Industry Members	2021	2023
Biochar Producers	$54,750,000	$330,130,000
Distributors and Value-Add Producers	$7,250,000	$38,880,000
Equipment Manufacturers	$94,380,000	$241,250,000
Total Revenue	**$156,380,000**	**$610,260,000**

Table 10: Global revenue generated by the biochar industry. Data are based on self-reported revenue categories for key industry categories.

Based on the complete datasets provided by IBI and EBC, the following information were extracted to highlights the key characteristics of biochar voluntary carbon credit prices in Europe:

- Price range for biochar carbon credits: 150 € - 550 € per ton/CO_{2eq}.
- Average price: 288 € per ton/CO_{2eq}.
- Median price: 220 € per ton/CO_{2eq}.
- Market trend: 72% of carbon credits are sold within the 150 - 270 € per ton/CO_{2eq}.

Despite this growth, only 23 companies have bought more than 1,000 tonnes in total.
However, even this figure is improving: in 2022, 16 companies announced purchases exceeding 1000 tonnes, up from 11 in the previous year.
A big achievement that biochar reached is that in the pool of company that are purchasing the biochar credits, there are a lot of big industry leader that are reference in their sector, as can be state in the figure 20 on the following page

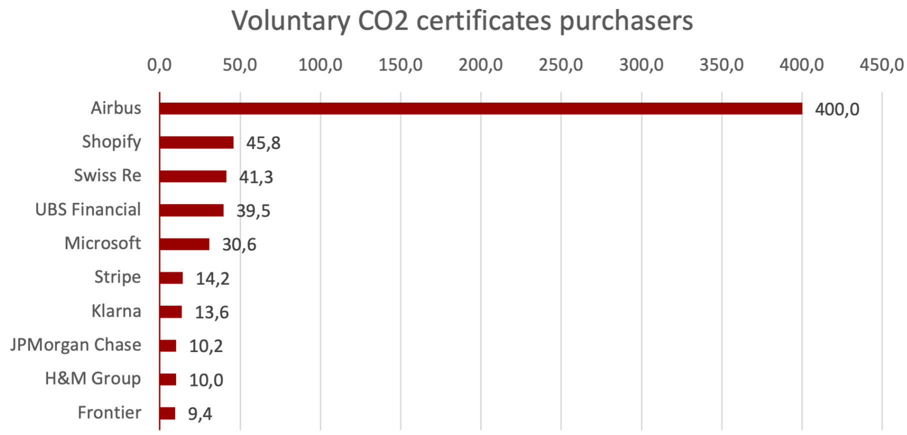

Figure 19: Most relevant company that acquire biochar credit. Data processed from CDR.fyi 2022 review

The big issues in the market is that 55,24% of producer does not receive financial credit revenue from selling biochar.

This is an incredible fact that is explainable only understanding the complexity of this market. Indeed, producer state that the reasons because they do not earn from voluntary market are the ambiguity in regulations, cost and complexity related to certifications process and no clear information availability for farmers.

Percent Revenue from BCR credits	**Total Global Production (mt/year)**	**Percent Global Production**
None	178036	55,24%
<10%	15236	4,73%
11%–20%	14455	4,48%
21%–30%	13544	4,20%
31%–40%	18985	5,89%
41%–50%	22484	6,89%
51%–60%	2735	0,85%
61%–70%	9000	2,79%
71%–80%	200	0,06%
81%–90%	500	0,16%
91%–100%	47134	14,62%

Table 11: Percent of total biochar producer revenue generated from biochar carbon removal credits in 2023. Data extracted from Global Biochar Market Report 2024 by IBI

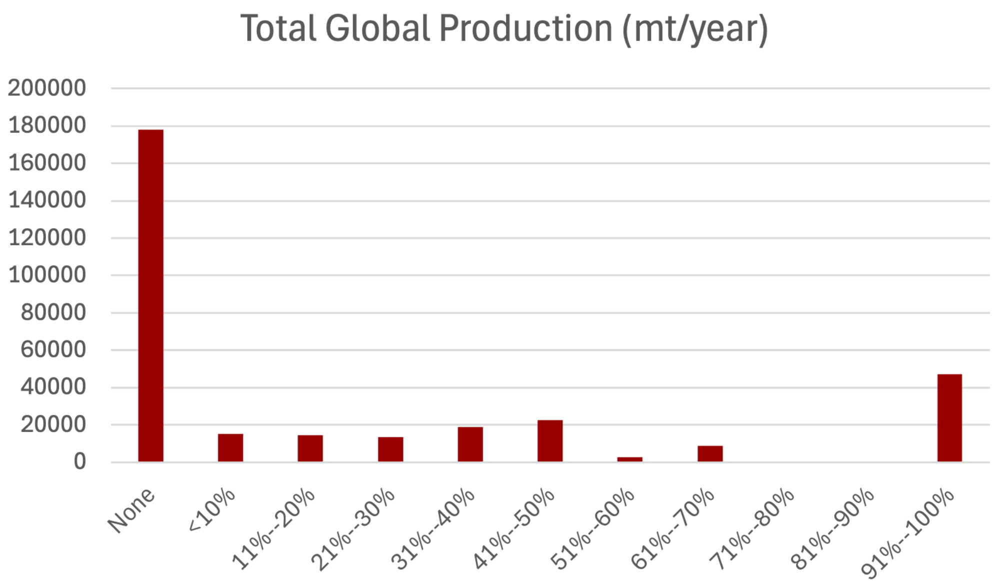

Figure 20: Percent of total biochar producer revenue generated from biochar carbon removal credits in 2023. Data extracted from Global Biochar Market Report 2024 by IBI

Analyzing the world context, only producers in South America and Africa understood the economic and environmental benefits: they have high BCR credit market participation, that, as reported in the Global biochar market

report 2023 "generate more than 90% of their total revenue from carbon credits sales".
In these regions, the combination of lower labor expenses and BCR credit prices that remain stable regardless of location seems to be the key for the development of the voluntary biochar market.
Other regions of the world have not demonstrated similar progress in the voluntary biochar credit market.
In Italy, no entities are issuing carbon credits for biochar production, reflecting both the lack of information and limited adoption in national offset initiatives.

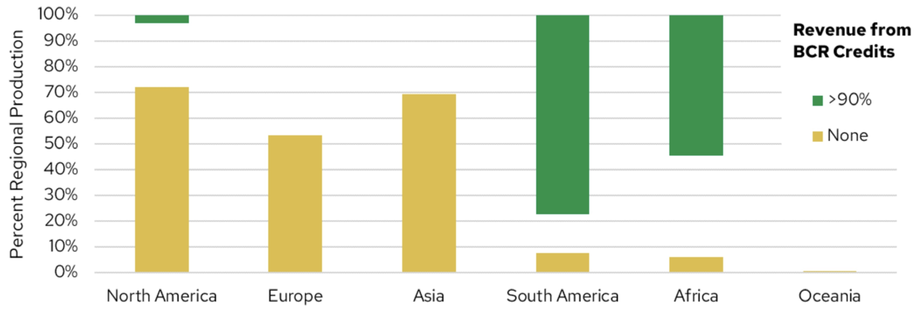

Figure 21: Total regional biochar production associated with BCR credit revenue buckets among biochar producers in 2023. Data extracted from Global Biochar Market Report 2024 by IBI

7.3 Wood distillate market opportunity

7.3.1 Wood distillate: what is it and how it is produced

Wood or vegetable distillate is a plant extract legally classified as a corroborant for agricultural. As defined by Emilia Romagna phytosanitary service "Agricultural corroborant are substances of natural origin that can enhance plant resistance against harmful organisms and protect plants from non-parasitic damage. Corroborant differ from plant protection products in that they act only by strengthening the plant's vigor, without exerting direct effects against pathogens or pests. They also differ from fertilizers because they do not primarily serve a nutritional purpose." In Italy, these substances have been regulated by Presidential Decree No. 55 of February 28, 2012, "Regulation amending Presidential Decree No. 290 of April 23, 2001.
Wood distillate obtained during biochar production is mainly composed by Acetic acid, polyphenols, and tannins, in addition to a variety of minerals and compounds, for a total of over 200 components.
The distillate is obtained through the direct condensation of smoke, where the oily part and vegetable tar are separated. This occurs during the pyrolysis, or gasification, of rich value waste biomass in a low-oxygen environment.
It means that for biochar producers it is very easy to implement a wood distillate production: they just need to add in the supply chain a system to extract and collect condensable molecules and generates a new revenues.
The technology employs counter-current steam distillation, relying solely on the water present in the wood's sap, without using chemical solvents.

New studies are showing powerful results of wood distillate application in other sectors such as Natural Mold & Fungus Prevention and in Cosmetics. Wood distillate process production can be implemented in the early stages of pyrolysis or gasification process:

- Extraction Method: obtained through counter-current steam, using only the physiological water contained in the wood sap.
- Temperature Gradients: extracted at different temperature gradients, with an exit temperature of up to 80°C from the reactor.
- Filtration: the wood extract is sent to a natural filter to remove any residues.
- Decantation: left to decant for at least three months to obtain an amber-colored wood distillate.
- Characteristics: consistent characteristics, organic, natural, and safe for the environment and humans.
- Properties: effective resistance inducer, no residues, and contributes to the sequestration of 1.5 kg CO_2/l of WD.

7.3.2 Wood distillate market analysis

Also if it contribute to reduce CO_{2eq}, it is not consider in the carbon credits market, so its value lies solely in the intrinsic benefits it provides to the agricultural and horticultural sectors.
Wood distillate European market is one of the smallest globally, yet it's expected to grow at a CAGR of 6,4% (2023-2030).
Slow pyrolysis production method dominated the market with 68,4% of revenue share in 2023. This process results mainly in a higher yield of wood vinegar with a higher concentration of acetic acid.
Agriculture accounted for the largest market revenue share of 42,8%, while food, medicinal and consumer products are projected to grow at the fastest CAGR of 6,0%
In Italy, wood vinegar is gaining popularity in organic agriculture, but not only, as a natural bio-stimulant, soil conditioner and plant protection product, with prices ranging from 8–20 €/l or 5-10 €/hectare depending on purity and volume bought.

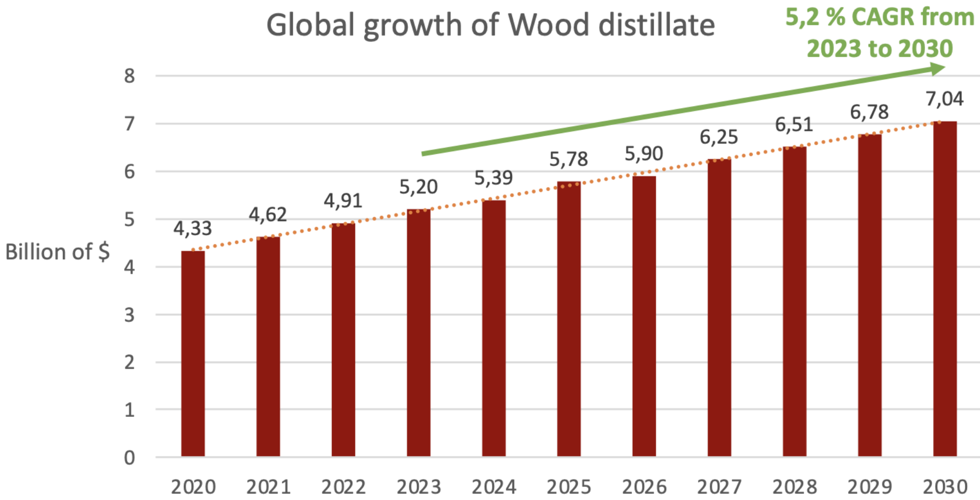

Figure 22: Wood distillate market analysis. Data extracted by Wood Vinegar Market Size (2024 – 2030).

The market is really strong also in the B2C sector, with an average product price in Italy of 17,31 €/l, offering a valid alternative to chemical corroborant without negatively impacting prices. The main drivers of its appeal for consumer is the absence of chemicals, making the product particularly attractive to consumers.
For Italian biochar producer, operating within a small niche market, it represent a crucial opportunity to increase biochar revenue, which are otherwise relatively low.

Figure 23: Italian wood distillate B2C prices analysis. Data extracted from personal interview (2025)

8 Advantages related to agricultural biochar application

Properly applying biochar to soil is a challenging task due to the complexity of the system: plants, soil, environment, agricultural practices and their interactions all work together through multiple interconnected mechanisms. It means that evaluating how biochar affects soil properties and crop growth depends on many factors. More than that must take into considerations all the different biochar characteristics that are strongly affected by initial feedstock and operational parameters.
In general biochar is considered as responsible for increasing crop yield, but this is due to the multiple benefits that brings to the soil-root-plant system. Indeed it can sustain: root and leaf growth enhancing photosynthesis, abundance of growth-promoting microorganisms that live in the root-zone and inside the plants, resistance to disease and food quality.
For roots, biochar impact on root biomass especially for volume, surface area, length, number of root tips, number of nodules (for legumes), root phosphorus concentration and fungal root colonization. In particular, some other considerations related root biochar interactions are:

- Root biomass and root length increase much more in annuals species than in perennials.
- Biochar shows better effects for biomass root increases in sandy soil followed by clay and then loam especially soils with pH higher than 7, due to the alkalinity nature of biochar that could, if necessary, compensate soil's acid characteristics.
- Biochar obtained with fast pyrolysis at temperatures between 450 °C and 600 °C, produced the greatest increase in the root length due to higher content of organic compounds on the pore surface biochar.
- An important consideration is that too much biochar in the rhizosphere can reduce biomass growth, crop yield and resistant to disease and enhance environmental stresses.

On the other side, biochar can boost leaves and photosynthesis and this is confirmed by a global meta-analysis published in 2020 conducted by He et al. that state that: "biochar amendment increased photosynthetic rate, transpiration rate, and water use efficiency by around 27% each. Stomatal conductance and chlorophyll concentration improved by 20% and 16%, respectively. Plant total biomass improved 25 wt% (shoot biomass 22 wt%, root biomass 34 wt%)".
More than that, they establish that biochar boost much more C3 plants than C4 plants and in particularly biochar with higher pH and lower carbon content is the best option for C3 plants.
The difference between them is related to reactions that occurs in the second stage of photosynthesis process and so in the compounds formed: for C3 plants it is glyceraldehyde 3-phosphate, with three carbon atoms, while for C4 plants it is oxaloacetate, which has four carbon atoms. Cereal crops,

maize, sorghum, and millet are C4 plants, while wheat, barley, oats, rye, and rice are classified as C3 plants. C4 species are typically found in warm climates with sufficient water availability, whereas C3 species are more common in temperate regions. Some general features are listed in table 12.

C3 Plants	**C4 Plants**
Common in temperate climates	Common in warm climates with good water availability
Photosynthesis rate peaks around 20°C with moderate light intensity	Photosynthesis rate peaks around 40°C with high light intensity
Less efficient under high light, temperature, and low CO_2	More efficient under high light, high temperature, and low CO_2
Higher photorespiration, especially at higher temperatures	Minimal photorespiration due to CO_2 concentration mechanism
Lower water-use efficiency	Higher water-use efficiency
Lower nitrogen-use efficiency	Can produce almost twice the dry matter per unit of leaf nitrogen

Table 12: Comparison between C3 and C4 plant characteristics

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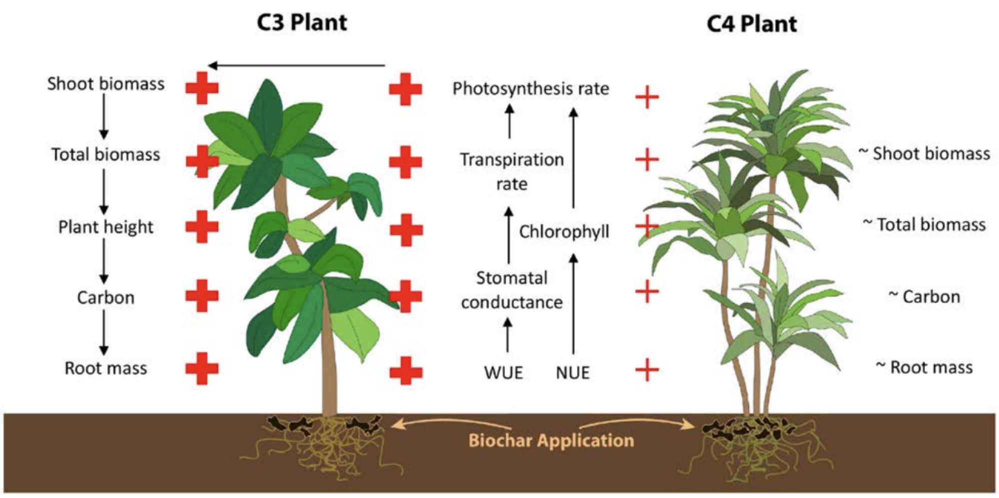

Figure 24: Effects of biochar amendment on plant photosynthesis rate, and thence on biomass and other properties, varied with C3 and C4 plants. The boldness of the red pluses indicates that the positive responses were greater for C3 plants than for C4. Image extracted from Farmers guide by Stephen Joseph et al. (2024)

Biochar can also enhance plant resistance against disease, insects, pathogenic bacteria and fungi attacks. It is due to soil modification promoted by biochar, as

- pH balancing, increase nutrient supply and availability, reduces pathogenic microorganisms, and increase beneficial microorganisms.
- Some compounds formed by organic molecules present in biochar have antimicrobial properties.

- Dissolution of silicon from biochar into the root-zone led to leaves and stalks tougher and more resistant.

- As said, biochar act as a sponge, so it can absorb also specific compounds from pathogens, reducing their activity. For the same reason, it can also act as antioxidant, reducing reactive oxygen species and so does stress from pathogens.

- Biochar act also as a store of electrons, that can help plants in fighting pathogens increasing CEC.

8.1 Biochar - soil interactions through time

When biochar is buried in soil, it undergoes a dynamic process in which the characteristics changes due to reciprocal interactions.

- In the first 4 weeks all the compounds present in biochar dissolves and leaves the carbon matrix formed by fixed carbon, which one remains more or less stable for centuries. This phenomenon happen thanks to water that infiltrate and promote dissolution. If soil is acid, nutrients release can be rapid. Those nutrients can contribute to seed germination and help fighting pathogens.

- By weeks 12 and 24, biochar surface become totally coated by soil organic matter and so fungi and micro-organism start to sneak up in pores carrying also nutrients. In the external surface, indeed, start to attach micro-agglomerates that increase CEC and water holding capacity.
  More than that, in this phase, also nutrients can be catch and stuck by the biochar matrix. This will guarantee a slow release when plant will ask for them.

- After 24 weeks, organo-mineral plaque layers form in the pores and lead to root hair infiltration. Micro-agglomerates grows and forms macro-agglomerates that can break off biochar. Now there is a proximate root contact with nutrients, that can be extracted when plants need them.
  The organic compound molecules from dead microorganisms and plant exudates can adhere to the surface of aged biochar. This interaction helps physically protect carbon biochar, leading to greater long-term storage in the soil and thereby enhancing biochar's effectiveness in carbon sequestration.

Obviously, time periods for the three stages are approximate because they depend on rain/irrigation, temperature, soil type, soil disturbance and agronomic practices.

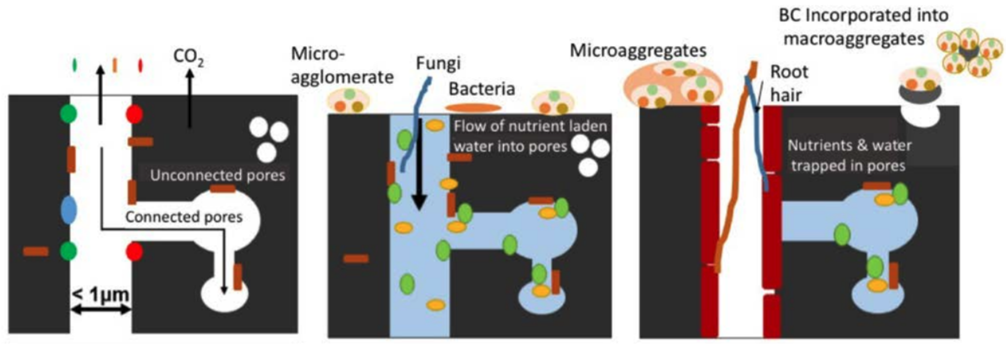

Figure 25: Schematic illustration of the ageing process on the surfaces and in shallow and deep pores in biochar (BC) added to soil. Image extracted from Farmers guide by Stephen Joseph et al. (2024)

Over time, biochar particles are fractionated by microorganism, soil fauna, cultivation practices and exposure to wet–dry and freeze–thaw cycle. This phenomena limits the interaction with fresh biomass and so it reduce agronomic benefits. In multiple years particle dimensions shrink and so they become more mobile in the soil.
Unless intercepted and retained by plant roots, biochar tends to migrate deeper into the soil, making it less available to plants. While this is often considered an agricultural loss for farmers, from a broader perspective it represents a long-term carbon stock in the soil.

8.2 Biochar and nutrient cycles

The effects on physical and chemical properties of soils depend on feedstock characteristics, pyrolysis temperatures and application rates.
It is important to consider that biochar also influences soil nutrients, particularly the nitrogen and phosphorus cycles, which can be altered by its presence. If properly managed, biochar can have a positive impact on nutrient cycling.

8.2.1 Biochar boost nitrogen cycle

To correctly assess the interaction between biochar and nitrogen cycle, it is mandatory to primarily analyze biochar nitrogen content to optimize application rate, also in relation with standard fertilization practices and limits.
The only counter effect is shown if nitrogen content is low, as generally the one obtained from woody biomass, and if it supply at low rate content (e.g. 5 t/ha), because biochar can reduce the immediate nitrogen content availability for plant absorbing the already present in soil. When biochar is produced at lower temperatures, it typically contains a lower carbon content but a higher concentration of secondary compounds, such as nutrients. In particular, biochars derived from manures (e.g., poultry litter) at low temperatures tend to have a high nitrogen content. When applied at high rates (e.g. higher than 20 t/ha), these types of biochar do not compete for nitrogen acquisition, reducing soil-root system nitrogen availability. This

allows plants to access nutrients, including nitrogen, right from the start. Furthermore, the total nitrogen concentration in the soil-biochar mix is increased.
One of the main advantages of biochar in relation to nitrogen cycle efficiency is its ability to reduce leaching losses, which indirectly enhances nitrogen availability.
Aged biochar (that has a fine surface layer of organic matter) can adsorb the N from fertilizers, reducing leaching losses by 26% on average.
Rasse et al. (2022) research, moreover, indicates that "biochar produced above 400°C reduces nitrous oxide emissions from dry-land soil, especially at high application rates (>10 t/ha)".
However, at higher application rates led to lower losses, but at higher application rate (> 40 t/ha) and with pH > 9, ammonia volatilization increases. For this reason, some pre or post treatment can be performed before field application.
Going deeply into nitrogen cycle dynamics, biochar can enhance the abundance of nitrogen fixing bacteria or increase root nodules (symbiotic nitrogen fixing). This process, as reported by Ahmad Z, et al. (2021), "can increase the nitrogen fixation by up to 60%, and by an average of 35% across all biochar".
More than that, biochar can also reduce green gas houses emissions thanks to the adsorption ability, but is not an easy task to associate the effectiveness of this process because it is strongly related to soil environment and so it depend by many environmental factors and by decomposition of biochar in soil.
In 26 on the following page is represented how the operational process parameters affect the Nitrogen use efficiency (NUE). NUE is defined as "the ratio of N uptake by plants to the total applied N fertilizer, and it is dependent not only upon the N supply potential of soil but also on the subsequent transport, mobilization, and storage of N by plants" (Ahmad et al.).
Particularly, figure 26 on the next page wants to show how great the operational parameters can affect the NUE, modifying values from + 40 % to - 35% and highlighting the importance of correct biochar selection.

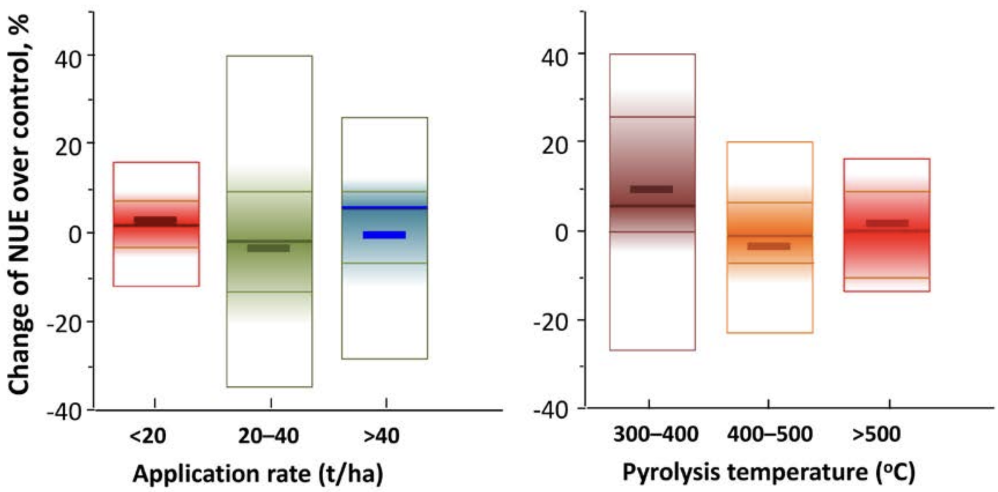

Figure 26: The range of nitrogen use efficiency (NUE) found in 22 studies, expressed as percentages of that of the control, for three application rate ranges and three pyrolysis temperature ranges. For each category the outer box covers the entire range of reported changes, while the inner shaded box captures the inner 50% of the values. The solid line represents the median and the short, thick bar is the overall average. Image extracted from Farmers guide by Stephen Joseph et al. (2024)

8.2.2 Biochar boost phosphorus cycle

Glaser et al. (2019) found thanks to meta-analysis works, that biochar is responsible of phosphorus availability increasing in agricultural soil by a factor from 3,4 to 5,9.
Higher effects are shown in low P soils, where arbuscular mycorrhizal fungi (AMF) invades biochar's pore increasing P uptake by plants.
Better results are showed for biochar obtained from manures and wastewater sludge or crop residues with an application rate above 40 t/ha. If biochar is produced at temperature lower than 450 °C and applied in acid soils the phosphorus cycle is much more boosted than in the case biochar is obtained with temperature above 450 °C and/or applied in soils with a pH in range of 6,5-7,5.
In figure 27 on the following page are represented how biochar and phosphorus effect on soil depending on biochar operational parameters.

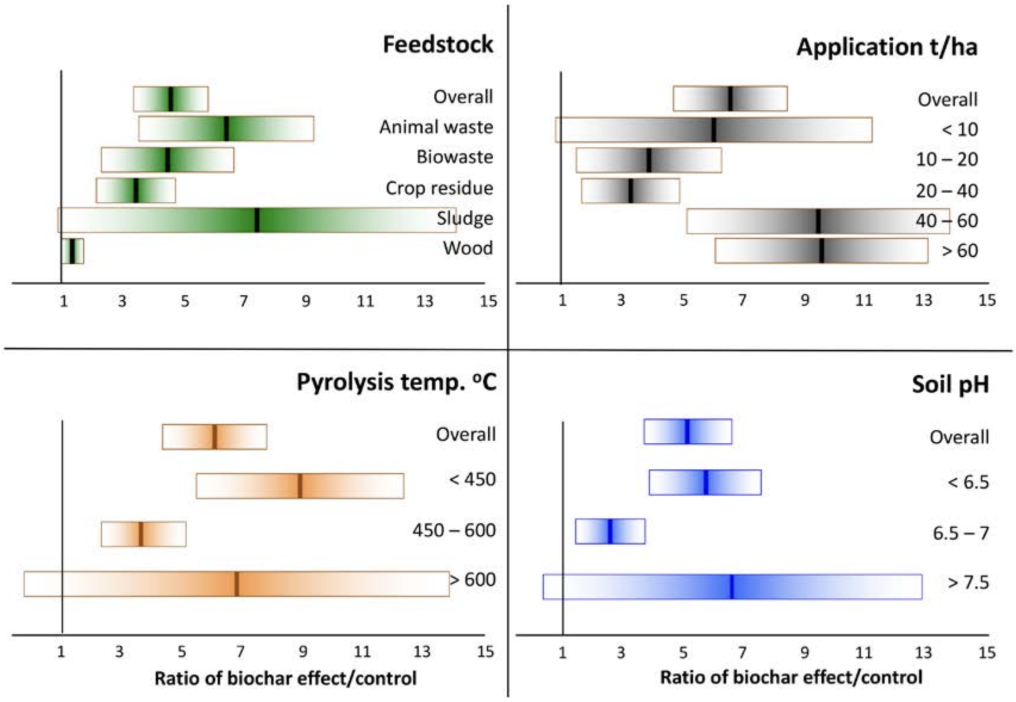

Figure 27: The effect of biochar amendments on phosphorus availability in agricultural soils as influenced by feedstocks, application rates, pyrolysis temperatures, and soil pH. The average for each category is indicated by a dark line in a shaded box that represents the 95% confidence range. Image extracted from Farmers guide by Stephen Joseph et al. (2024)

8.3 Biochar effects on hydrological properties

First of all, hydrological properties are affected by different soil characteristics such as particle size, structure, presence of multiple layers, salinity, pH, porosity, permeability and organic matter content.
From a physical point of view, the hydrological properties of soils are well generally taken into account by following physical parameters that resume the properties listed before:

- Water-holding capacity or Field capacity (FC) is the maximum amount of water the soil can hold, measured after excess water has drained.
- Wilting Point (WP) is the amount of water left after then plant can no longer extract water from the soil.
- Available Water Capacity (AWC) = FC – WP. Sandy soils can hold least water since they drain well. Clay, with its fine pores, can hold most water.
- Saturation water (SAT): Saturation water content is the maximum volumetric water content a soil can hold when all the pore spaces are completely filled with water and so, no air contained inside.
- Saturated hydraulic conductivity K_{sat}: it measure the ability of soil in saturated condition to transmit water through soil pores.

These parameters are used to assess the overall soil water retention. In practice, soil is considered to have high water retention if it is characterized by:

- High Porosity.
- High surface area.
- Low particle size.
- High carbon content.

Analyzing meta-analysis conducted by Edeh et al. (2020) and the one of Wu et al. (2022), they worked on the impacts of hydraulic properties in relation to application rate, soil type and texture, looking at changes in physical parameters as particle size, specific surface area and porosity. In general, with an application rate over 30 t/ha, all the physical parameters exposed before increase, except for bulk density that decease and K_{sat} that can reduce or increase depending on soil type and biochar size.
Going deeply on K_{sat} changes, as known, sandy soils can hold less water since they drain well due to higher particle size and coarse structure, while clay, with its fine pores and higher chemical bound interaction, can hold most water.
So, biochar could affect much more sandy soil than clay soil because it induce bigger changes in the texture than in clay soil, filling pores of coarse-textured soils, trapping much more water.
In general, as confirmed also by Lehmann et al. (2015), "the hydraulic conductivity of the soil may increase after the application of biochar with larger particles than the soil particles, and may decrease after application of biochar with smaller particles than the soil particles."
So, as general rule defined from a data analyses made on Lim, T.J et al.(2016) studies, in sandy soil the hydraulic conductivity decrease, in clay soil it increase and in all the other conditions in the middle is depends on biochar particle size and soil porosity.

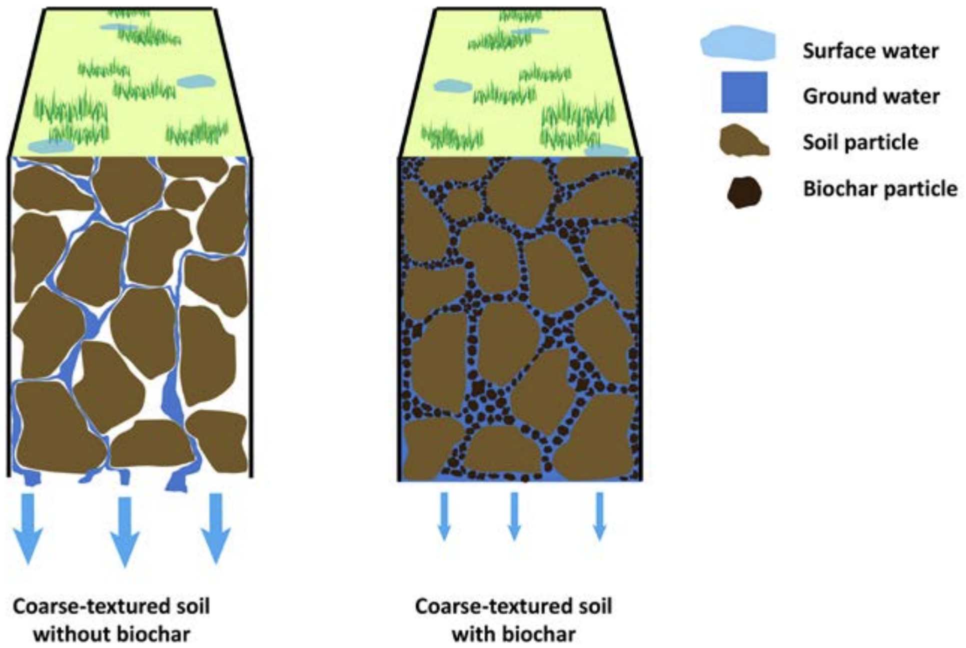

Figure 28: Schematic illustration of the effect of biochar on hydraulic conductivity of coarse-textured soil. A large addition of fine biochar can fill the pores of coarse-textured soils, trapping much more water. Image extracted from Farmers guide by Stephen Joseph et al. (2024)

Comparing results from Edeh et al. (2020) and Wu et al. (2022) for average environmental conditions and type of biochar and for supplying rate over 30 t/ha the conclusion are more or less the same (all percentage refer to volume %):

- AWC increase by 27 - 28,5%.
- Water use efficiency (WUE) increase by 4,7%.
- FC increase by 20,4%
- WP increase by 16,7%
- Total porosity (TP) increase by 7 - 9,1%
- Water content increase by 11%

For what concerning links between biochar operational parameters and soil properties changes, the focus must go on soil porosity and water content, but is not easy to extract a defined correlation between factors.
In figure 29 on the next page are represented results.

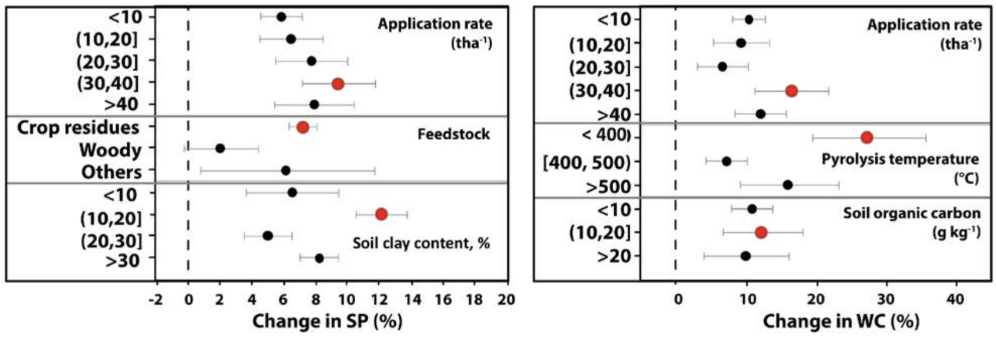

Figure 29: Changes in soil porosity (SP) (left), and soil water content (WC) (right), after biochar application. Changes are characterized by the values of the following attributes, listed on the Y axis: application rate(t/ha), feedstock, soil clay content (%), pyrolysis temperature, and SOC content. The error bars represent a 95% confidence interval. The greatest effects are shown in red. Image extracted from Farmers guide by Stephen Joseph et al. (2024)

8.4 Biochar effects on pH

The application of biochar can influence both soil pH and redox potential (Eh). In soils that are carbon-deficient, acidic and highly oxidised, biochar tends to raise the pH and reduce the Eh, helping to create conditions more favorable to nutrient availability and microbial activity. However, excessive application may push these parameters beyond optimal levels, potentially leading to adverse effects.

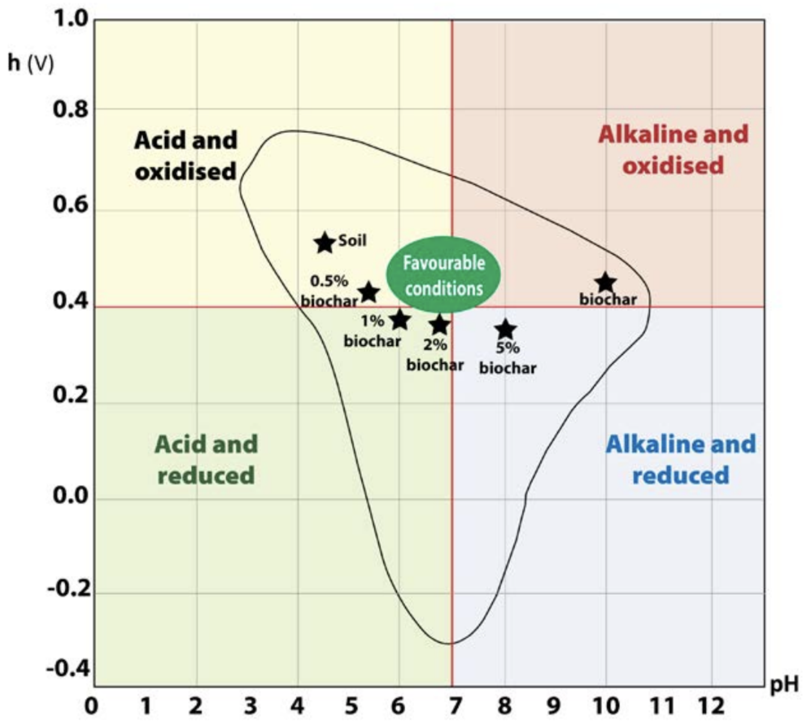

Figure 30: The full range of Eh and pH in soils and the relationship with extreme soil conditions, showing also the normal range in soils and the limited favorable conditions for plant growth. Biochar can reduce Eh and increase pH, bringing soil to more favorable conditions for plant growth. Too much biochar can result in the pH increasing above the favorable range. Image extracted from Farmers guide by Stephen Joseph et al. (2024)

8.5 Biochar effects on aggregation properties

As anticipated, biochar develops soil aggregate stability and the meta analysis conducted by Islam et al. (2021) confirm that: "comparing 119 published articles the results tells that, in average, soil aggregation can increase by 16,4%."
The relation between operating process parameters and changes in soil aggregation are reported in figure 31 on the following page.

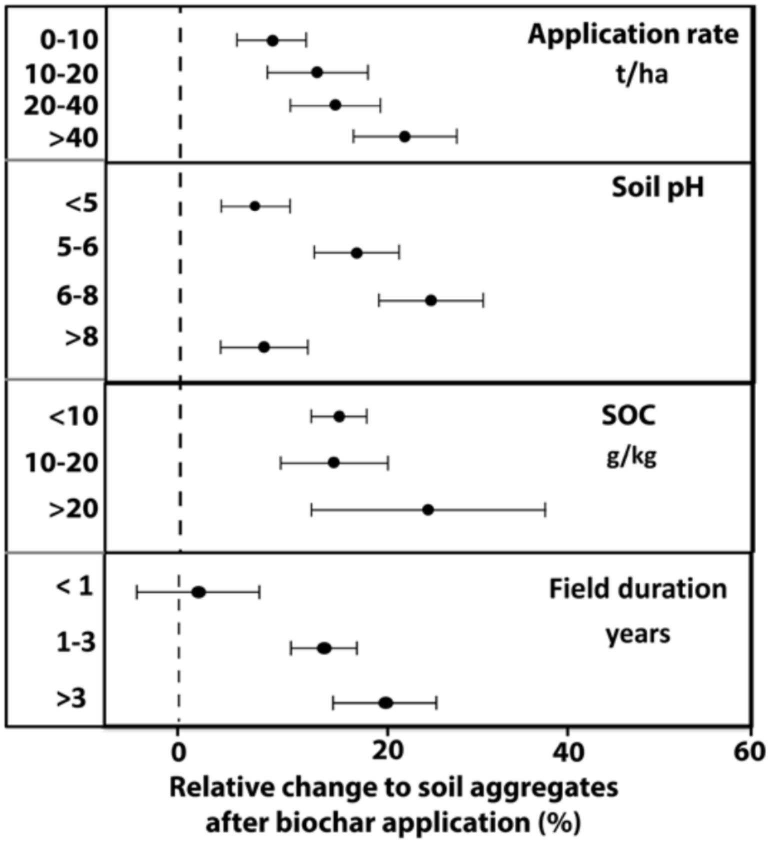

Figure 31: Changes in soil aggregation in response to biochar application rate, soil pH, soil organic carbon percentage (SOC), and field duration. Image extracted from Farmers guide by Stephen Joseph et al. (2024)

Information that can be extracted from the studies highlights that soil aggregation:

- Increase linearly with biochar application rate to beyond 40 t/ha.
- It is maximized if soil has pH in range between 6 and 8.
- Greater results are found in loam-textured soils (+20 wt%) than in sandy soils (+13 wt%).
- The effect became stronger over time: it is minimal during the first year, but increased to more than 20 wt% after three years.

In conclusion, woody biochar, produced at temperature higher than 600 °C, with pH lower than 8 are the best option to improve aggregate stability. This is because generally this type of biochar has great porous structure, presence of metals, high CEC and surface areas that can adsorb minerals and organic matter, promoting aggregation.
Also, woody feedstock produce biochar characterized by high value of C/N ratio that provide a favorable environment for fungi growth, which in their turn promote macro aggregate formation.

8.6 Biochar and the promotion of soil biodiversity

Adding something in soil change the soil balance and stimulate the microorganism that populate this area. Indeed, biochar can be seen as a promoter of growing of bacteria and fungi, but moreover, it promotes the diversity that result in enhancing the subsoil activity.
The promoted outcomes that an enhanced microbial abundance and diversity bring to agriculture are the following:

- Micro-aggregates and soil structure.
- Chlorophyll and plant biomass.
- Biochemical recycling.
- Soil enzyme activity.
- Soil Eh and root membrane potential.
- Contaminants degradation and immobilization.

Thanks to a meta-analysis conducted by Singh et al. (2022) focus on the effect on the microbial activity, some general observations have been highlighted:

- Bacterial diversity is push by biochar produced from herbaceous feedstock as green waste, lentil stalks, maize stover and straws.
- Fungal diversity is push by biochar produced from lignocellulose waste as rice husks, rice hulls, shells of nuts, coffee husks, corncobs and vineyard pruning.
- The biochar application rate must be under 40 t/ha to be more effective.
- Operating temperature lower than 500 °C is strongly suggested.
- In coarse medium textured soils biochar promote much more bacterial growth, while in fine-textured soils fungal diversity is the one more enhanced.

In figure 32 on the next page are reported the biochar operating parameter and the effect that they have on microorganism diversity increases.

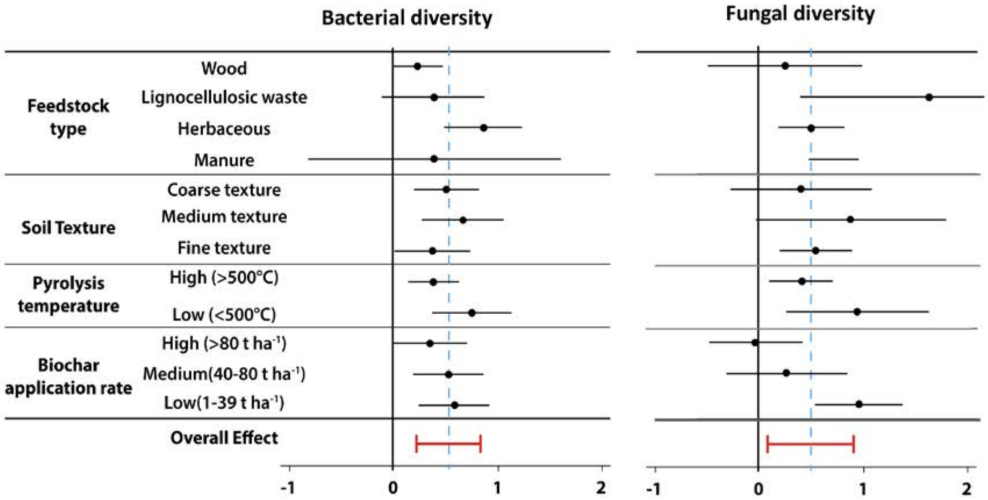

Figure 32: Changes in bacterial (left) and fungal (right) diversity due to biochar addition to soil, for different biochar feedstock types, soil textures, pyrolysis temperatures, and application rates. Bars represent 95% confidence intervals. The red bars and dashed lines show the overall grand mean effects. Image extracted from Farmers guide by Stephen Joseph et al. (2024)

9 Principles and methods of biochar application

The principles and methods of biochar application consider two main aspects: whether the biochar has been treated and how it is applied to the soil.
Choices on type of biochar and how to supply it depends on the boundary conditions, such as the crop or plant, environmental conditions, soil physical and chemical characteristics and financial aspects.

9.1 Untreated biochar

In general biochar can be supply into the soil directly after its production. The "core rule" is that generally to a specific crop must supply biochar obtained with waste coming from that specific crop, so, as example, for corn should be applied biochar obtain from corn stalks or corncob. The reason behind this is that there are already present the macro and micro nutrients needed by that specific crop or plant.
Some good results can be achieved also mixing feedstock with complementary mineral and nutrient compositions, but the predominant one should be always the one obtained from the particular crop.
If no specific biochar is available, the best option should be use biochar obtained from mixing feedstock because they contain a great variety of nutrients.
Moreover, as well explained in chapter 3 and 4, must always consider that the initial feedstock and the operating parameters, especially temperature, determine the amount of nutrients that remains in final product.
The general idea is that when biochar is produced at mid-lower temperature there is less volatilization and so higher amount of nutrients that asses to biochar fertilizer value, obviously not comparable with a prepared fertilizer. Drawbacks are less amount of carbon and higher probability to find some pollutants, heavy metals or salts.
The agricultural feedstock that contains higher amount of nutrients are:

- Manure, animal waste, chicken feather and food waste contains highest amount of nitrogen.
- Straw and grass contains great values of potassium, but are not rich in nitrogen and phosphorus.

However, untreated biochar could be supply not only with the goal of directly enhance productivity, but could also be that focus is related to improve others soil properties or characteristics. Table 13 on the following page summarizes recommended agricultural practices.

Objective	Recommended Biochar Practice
To maximize the amount of carbon and macro and micro-nutrients that are returned to the soil	Pyrolyze the crop residue at a low temperature (e.g. 400 °C – 450 °C).
To maximize income from carbon credits	Use biochar produced at temperatures greater than 500°C. These have a higher content of carbon and significantly longer lifetime than biochar produced at lower temperatures.
To improve water-holding capacity or enhance water use efficiency	Add finely-ground biochar produced at a higher temperature (500°C–600°C).
To reduce levels of toxic metals or bio-availability of organics	Add finely-ground biochar produced at 500 °C – 700 °C, or biochar produced at a low temperature (around 400 °C) that has high contents of oxygen functional groups and iron.
To address physical and chemical soil constraints at the same time, or to meet a greater range of constraints from a single feedstock	Combine low- and high-temperature biochar. The specific ratio may depend on the relative severity of individual constraints, including financial.
To raise the pH of acidic soil	Use a biochar with a pH greater than 7.
For basic soil	Use a biochar with a pH between 6 and 6.5, which can be produced from lower-temperature pyrolysis (350 °C – 400 °C), or by treating biochar with an acid (preferably phosphoric, acetic, or citric), or wood vinegar.

Table 13: Recommended biochar production and application practices based on soil and environmental objectives. Tables content extracted from Farmers guide by Stephen Joseph et al. (2024)

9.2 Pretreatment of biomass to produce biochar

A good method to improve biochar performance and asses wanted specific characteristics is pre-treating biomass before pyrolysis.
In this way, mixing biomass with other compound, it is possible to increase carbon content or biochar yield or amount of retained nutrients.
Common pretreatments involve the following additives:

- Clay, diatomite, lime, zeolites and similar. With a mixing in the range of 20 - 30 wt%, the goal here is to increase fixed carbon yield. Moreover, due to acid catalyst nature of clay, it lead to increased formation of functional group (carbon and oxygen) and an increase of CEC.

- Nutrients as rock phosphate, ash from wood fire, bones and similar. This method directly asses to biochar fertilizer value.

- Chemicals as phosphoric acid, potassium hydroxide, chlorides of Mg, Fe, Cu and similar. Using chemicals before pyrolysis results in site that bind phosphates and nitrates into the biochar.
  If biomass is pre-treated with superphosphate, ground bones or phosphoric acid, biochar yield increase.
  Typically, the proportion of phosphate-mineral to biomass are also here 20 – 30 wt%.
  In general, the presence of chemicals bind carbon and so this reduce the amount of carbon loss during pyrolysis.

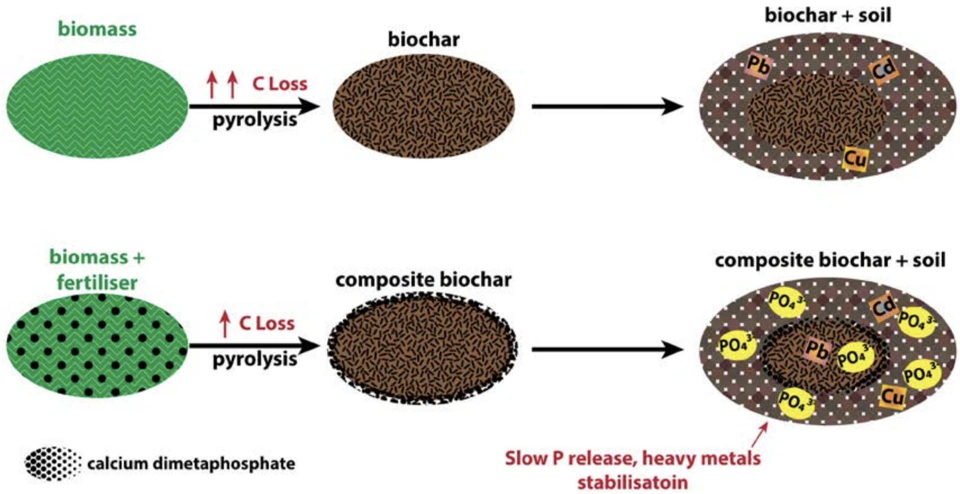

Figure 33: Schematic of adding a high-P mineral or chemical to biomass and co-pyrolysis to improve biochar carbon retention, slow nutrient release, and stabilize heavy metals in soils. Image extracted from Zhao et al. (2016)

9.3 Ageing biochar

Another method to modify biochar properties is ageing. In this way can be reached higher yields, greater plant resistance to stresses and an overall increasing of soil health. Commonly it is obtained using three different techniques:

- Soil or drums interaction, generally at warmer temperatures (25 °C, but at 60 °C it is the most effective approach) in a timescale of few months. In this way can be obtained organo-mineral complexes, which increase CEC and help build soil carbon. Another way is using a drum and add water at 5,5 pH in order to improve biochar ability to retain nitrogen.

- Co-composting with biomass and minerals. In such a way the amount of nutrients increase.

- Use biochar as feed for animals and collect manure. Generally a few amount of molasses is added. During the digestion, biochar acquire nutrients and react with stomach acid and enzyme. Biochar, once collected and dried from animal excretes, result in higher CEC value and higher nutrient content.

9.4 Biochar post treatment

Post-production treatment is one of the most commonly employed methods for modifying biochar properties. Generally mixing is made with fertilizer (minerals, organic or inorganic high-NPK). The product is defined biochar compound fertilizer (BCF).
Looking to most relevant experimental results, biochar shows to works better if combined with fertilizer or compost. This statement is confirmed by multiple meta analysis studies such as Ye et al. (2019) and Bai et al. (2022). They confirm that generally biochar enhance crop's productivity, but both studies show that biochar plus fertilizer was substantially more effective than fertilizer alone or biochar alone, against either baseline.

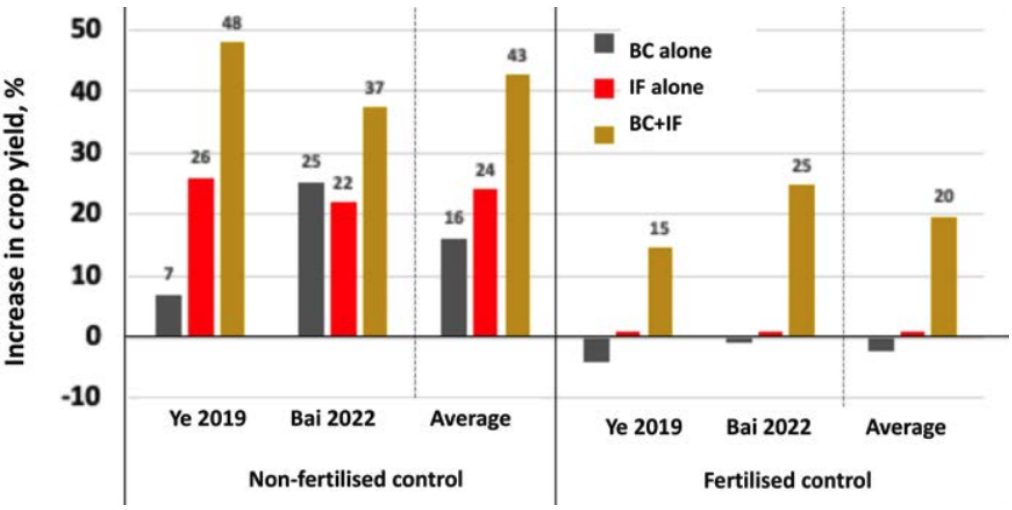

Figure 34: Average increases in crop yields relative to fertilised and non-fertilised soil controls after applications of biochar (BC), fertiliser (IF), or a combination (BC+IF). Data were combined from two meta-analyses each of over 55 studies (Ye et al. and Bai et al.). Each data bar represents the overall average from many comparisons of all kinds of biochar, for all application rates, all crops, all soils, and all climate conditions. The average of the results from the two studies is also shown. Image extracted from Farmers guide by Stephen Joseph et al. (2024)

In general, thanks to the studies reported above can be state that:

- In countries where fertilizer use is permitted or is a common practices, mixing with biochar, the mean overall yield grow by 20 wt%.
- Biochar obtained from cereal feedstock at low temperature general produce greater yield increase due to higher nutrient content.
- Acidic, sandy, clayey, leached, oxidized, low organic, or low cation exchange capacity soils had higher yields when biochar was added at 5 t/ha or less, compared to yields from non-fertilized controls.

One of the biggest advantages that BCF offers is the reduction of fertilizer losses due to biochar sorption capability.
The most effective ways to combine organic fertilizers with biochar for optimal plant growth is to quench the biochar at the end of pyrolysis using

manure, bio-sludge, minerals or chemicals.
As general rule, after mixing it's necessary to dry all organic liquids and mineral to obtain stronger bond of nutrients with biochar.
In table 14 are reported some general rules:

Soil/Fertilizer Type	**Recommended Biochar and Mineral Practice**
A general-purpose fertilizer using a woody biochar	Use a mixture of biochar and minerals in the proportions of: 10 biochar, 1,5 kaolinite, 1,5 bentonite, 2 basalt dust, 1,5 diatomaceous earth, 1 wt% rock phosphate.
Clayey soils	Reduce the amount of clay to 10 biochar : 0,5 clay, using both bentonite and kaolinite, and add gypsum to help break up the clay.
Sandy soil	Add more clay (10 biochar : 2–5 clay).
Soils that are very low in most micronutrients	Soak the biochar in a solution of sea minerals or equivalent.
Only a few micro-nutrients are lacking from the soil	Add the specific micronutrient to the other minerals, preferably as a liquid. Determine the amount to add from a soil analysis and the biochar application rate.

Table 14: Biochar-based amendment strategies for different soil types and nutrient conditions. Data extracted from Farmers guide by Stephen Joseph et al. (2024)

9.4.1 A general overview on urea and biochar

Particularly interesting nowadays is mixing biochar with urea. From both chemical and physical perspectives, urea is one of the most commonly used chemical fertilizers, but it is highly susceptible to leaching and volatilization, so mixing it with biochar can significantly reduce these losses.
To properly create biochar-urea composite there are two methods:

- Mix liquid urea (obtained by heating it) with biochar produced at high temperature and treated with acid in order to reach 6,5 pH. After that can be add bentonite clay at (80 °C) that coats biochar and expand pores that can be filled by residual nitrogen.
- Using low-pressure pellet machine or a granulator and pelletize all component together thanks to heat supply.

The formed material is called biochar-mineral-urea (BMC) granules. This composite allows slow release and preserves a high ratio of ammonium to nitrate for a longer period compared to chemical urea fertilizer.
It provides a sustainable alternative to reduce chemical urea needs, nitrogen

loss in croplands and avoid pollution. Indeed, multiple studies such as Wei at al. (2020), but moreover the ICHAR association, confirms that "it is possible to reduce fertilizer use by 30 vol% to 50 vol%, effectively replacing it with biochar leading to a reduction in costs for farmers."
Nowadays this advantage is coming really relevant considering the socio-politic and economic aspects related to urea prices that were strongly affected by COVID-19 pandemic and after by Ukraine and Russia war.
Going deeply in market analysis, urea prices started to rise at the end of 2021, mainly because natural gas became more expensive and global supply chains were still affected by the COVID-19 pandemic. The situation got worse after Russia invaded Ukraine, which caused urea prices to hit record levels, reaching around 900 $ to 1050 $ per tonne (according to data from the Black Sea FOB and FAO). In 2023, prices slowly started to go down thanks to lower gas costs and better transport and logistics. However, they still remained above pre-crisis levels.
In 2025, urea prices have increased by 57,50 $/t since January, which correspond to +17%. They are expected to reach 387,85 $/t by the end of this quarter. Looking ahead, forecasts say urea will trade at about 367,15 $/t in the next 12 months.

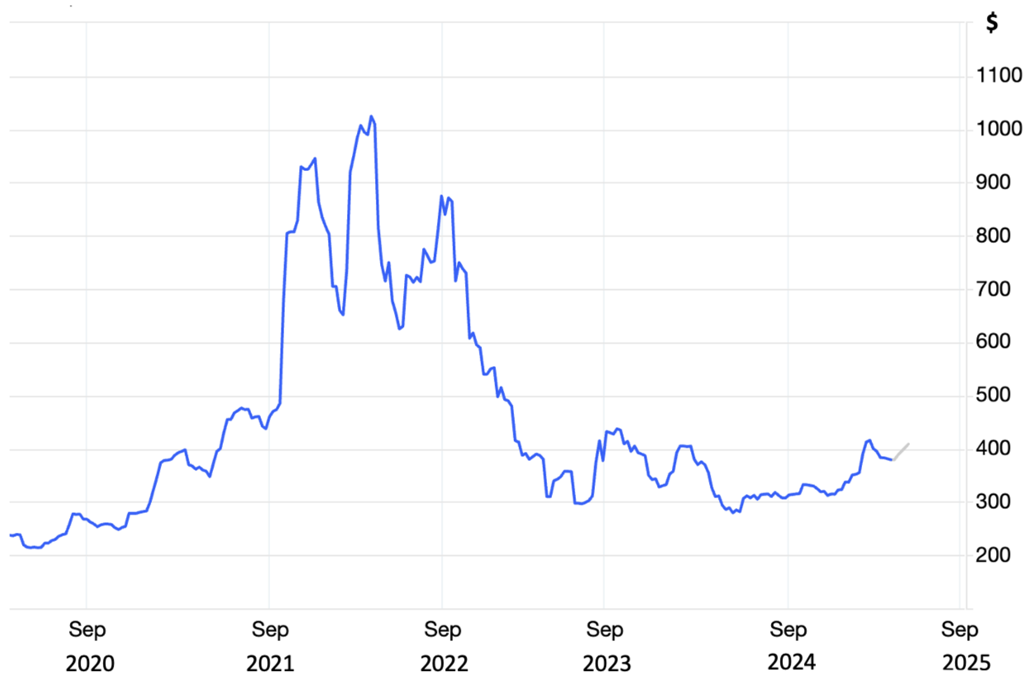

Figure 35: Urea prices from 2022 to 2024. The gray line represent predicted values for 2025. Image taken from "Global Trading Economics Analysis - tradingeconomics.com"

In conclusion, using BMC, can be reduce urea dependency by 30-50 vol% and provides substantial benefits from an agronomic, environmental and economic standpoint.

9.5 Methods for biochar field application

Once selected biochar characteristics and supply rate, it must be correctly applied in order to obtain desired effects.
There are different methods to accomplish this task, but there are some general aspects that should be always take into account:

- To optimize cost and time, biochar mixing with fertilizer it is always a good choice.
- Dust pollution and loss of biochar due to water and/or wind erosion should always be avoided. Dry and small size biochar must be supply under soil or wetting it with water, liquid fertilizer or slurry. Another way is to increase the dimension, forming granulate or pellet.
- To maximize effects, biochar should be placed in the root zone (rhizosphere), where root secretions can reach it. If farmers are dealing with seasonal crops, the distance between seeds and BCF should be in the range of 10 - 50 cm, while in the case of straight biochar it could be much near, in the range of 2 - 5 cm, especially with furrow irrigation system.
- It is not mandatory supply it every year, but in order to amplify agricultural benefit it should be done. Every year, rates can be reduced because biochar accumulates and ages in soil, enhancing short and long term benefits. It must be remembered that a portion of it can be lost due to downward movement.
- In conventional crop systems it can be incorporated using standard farm machinery without changing routine operations.

9.5.1 Methods of application

There are different methods of applications and they depend on agricultural crop or plant characteristics and practices.

- Top - dressing: generally used for multi-annual already established crops. It consists of spreading the material on the topsoil. Its main advantage is the ease of application, however, if not properly pretreated, it can be susceptible to losses due to wind and water erosion.
  In cases a new orchard, trees or new multi annual-plants system is established, it could be directly placed in holes made for plants. For hole of 30 cm diameter, 15 cm depth, the Japanese Biochar Association suggest to apply from 1 to 2 l of biochar before planting to accelerate the growing of plant and resistance to stresses.
- Uniform topsoil mixing: this process happens before planting and after agricultural practices used to prepare soil.
  The idea is to spread it in the top soil using manure or lime spreader depending on the moisture, and then, using rotary hoeing, disking or chisel tillage incorporate it under soil. This is a delicate phase where the tilling practices must be accurately metered in order to accurately place biochar in rhizosphere.

- Banding: if mechanized agricultural machinery are used, biochar alone or biochar plus seed or fertilizer could be banded. This technique consist in open a narrow furrow and insert the amendments in soil. Generally, after this process the band is also automatically closed by a mechanical blade avoiding losses through evaporation and soil drying. It is really useful for already existing plants or trees or during seeding for put in contact biochar and future crop roots.

- Subsoil injection: considering modern an more innovative agricultural practices, to reduce soil losses and erosion, reduced or no tillage methods are always more used. This methods is quite similar to bending, but it use a blade or a probe that creates a hole and directly inject it the soil and then close it.

- Employing animals: this method consists of feeding animals with biochar, which helps integrate it into the soil of established pastures without disturbing the surface.
  It's based on livestock animals that eat and defecate biochar and then on insect or similar organisms. An example are earthworms or dung beetles that have been seen to naturally move biochar deeper into the soil. Similar methods can be used with chickens and other free-range animals to spread biochar mixed with manure.

- Pot cultivation: generally biochar can be used in order to increase water retention and air permeability. It is applied at the bottom of the pot and it represent 10-30 vol% against total soil volume. In order to prevent root rot, biochar may be intensively applied to the bottom of the pot.

- Hydroponic cultivation: with farming 4.0 it has recently gained popularity, especially for fruiting vegetables like tomatoes, cucumbers, and eggplants. Various systems are used, including ridge setups and containers with limited soil.
  In these sector, biochar can be beneficial due to its ability to enhance water retention and soil permeability reducing costs for producer.
  Due to the high control levels that those cultivation must be compliant with, biochar nutrient content should be considered when used alongside nutrient-rich hydroponic solutions in order to supply the correct amount of nutrients to plants. Typically, biochar is mixed at 10–20 vol% for ridge systems and 10–50 vol% for containers. In some cases, biochar alone can even replace soil entirely.

10 Methodologies

The following section presents the methodologies used to assess how biochar can enhance agricultural activities, with a focus on the relationship between biochar additions to soil and changes in hydraulic properties that affect crop yields. The idea is to do a step on the already existent results and assess direct benefits given by biochar to crop biomass production. For doing that, multiple simulations were done using AquaCrop software.

10.1 AquaCrop

AquaCrop, created and managed by FAO (Food and Agricultural Organization of United states), "is a crop growth model developed by the Land and Water Division of FAO to address food security and to assess the effect of environment and management on crop production. AquaCrop simulates yield response to water of herbaceous crops, and is particularly suited to address conditions where water is a key limiting factor in crop production." It is a water-driven model that assesses crop responses based on soil water balance with a daily time step, where it simulates crop growth, development, and senescence using the canopy cover (CC) curve, which is mainly determined by initial crop characteristics as CC_0, canopy growth coefficient (CGC), maximum CC (CC_x), and canopy decline coefficient (CDC).
AquaCrop is based on a continuous soil-crop-atmosphere structure where the user can defined input parameter to simulate crop growth. In particular soil modules, crop modules, atmosphere modules and management modules. Using data set already present is possible to simulate a multitude amount of different scenario, but, moreover, those data can be modify in order to better represent the real field features.

10.2 AquaCrop calibration

AquaCrop does not have a built-in method to automatically include biochar in soil.
Therefore, considering that AquaCrop is an hydraulic based model, the only way to simulate biochar addition is to manually manipulate soils characteristics, specifically Wilting point, field capacity, saturation (SAT) and saturated hydraulic conductivity K_{sat}.
It's really important to emphasize that using this strategies to assess agricultural biochar benefits, there will only reflect changes in hydraulic properties. The following benefits that biochar brings will not be considered:

- Nutrient additions and nutrients cycles boost.
- pH fluctuations.
- Changes due to aging factors.
- Root biomass increase.
- Biodiversity increase.

- Resistance to disease stresses.
- CEC increase

The reasons behind that are related to AquaCrop limitations that does not gives the opportunity to consider all this other features and so the intentions are strictly focus on how hydrological changes can affect the agricultural yield using a specialized simulation tool.
To properly change hydraulic properties must assess news hydraulic parameters and so this was done using results obtained from Edeh et al. (2020) with "A meta-analysis on biochar's effects on soil water properties".

Physical parameters	BC parameters for clay soil
PWP	-0,40 vol%
FC	3,50 vol%
SAT	4,00 vol%
K_{sat}	28 %
Physical parameters	BC parameters for sandy soil
PWP	22,20 vol%
FC	23,90 vol%
SAT	7,90 vol%
K_{sat}	-64,6%
Physical parameters	BC parameters for loamy soil
PWP	10,90 vol%
FC	13,70 vol%
SAT	5,95 vol%
K_{sat}	-18,30%

Table 15: Hydraulic properties modifications given by biochar addition

On those data, some important considerations and assumptions were done because Edeh et al. (2020) gives only information for clay (fine textured) and sandy (coarse textured) soil and no direct information on saturation:

- For saturation conditions, considering that their physical meaning corresponds to the complete filling of soil pore spaces with water, I assumed that saturation can be considered linearly dependent on changes in porosity due to biochar addition. Therefore, the increase in soil saturation is assumed to be equal to the increase in porosity.
- For loamy, considering that is a type of soil that consists of a balanced mixture of coarse and fine textured soil, changes in hydraulic properties were estimated by averaging the changes observed in sandy and clay soils.
- In previous chapter was reported that K_{sat}, looking at average values extracted from the meta-analysis, decrease when biochar is applied.

This statement can not be taken as general rule because K_{sat} behavior's depend on soil: in coarse-textured soils, biochar reduced K_{sat}, while in fine-textured soils, it led to an increase. The reason behind that is the relation between biochar size and pore size. Coarse soils naturally have larger pores, which favor water movement. However, biochar tends to reduce these larger pores, filling them with smaller particles, thus lowering K_{sat} but improving water retention. On the other hand, in compacted fine soils, biochar enhances pore structure by promoting the formation of macro aggregates and creating larger pores, thereby increasing K_{sat} and improving water infiltration.

- Soil physical characteristics changes with biochar application rates, so the data reported in 15 on the preceding page are referred to an average application rate, in the range of 30–70 t/ha.

Considering all constraints, three soil types were calibrated and used for all simulations.

Physical parameters	Clay	BC parameters	Clay + BC
Wilting point (vol%)	39	-0,40	38,84
Field capacity (vol%)	54	+ 3,50%	55,89
Saturation (vol%)	55	+ 4,00%	57,20
K_{sat} (mm/day)	35	+ 28%	44,80

Table 16: Changes in soil hydraulic parameters with biochar addition for clay soil

Physical parameters	Sandy	BC parameters	Sand + BC
Wilting point (vol%)	6	+ 22,20%	7,33
Field capacity (vol%)	13	+ 23,90%	16,11
Saturation (vol%)	36	+ 7,90%	38,84
K_{sat} (mm/day)	3000	- 64,6%	1062

Table 17: Changes in soil hydraulic parameters with biochar addition for sandy soil

Physical parameters	Loam	BC parameters	Loam + BC
Wilting point (vol%)	15	+ 10,90%	16,64
Field capacity (vol%)	31	+ 13,70%	35,25
Saturation (vol%)	46	+ 5,95%	48,73
K_{sat} (mm/day)	500	- 18,30 %	408,5

Table 18: Changes in soil hydraulic parameters with biochar addition for loamy soil

10.3 Application depth and soils-biochar relations

As a first task, the aim is to test the importance of application depth and the interactions between biochar and soil.

At this stage, only the effects of biochar on soil water movement have been considered, without evaluating its impact on final crop performance.
The focus was placed on water content within the effective root zone (Wr) over time. Tests were conducted on all soil types under three scenarios:

- Baseline: no biochar addition, soil characteristics remain as default
- Biochar at 30 cm depth: biochar modifications of first 30 cm of soils
- Biochar at 50 cm: biochar modifications of first 50 cm of soils

The total soils depth was set at 1 m, with no groundwater table and the crop selected was Alfalfa (Artemis variety, C3) with maximum rooting depth fixed at 0,95 cm and growing period from March 22 to December 31.
This crop was selected due to low complexity levels of growing mechanisms.
No climate and no irrigation events were set, as the objective at this stage is solely to observe how water moves through soil layers.
All runs started in specific soil saturation conditions.

10.4 Relations between biochar additions and crop response

For this task, the aim is to investigate relations between biochar addition and crop response, so simulations where carried out under realistic conditions.
Also here the Wr was taken into account.
Based on the previously obtained results, for this step, analysis focused on sandy and loamy soils, considering two scenarios: a baseline (no biochar) and soil with biochar added to the top 50 cm.
Total soil depth was set at 1 m with no groundwater table. The total soil depth and the 50 cm biochar application were also maintained for all subsequent simulations.
The initial simulation conditions were:

- Crop: paddy rice, sown on March 22 and harvested on July 3. It is a C3 crop with a rooting depth of 0.6 m.
- Climate: LosBanos (a specific default climate suitable for paddy rice) with specific climatic events of 2004.
- Initial condition: saturation of baseline soil.

After analyzing results, additional simulations were performed using saturated initial conditions for the soil + biochar scenario, in order to assess differences in water drainage behavior.

10.5 Biochar in relation with crop response and leaf expansion

For this part the focus was set on the relations between Wr and water content in effective root zone at upper threshold for leaf expansion (Wr(exp)).
Stress that reduce leaf expansion happen when water content in the root zone

(Wr) drops below the threshold for leaf expansion and so canopy expansion declines, reducing biomass production. Moreover, the focus was placed on how biochar can support crops under water stress conditions by analyzing the differences between Wr and Wr(exp) in both the baseline and the soil + biochar scenarios.
The generic features considered were:

- Crop: Teff, a gluten-free grain from Ethiopia, sown on March 22 and harvested on June 28. It is a C3 crop with a rooting depth of 0,6 m.
- Climate: Climatic conditions in Foggia based on events recorded in 2004.
- Initial conditions: default initial conditions set at specific field capacity of selected soil.

In this simulations all runs were carried out with a defined schedule of irrigation events, detailed in table 19, in order to simulate a more realistic scenario in a climate where irrigation is necessary.
The irrigation method used was basin with 100% surface wetting.

Event	Day	Date	Net application (mm)
1	1	22 March 2000	10
2	10	31 March 2000	30
3	20	10 April 2000	30
4	30	20 April 2000	30
5	40	30 April 2000	50
6	50	10 May 2000	100
7	60	20 May 2000	100
8	70	30 May 2000	100
9	80	9 June 2000	50
10	90	19 June 2000	100

Table 19: Irrigation events for Teff crop

10.6 Crop response and volume water demand with irrigation

For this section the aim was to observe irrigation efficiency and biomass changes for soils treated with biochar, looking at the overall year performances.
Simulations were done for Teff (0,5 m rooting depth) and Alfalfa (0,6 m rooting depth) with irrigation events respectively reported in 19 and 20 on page 92.
All the conditions are the same as previously runs except for no climate selection, in order to only evaluate irrigation effects and saturation conditions, taken as the one of baseline soil to reduce initial water abundance.
New parameters are taken into account in this section in order to evaluate water movement in soil an assess soil's performance:

- Total water content: it is the total water content present in root zone at the end of simulation.
- Run off: refers to the portion of applied water that flows across the land surface and is not absorbed by the soil. It represents an inefficiency in field application.
- Infiltrated water: it is the portion of irrigation water that has entered in the soil profile, potentially available for plant uptake.
- Deep percolation ratio: it is the ratio of applied water that percolates below the plant root zone, making it unavailable to the crop and total water delivered to the field. It is calculated as:

$$\text{DPr} = \frac{V_{\text{dp}}}{V_{\text{f}}} \tag{2}$$

  where:

  - V_{dp} = volume of water percolating below the root zone [m^3]
  - V_{f} = volume of water delivered to the field [m^3]

Event	Day	Date	Net application (mm)
1	1	22 March 2000	10
2	10	31 March 2000	30
3	20	10 April 2000	30
4	30	20 April 2000	30
5	40	30 April 2000	50
6	50	10 May 2000	100
7	60	20 May 2000	100
8	70	30 May 2000	100
9	80	9 June 2000	50
10	90	19 June 2000	100
11	100	29 June 2000	50
12	110	9 July 2000	70
13	120	19 July 2000	50
14	130	29 July 2000	100
15	140	8 August 2000	50
16	150	18 August 2000	100
17	160	28 August 2000	50
18	170	7 September 2000	100
19	180	17 September 2000	50
20	190	27 September 2000	80
21	200	7 October 2000	80
22	210	17 October 2000	20
23	220	27 October 2000	20
24	230	6 November 2000	80
25	240	16 November 2000	20
26	250	26 November 2000	10
27	260	6 December 2000	20

Table 20: Irrigation events for Alfalfa crop

10.7 Comparison C3 and C4 crops and biochar benefits

The aim of this section was to compare C3 and C4 crops under identical conditions and evaluate which one benefits more from biochar application in terms of growth enhancement and stress resistance. Alfalfa was selected as the representative C3 crop, with a maximum rooting depth set at 0.95 m, while Sugarcane was chosen as the C4 crop, with the same rooting depth. In both cases, soils were initialized at field capacity, and no specific climatic events were imposed.
For each soil type, two different irrigation regimes were considered, one stricter than the other, to assess how biochar performs under varying levels of water stress. The stricter regime is the one previously used (see table 20), while the second follows the same irrigation calendar but with a higher water supply of water: 300 mm more than the firs one (1850 mm vs 1550 mm) homogeneously distributed across the growing period.

11 Results

Analyzing literature results, it is not an easy task to assess the general benefits of biochar in enhancing crop productivity and reducing water stress. For this reason, multiple studies have been analyzed to adopt a broader and more generalized approach. Based on the analyses by Schmidt et al. (2021), Dai et al. (2020), Baronti et al. (2014) and Omondi et al. (2016), it can be stated that, under general conditions involving, average supplying rate (30-70 t/ha) various crops, soils, environmental contexts, and stress factors, biochar (without fertilizer addition) has led to the following outcomes:

- A yield increase of 13–16% was observed. It must be noted that yield is a fixed percentage of total biomass production specific to each crop. This proportion may vary slightly under conditions of severe stress; however, such scenarios are not considered in the following analysis.
- Water availability increase of 8-15%, in generic soil.

No information related to stresses are present because they strongly depend on the specific boundary conditions, so there are no general analysis on this topic because it could not be possible to extract relevant results.
This is true also for all other subsequent data analyzed.
In the following section there will be a deep analysis of simulations results.

11.1 Application depth and soil's-biochar relations results

11.1.1 Sandy soil

Month	Wr sand (mm)	Wr sand + BC30 (mm)	Wr sand + BC50 (mm)
3	32,2	40,6	41,6
4	39	43,6	47,2
5	55,4	59,2	61,7
6	74,1	78,4	81
7	90	95,1	98
8	96,7	102,6	105,8
9	92,6	98,9	102,4
10	91,6	97,8	101,3
11	91,5	97,4	101
12	91,3	97,2	100,7

Table 21: Wr at different biochar application depth in sandy soil

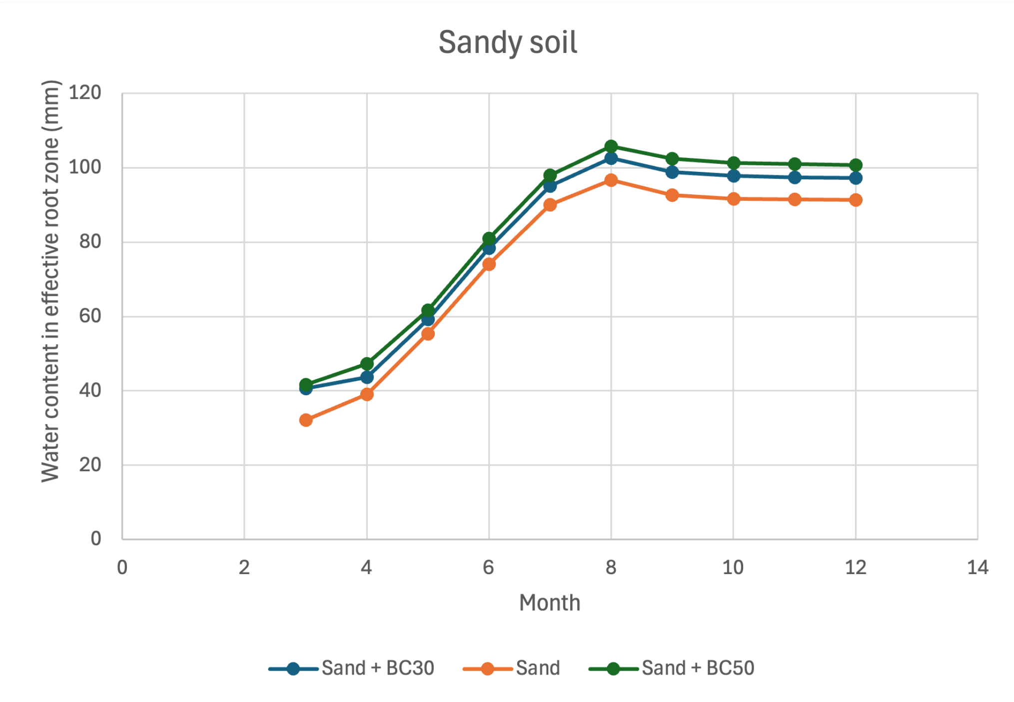

Figure 36: Wr trend in sandy soil with different biochar application

11.1.2 Loamy soil

Month	Wr loam (mm)	Wr loam + BC30 (mm)	Wr loam + BC50 (mm)
3	91,9	104,3	105,6
4	100,4	108,1	113,2
5	130,1	134,1	137
6	180,1	183,4	185,6
7	227,4	230,8	233
8	252,7	256,3	258,8
9	249,5	253,3	256
10	246,3	250,3	253,1
11	243,3	247,5	250,5
12	240,5	244,9	248

Table 22: Wr at different biochar application depth in loamy soil

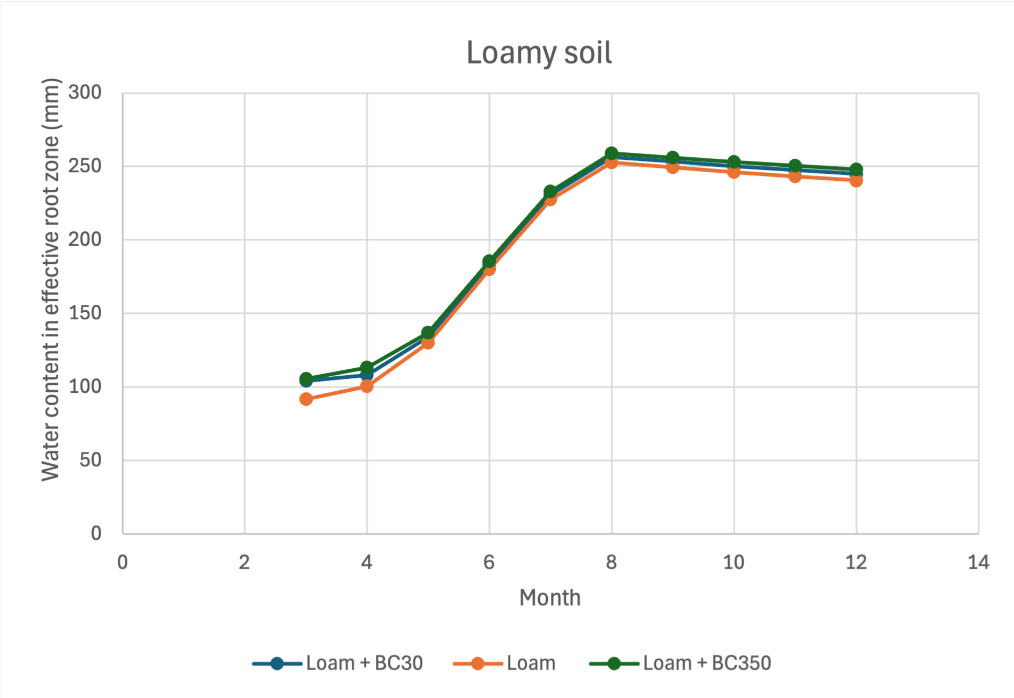

Figure 37: Wr trend in loamy soil with different biochar application

11.1.3 Clay soil

Month	Wr clay (mm)	Wr clay + BC30 (mm)	Wr clay + BC50 (mm)
3	162,5	166,7	166,7
4	226,3	227,8	229
5	310	309,1	310,5
6	396,1	395,1	395,8
7	477,4	476,5	477,1
8	521,7	521,1	521,6
9	516,9	516,6	517
10	512,7	512,6	512,8
11	509,8	509,9	510,2
12	507,9	508	508,3

Table 23: Wr at different biochar application depth in clay soil

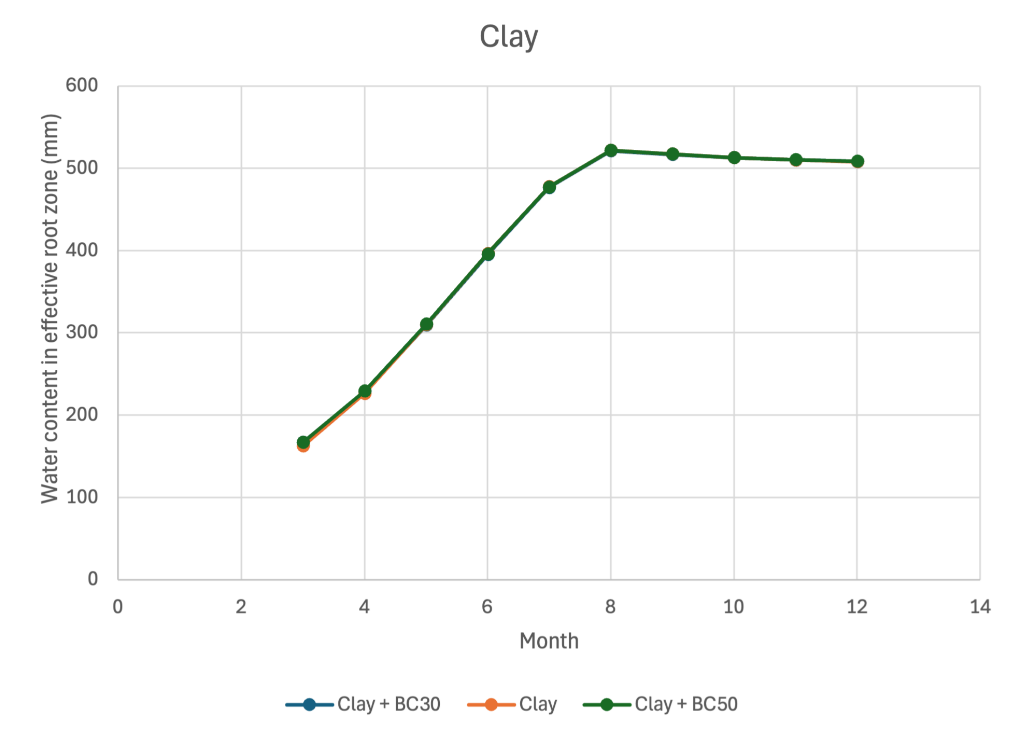

Figure 38: Wr trend in clay soil with different biochar application

11.1.4 Results analysis

The goal of this analysis was to simulate in same conditions how Wr changes in relations with different soil type and application depth. As shown in the three graphs 36 on page 94, 37 on the preceding page, and 38, which illustrate the Wr trend, biochar significantly enhances the water-holding capacity in sandy soil compared to the other soil types. Also in loamy soil can be observed great improvements, though not as pronounced as in sandy soil, while in clay soil, differences are nearly negligible.
For this reason, the following graphs (39 and 40) present the differences in Wr among the three scenarios specifically for sandy and loamy soils.

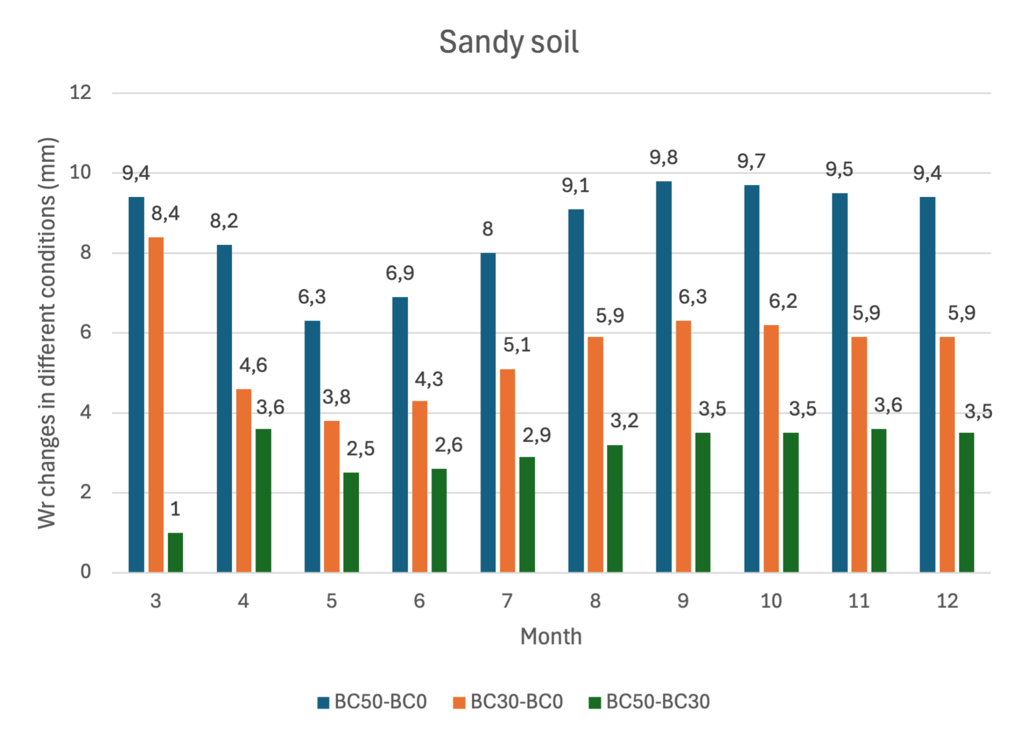

Figure 39: Wr differences between sandy baseline and sandy soil + BC

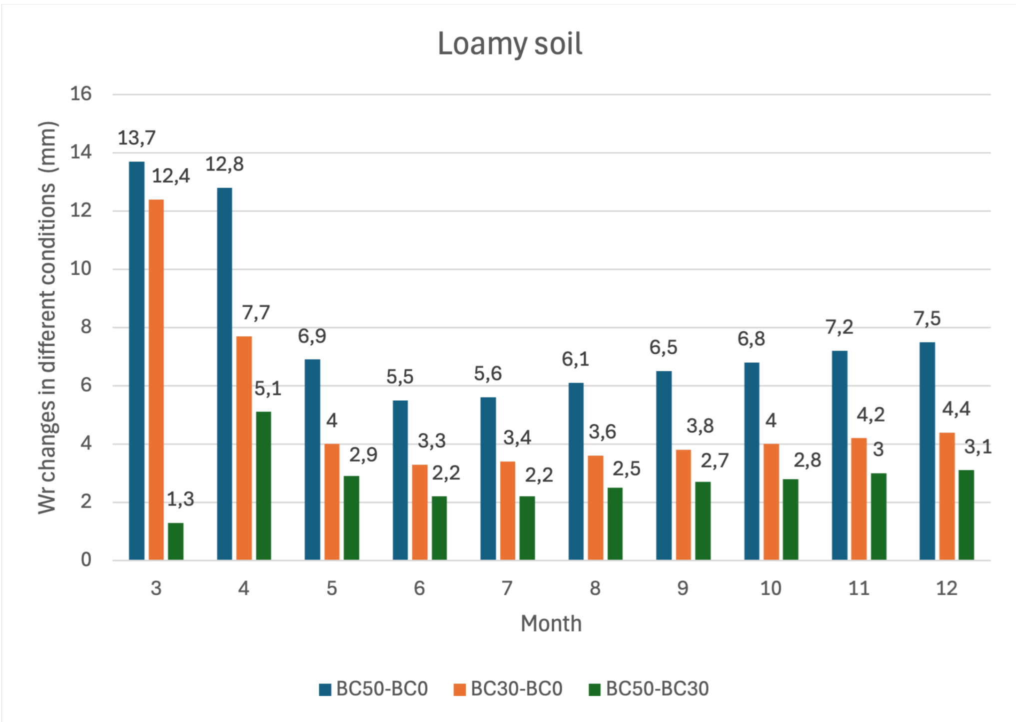

Figure 40: Wr differences between loamy baseline and loamy soil + BC

The results indicate that sandy soil benefits the most from biochar addition, outperforming all other scenarios.
This can be confirmed by overall Wr in the three scenario, defined as the sum of the total differences in Wr over the total period.

Soil	Wr BC50-BC0 (mm)	Wr BC30-BC0 (mm)	Wr BC50-BC30 (mm)	% of saving water BC50-BC0 (%)	% of saving water BC30-BC0 (%)
Sand	86,3	56,4	29,9	11,4	7,5
Loam	78,6	50,8	27,8	4,0	2,6
Clay	7,7	2,1	5,6	0,2	0,1

Table 24: Overall differences in Wr for all scenario

Furthermore, applying biochar at greater depths leads to increased benefits, as a larger portion of the soil profile experiences improved hydraulic properties. Due to that and considering common application methods, from now on, all simulations will use the scenario with biochar applied to the top 50 cm of soil.
In conclusion, it is important to emphasize that the initial saturation condition is maintained, as previously discussed in "Principles and methods of biochar application", since biochar should be applied under highly wet conditions to reduce losses.

11.2 Relations between biochar additions and crop response results

Following analysis will investigate how biochar can enhance crop productivity in three soils.
For farmers, the main indicator of interest is the biomass produced, which reflects the total amount of crop growth.
Each crop has a specific index called the Harvest Index (HI), which represents the fraction of total biomass that is converted into yield. The HI remains constant, as in these cases, unless affected by high stress conditions.
Another important parameter is canopy cover (CC), that, as reported in AquaCrop manual: "it is the foliage development is expressed through green canopy cover (CC). The green canopy cover (CC) is the fraction of the soil surface covered by the canopy and it ranges from zero at sowing (0% of the soil surface covered by the canopy) to a maximum value at mid-season which can be 1 when a full canopy cover is reached and 100% of the soil surface is covered by the canopy. The shadow on the soil surface of the canopy cover when the sun is right overhead is the canopy cover" (Understanding AquaCrop – Training handbook I. – August 2023).
Also ET water productivity is an important parameter and it is defined by AquaCrop Manual as: "it is the relationship between crop yield and evapotranspiration. It is expressed as kg (yield) per m^3 of water (evapotranspired). It is typically used as an indicator to assess the performance of a system. AquaCrop use it to identify the environments in which (or management strategies by which) the yield per unit water (ET) can be maximized. This type of performance indicator is useful under conditions of scarcity of water resources" (Understanding AquaCrop – Training handbook I. – August 2023).

Concluding, in this simulation there will also be considered two stresses:

- Canopy expansion (%): tells us the percentage reduction in increase in the total leaf area of a plant, allowing for greater light capture and photosynthetic capacity. It involves the growth of leaves and stems, contributing to biomass accumulation.
- Stomatal closure (%): is the process by which the pores (stomata) on the surface of leaves close to reduce water loss through transpiration, in response to drought. This reduce plant activity and so biomass formation.

In no stress conditions, these parameters remains at 0%.

11.2.1 Sandy soil

Month	Wr sand + BC50 (mm)	Wr sand (mm)
3	45,8	35,8
4	52,9	41,1
5	61,4	50,1
6	78,9	63,9
7	76,9	61,3

Table 25: Wr for paddy rice in sandy soil

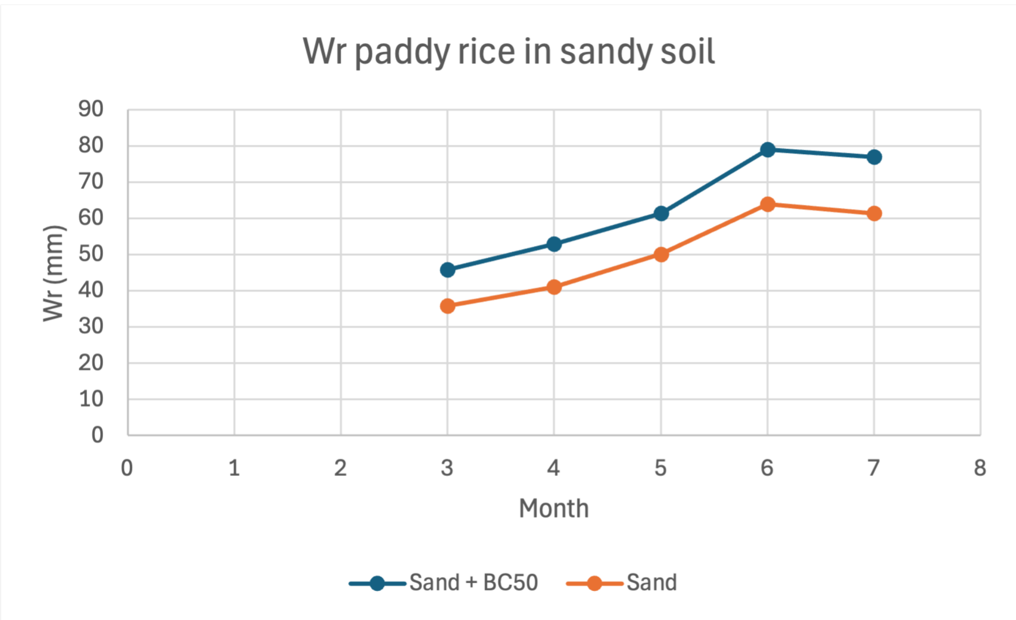

Figure 41: Wr trend for paddy rice in sandy soil

Parameters	Sand + BC50	Sand
Biomass (%)	36	30
Biomass produced (t/ha)	5599	4675
Potential biomass produced (t/ha)	15647	15647
ET water productivity(kg/m^3 evotranspired water)	1,08	0,95
Dry yield (t/ha)	2430	2022
CC (%)	21,1	17,3
Canopy expansion (%)	68	70
Stomatal closure (%)	10	14

Table 26: Agricultural parameters for paddy rice in sandy soil

11.2.2 Loamy soil

Month	Wr loam + BC50 (mm)	Wr loam (mm)
3	112	98,4
4	125,4	109,5
5	122,3	110,9
6	172,6	152,9
7	174,6	152,6

Table 27: Wr for paddy rice in loamy soil

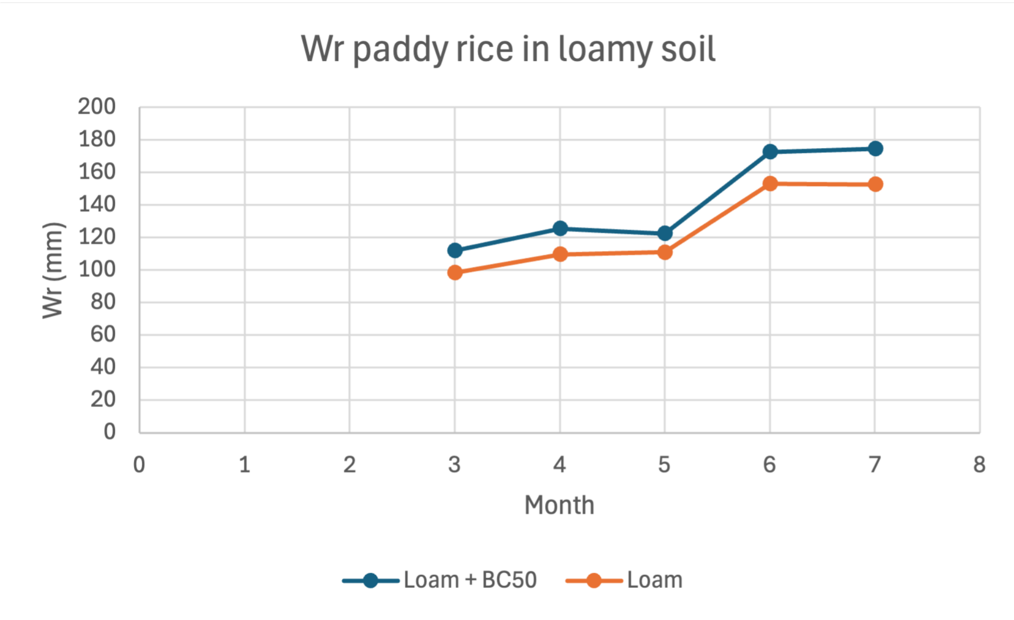

Figure 42: Wr trend for paddy rice in loamy soil

Parameters	Loam + BC50	Loam
Biomass (%)	42	37
Biomass produced (t/ha)	6536	5822
Potential biomass produced (t/ha)	15647	15647
ET water productivity(kg/m^3 evotranspired water)	1,03	0,96
Dry yield (t/ha)	2833	2524
CC (%)	24,5	21,5
Canopy expansion (%)	70%	71%
Stomatal closure (%)	9%	10%

Table 28: Agricultural parameters for paddy rice in loamy soil

11.2.3 Clay soil

Month	Wr clay + BC50 (mm)	Wr clay (mm)
3	179,4	174,2
4	225,1	218,9
5	232,6	228,8
6	270	260,4
7	272,3	262,2

Table 29: Wr for paddy rice in clay soil

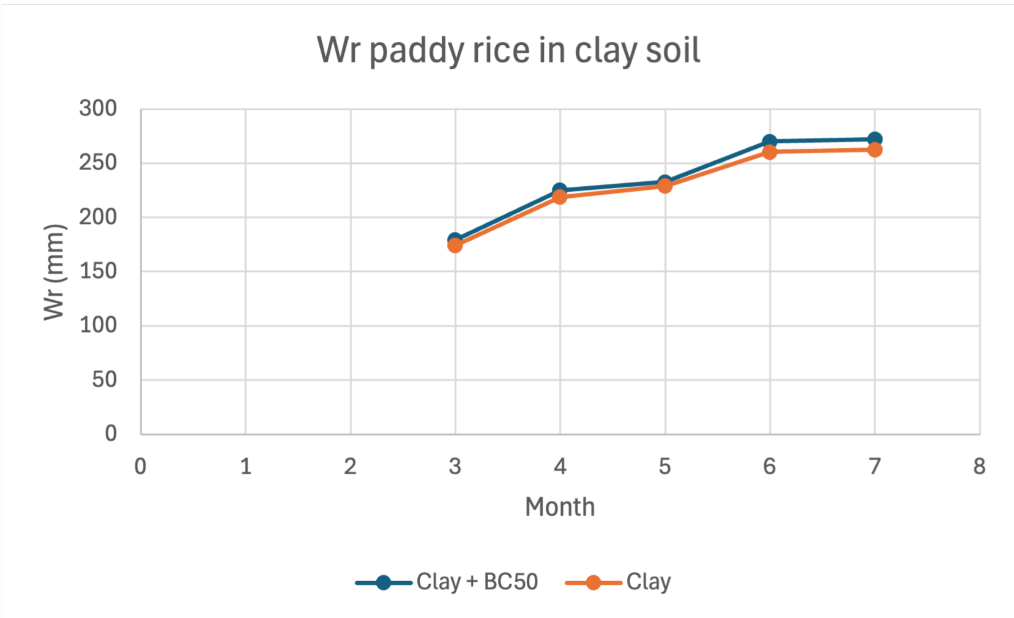

Figure 43: Wr trend for paddy rice in clay soil

Parameters	Clay + BC50	Clay
Biomass (%)	19	19
Biomass produced (t/ha)	2969	2904
Potential biomass produced (t/ha)	15647	15647
ET water productivity(kg/m^3 evotranspired water)	0,5	0,48
Dry yield (t/ha)	1289	1260
CC (%)	10	10
Canopy expansion (%)	81	79
Stomatal closure (%)	11	13

Table 30: Agricultural parameters for paddy rice in clay soil

11.2.4 Results analysis

Parameters	Sand + BC50	Loam + BC50	Clay + BC50
Biomass (%)	6	5	0
Biomass produced (t/ha)	924	714	65
ET water productivity (kg/m^3 evotranspired water)	0,13	0,07	0,02
Dry yield (t/ha)	408	309	29
CC (%)	3,8	3	0
Canopy expansion (%)	-2	-1	2
Stomatal closure (%)	-4	-1	-2

Table 31: Differences in parameter results were obtained by comparing baseline conditions with soils treated with biochar

In table 31, can be observed results in term of crop response considering the differences in value obtained from soil treated with biochar and respective baseline.
Also here, in term of agricultural results, biomass, yield and CC increase much more in sandy soil treated with biochar as a consequences of hydraulic results. Also in loamy soil can be achieved really great results.
A decrees in canopy expansion and stomatal closure means a reduction in stresses.
For farmers, this translates to a yield increase of 6% in sandy soil and 5% in loamy soil, achieved with the same amount of water supplied. In clay soil biochar does not shows interesting results.
Going deeper into the analysis, table 32 on the next page presents data on total drainage water in both baseline and biochar treated soils, as well as the resulting effective water savings. Drain water refers to the portion of water that leaves the soil profile due to gravitational forces and is considered a loss. The data show that, thanks to biochar, the soil's water-holding capacity improves, an effect that is especially pronounced in sandy soils.

Soil	Drained water with BC50 (mm)	Drained water in soil baseline (mm)	Water saving with BC50 (mm)	% of water saving with BC50 (%)
Sandy	361,2	395,7	34,5	8,72
Loam	203,6	235,7	32,1	13,62
Clay	73,6	87,6	14	15,98

Table 32: Comparison of total drain water in baseline soil and in biochar treated soils

Going deeper into the data extracted from the simulation software, figure 44 illustrates the soil water content at various depths in the sandy + BC50 soil profile. A clear drop in water content is observed at the interface between layer 5 and layer 6, decreasing from 16 vol% to 13 vol%. This transition marks the boundary between the biochar amended upper layers and the untreated sandy soil below. The data clearly demonstrate that biochar significantly enhances the water retention capacity of the upper soil layers, helping to maintain more stable moisture levels over time and so guaranteeing higher water availability for plants. In contrast, the untreated sandy layer exhibits lower water content, indicating the sharply decreasing of water content at the boundary between layers.

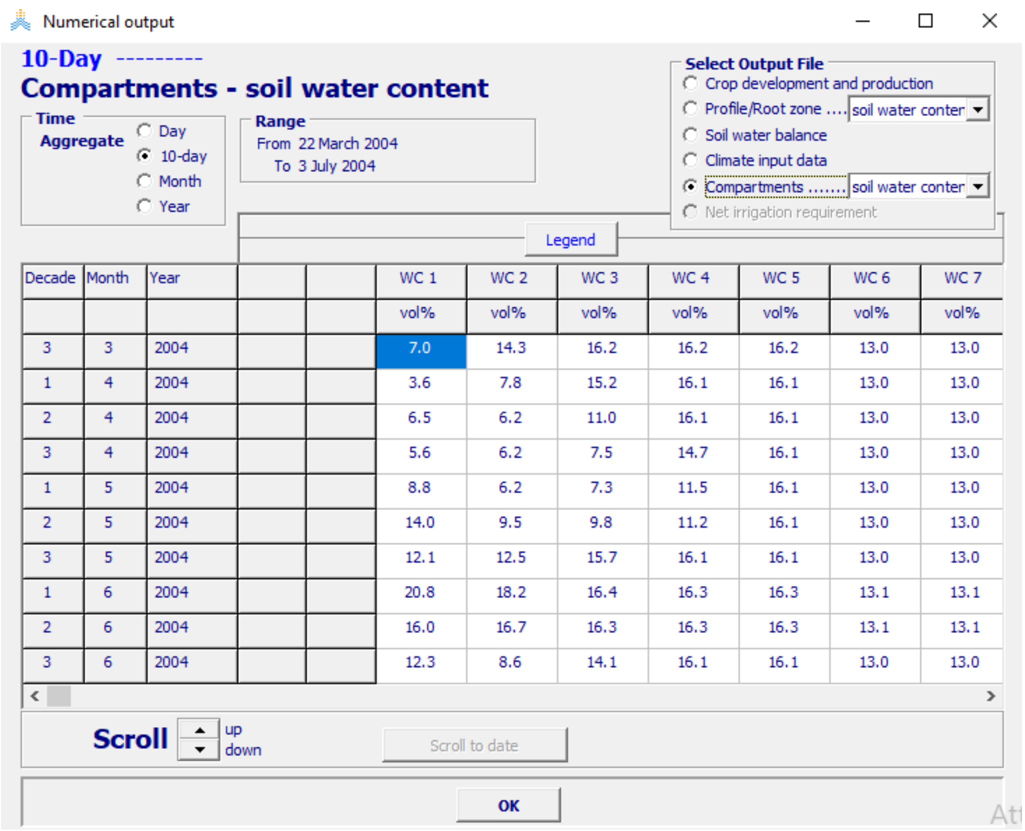

Figure 44: Water content at different soil's depth through time in sandy soil + BC50

11.3 Biochar in relation with crop response and leaf expansion results

In this section the focus is put on how biochar can sustain crop during stresses condition, in particular observing the difference between Wr and Wr(exp) under a defined schedule of irrigation events 19 on page 90. It is important to underline that Wr(exp) does not depend only on crop, but also on soil, climate and all other boundary conditions, so for each simulation there are different values of Wr(exp).
The simulation are performed only for loamy and sandy soil due to the relevance of the results of these two cases in previously simulations.

11.3.1 Sandy soil

10 days period	WR leaf expansion for sand + BC50 (mm)	WR leaf expansion for sand (mm)	Wr sand + BC50 and irrigation (mm)	Wr sand and irrigation (mm)
3	39,9	32,3	45,6	36,8
4	42,7	34,6	57,4	47,2
5	53,1	43	63,3	50,9
6	62,9	51	70,5	55,8
7	70,1	57,7	86,1	70,5
8	76,5	63,9	81,3	66,2
9	77,1	64,5	83,6	68,5
10	78,7	65,8	69,1	55,9
11	77,8	65,1	78,9	64,5
12	79	66,2	79,1	64,1

Table 33: Teff Wr and Wr(exp) in sandy soil with irrigation

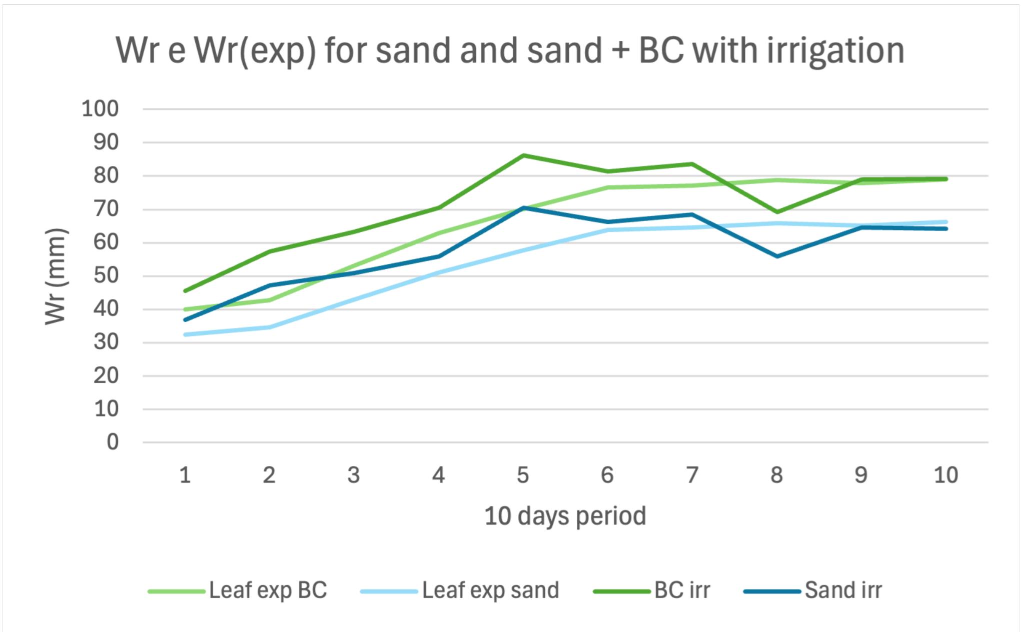

Figure 45: Wr and Wr(exp) trend for Teff in sandy soil with irrigation

Parameters	Sand + BC50	Sand
Biomass (%)	92	87
Biomass produced (t/ha)	6797	6461
Potential biomass (t/ha)	7419	7419
Dry yield (t/ha)	2048	1976
Drained water (mm)	387,6	403,6
Canopy exp (%)	3	6
Stomatal closure (%)	2	5

Table 34: Agricultural parameters for Teff in Foggia climate under a scheduled irrigation events in sandy soil

11.3.2 Loamy soil

10 days period	WR leaf expansion for loam + BC50 (mm)	WR leaf expansion for loam (mm)	Wr loam + BC50 and irrigation (mm)	Wr loam and irrigation (mm)
3	87,7	77,6	100,5	87,8
4	94	83,3	122,9	108,5
5	117	103,6	142,6	124,9
6	138,6	122,7	161,7	141,4
7	155,4	138,9	192,4	171,2
8	170,5	153,7	198,2	176,8
9	172	155,2	202,4	181
10	175,4	158,2	181,6	160,2
11	173,5	156,5	185,7	164,4
12	176,4	159,1	192,2	171

Table 35: Teff Wr and Wr(exp) in loamy soil with irrigation

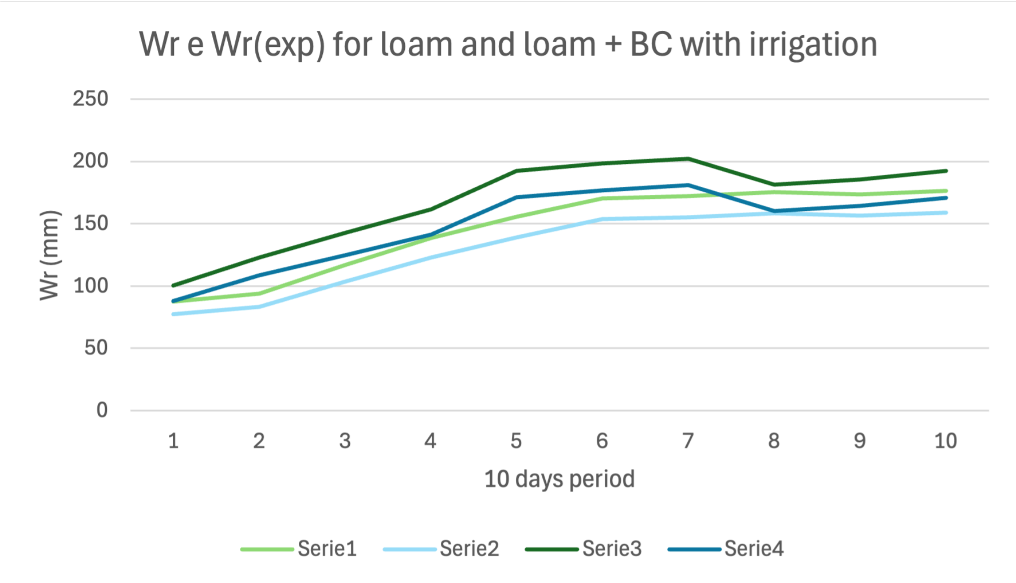

Figure 46: Wr and Wr(exp) trend for Teff in loamy soil with irrigation

Parameters	Loam + BC50	Loam
Biomass (%)	94	94
Biomass produced (t/ha)	6972	6944
Potential biomass (t/ha)	7419	7419
Dry yield (t/ha)	1888	1876
Drained water (mm)	344,3	343,2
Canopy exp (%)	no	no
Stomatal closure (%)	1	1

Table 36: Agricultural parameters for Teff in Foggia climate under a scheduled irrigation events in loamy soil

11.3.3 Results analysis

In this case, the results differ slightly, as biochar does not show any significant advantages in loamy soil in terms of productivity, water-holding capacity or stress reduction. Probably this is due to the already favorable environmental condition in relation with soil and crop type and so biochar addition could not bring any relevant advantages.
For sandy soil, also if results tells that the environmental condition are quite well, biochar helps a lot improving biomass production by 5%, reduce stress canopy expansion and stomatal closure by 3% and reduce drained water of 16 mm over all the growing period. However, in both cases, biochar addition demonstrates its ability to help retain water in soil as shown in 45 on page 105 and 46 on the previous page, which illustrate the differences between Wr and Wr(exp) for baseline soil and soil + BC50.
The graphs clearly show that with biochar application the amount of water exceeding the canopy expansion threshold is significantly higher compared to the baseline scenario. This is confirmed also in 37 where it shows the total water margin (abundance) in both conditions for two soil types (sand and loam). The addition of biochar consistently increases the water margin respect to canopy expansion threshold, confirming its beneficial effect on plant-available water. However, the effect is significantly more pronounced in sandy soil, where biochar enhances the water margin by 57,3 vol%, compared to 23,2 vol% in loamy soil. This highlights biochar's particularly strong potential to improve water retention in coarse-textured soils.

Soil type	Total Wr - Wr(exp) in soil + BC50 (mm)	Total Wr - Wr(exp) in baseline soil (mm)	Water abundance over canopy exp threshold with biochar addition (mm)	Percentage of water abundance
Sand	57,1	36,3	20,8	57,3%
Loam	219,7	178,4	41,3	23,2%

Table 37: Water abundance thanks to biochar addition respect to canopy expansion threshold

$$\% \text{ of water abundance} = \frac{(\text{Total Wr - Wr(exp) in soil + BC50}) - (\text{Total Wr - Wr(exp) in baseline soil})}{\text{Total Wr - Wr(exp) in baseline soil}} \quad (3)$$

For sandy soil, in the latest measures, Wr is lower than Wr(exp), but using biochar the gap between the available water and the expansion threshold is smaller and so this demonstrate the biochar ability in mitigate water stress. Moreover, figures 47 and 48 show the differences between the recorded Wr values and the threshold for Wr(exp). This highlights biochar's buffering capacity under water stress conditions. It is particularly interesting to observe in 47 that, even when Wr is lower than Wr(exp), the biochar treated soils still show a greater ability to support crops.

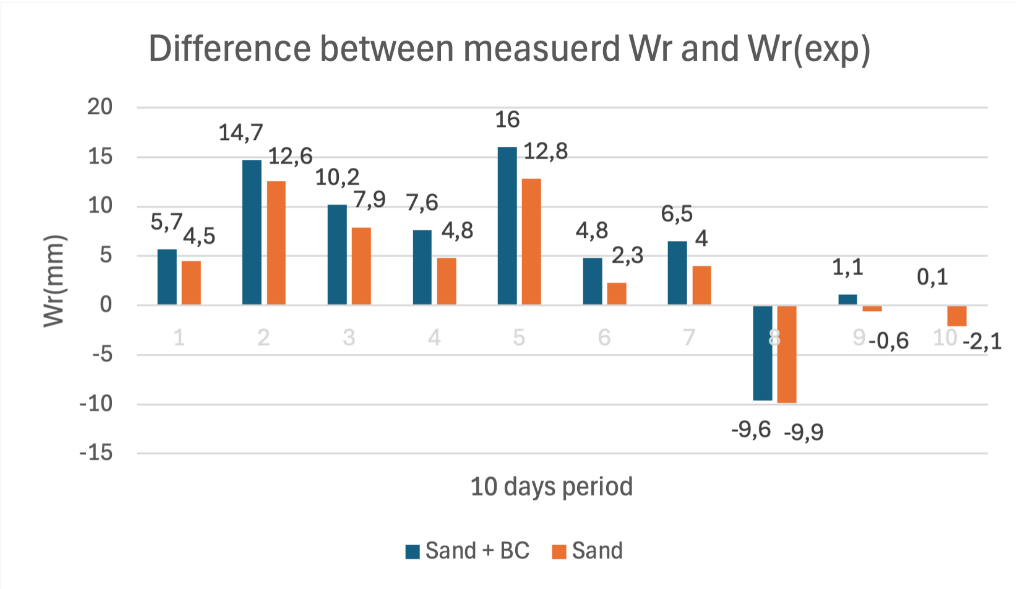

Figure 47: Differences between Wr and Wr(exp) for Teff in sandy soil

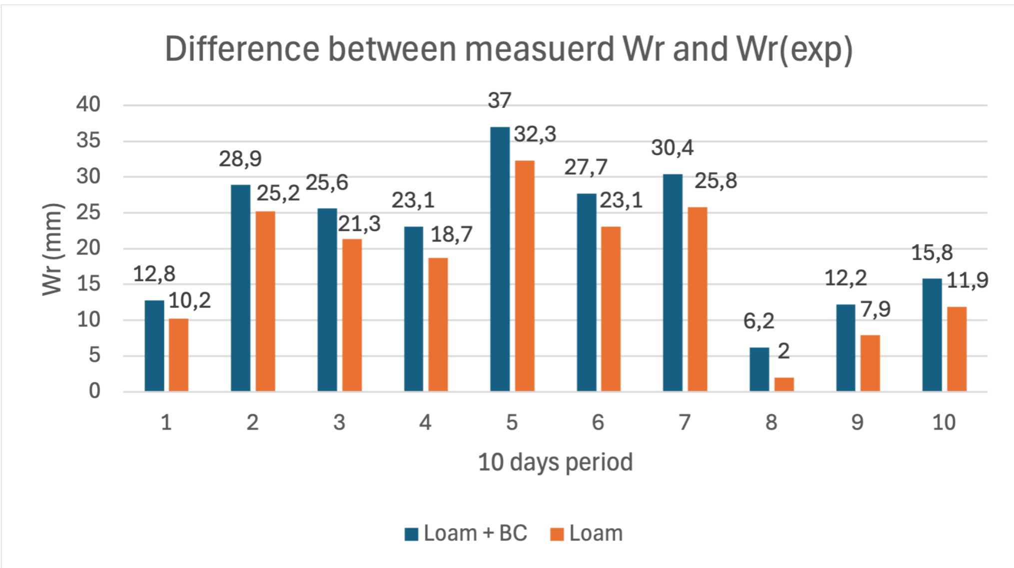

Figure 48: Differences between Wr and Wr(exp) for Teff in loamy soil

11.4 Crop response and volume water demand with irrigation results

For this section the aim was to observe irrigation efficiency and biomass changes for soils treated with biochar, looking at the overall year performances.
In following section is calculated also "Deep percolation*" that is defined in equation 2 on page 91, but it specifically considers only the volume of water that percolates below the root zone, excluding drainage that leaves the soil horizon on the first day. This adjustment is made to provide a more realistic estimate, removing water that does not contribute to crop growth.
The reason for including this initial excess water in the simulations is that, as previously explained, biochar is typically applied under wet conditions in real-world agricultural practices.

11.4.1 Teff

Parameters	Sand	Sand + BC50	Loam	Loam + BC50
Irrigation (mm)	600	600	600	600
Biomass ratio (%)	85	93	99	99
Drained wat (mm)	548,3	506,8	366,9	343,4
Total water content (mm)	120,2	134,8	298	318,9
Infiltrated (mm)	600	600	600	600
Drained first day (mm)	230	212,1	114,3	94,8
Deep percolation ratio	91,38%	84,47%	61,15%	57,23%
Deep percolation*	53,05%	49,12%	42,10%	41,43%

Table 38: Agricultural results with irrigation for Teff crop

11.4.2 Alfalfa

Parameters	Sand	Sand + BC50	Loam	Loam + BC50
Irrigation (mm)	1550	1550	1550	1550
Biomass ratio (%)	49	61	78	80
Drained wat (mm)	886,5	736,2	487,1	457,7
Total water content (mm)	109,2	120,4	274,4	292,6
Infiltrated (mm)	1550	1550	1550	1550
Drained first day (mm)	230	212,1	114,3	94,8
Deep percolation ratio	57,19%	47,50%	31,43%	29,53%
Deep percolation*	42,35%	33,81%	24,05%	23,41%

Table 39: Agricultural results with irrigation for Alfalfa crop

11.4.3 Results analysis

Analysis and Discussion of Results The tables 38 and 39 presented summarize the outcomes of simulations carried out for Teff and Alfalfa under controlled irrigation conditions, comparing baseline soils with those amended

with biochar applied in the top 50 cm.
In sandy soil, for Teff biomass ratio increases from 85% to 93%, and for Alfalfa, from 49% to 61%. These represent gains of 8% and 12% respectively. In contrast, in loamy soils, the effect is much smaller or negligible: biomass in Teff remains unchanged at 99%, while in Alfalfa it increases only slightly from 78% to 80%. These results confirm that biochar has a greater agronomic impact in coarser-textured soils and that it shows greater performances in if field is under stress.
Biochar also significantly reduces the volume of drained water, especially in sandy soils. For Alfalfa, the reduction reaches approximately 150 mm (from 886,5 mm to 736,2 mm), corresponding to a 17 vol% decrease in water loss due to drainage. Teff shows a similar trend, with drained water decreasing by around 42 mm (from 548,3 mm to 506,8 mm) in sandy soils. In loamy soils, the reductions are smaller but still present (23,5 mm for Teff and 29,4 mm for Alfalfa).
Notably, infiltration remains constant across all conditions, which confirms that improvements are due to changes in soil hydraulic properties rather than differences in water input. This is also confirmed by the fact that no run off was observed.
The deep percolation ratio shows a marked reduction with biochar. In sandy soils, the ratio decreases by about 6,9% for Teff and 9,7% for Alfalfa. Loamy soils show smaller improvements, with reductions of 3,9% and 1,9%, respectively.
When considering Deep Percolation*, which excludes drainage from the first simulation day to better isolate water that actively participates in crop processes, reductions are again more significant in sandy soils (4% for Teff and 8,5% for Alfalfa) than in loamy ones (0,6–0,7%). These findings indicate that biochar effectively retains more usable water within the root zone during the crop cycle, particularly in coarser soils.
Biochar-treated soils also show an increases in total water content at the end of the simulations. In sandy soils, the increase is approximately 12 vol% for Teff (from 134,8 mm to 120,2 mm) and 10% for Alfalfa (from 120,4 mm to 109,2 mm), whereas in loamy soils, the gain is slightly lower (7 vol% for both crops). This aligns with the observed improvements in biomass and reduced percolation losses. These performance increses are evaluated with same formula used before, equation 3 on page 108

11.5 Comparison C3 and C4 crops and biochar benefits results

The following data and graphs represent biomass and stress levels under low and high irrigation regimes, for both sandy and loamy soils, with and without biochar addition for Sugar cane (C4) and Alfalfa (C3).

11.5.1 Low irrigation regime

Parameteres	Sugar cane sand	Sugar cane sand + BC50	Alfalfa sand	Alfalfa sand + BC50
Biomass	72%	74%	68%	74%
Canopy expansion	27%	23%	53%	50%
Stomatal closure	21%	17%	22%	18%

Table 40: Biomass production and stresses under low irrigation regime for C3 and C4 crop in sandy soil

Parameteres	Sugar cane loam	Sugar cane loam + BC50	Alfalfa loam	Alfalfa loam + BC50
Biomass	80%	80%	84%	86%
Canopy expansion	14%	15%	43%	41%
Stomatal closure	14%	14%	10%	9%

Table 41: Biomass production and stresses under low irrigation regime for C3 and C4 crop in loamy soil

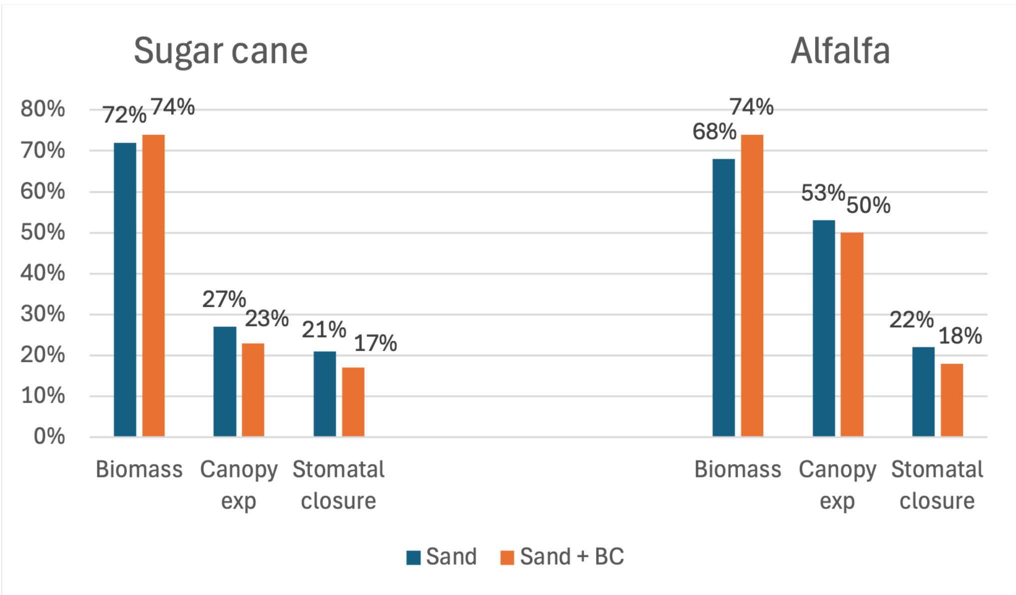

Figure 49: Comparison of Sugar cane and Alfalfa biomass production and stresses in sandy soil with low irrigation regime

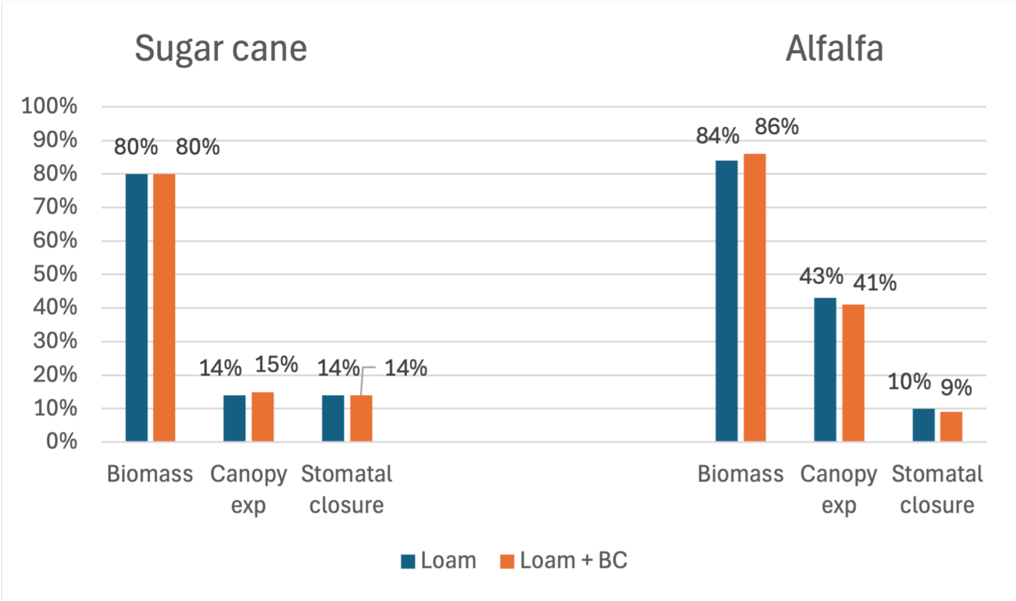

Figure 50: Comparison of Sugar cane and Alfalfa biomass production and stresses in loamy soil with low irrigation regime

11.5.2 High irrigation regime

Parameteres	Sugar cane sand	Sugar cane sand + BC50	Alfalfa sand	Alfalfa sand + BC50
Biomass	86%	89%	75%	81%
Canopy expansion	16%	10%	49%	45%
Stomatal closure	17%	15%	16%	12%

Table 42: Biomass production and stresses under high irrigation regime for C3 and C4 crop in sandy soil

Parameteres	Sugar cane loam	Sugar cane loam + BC50	Alfalfa loam	Alfalfa loam + BC50
Biomass	97%	98%	92%	94%
Canopy expansion	no	no	40%	38%
Stomatal closure	6%	5%	5%	4%

Table 43: Biomass production and stresses under high irrigation regime for C3 and C4 crop in loamy soil

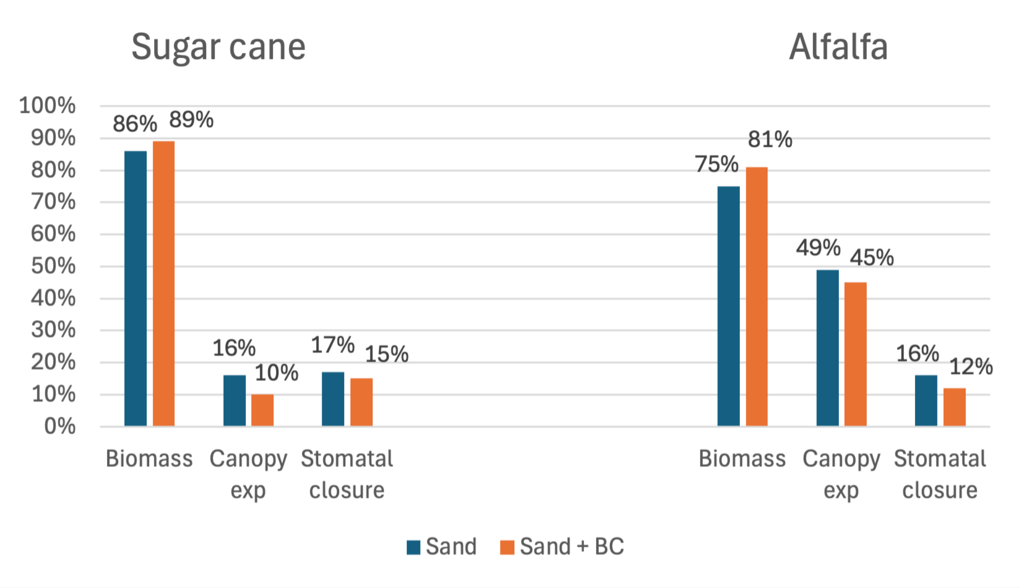

Figure 51: Comparison of Sugar cane and Alfalfa biomass production and stresses in sandy soil with high irrigation regime

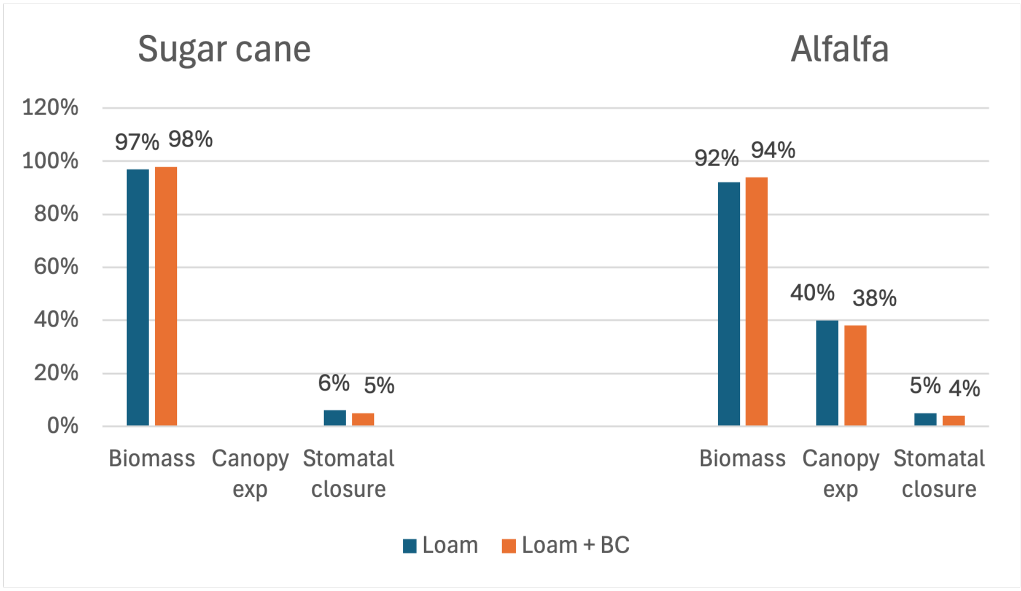

Figure 52: Comparison of Sugar cane and Alfalfa biomass production and stresses in loamy soil with high irrigation regime

11.5.3 Results analysis

In figures 53 on the following page, 55 on page 116, 54 on page 115 and 56 on page 116 are represented the differences in biomass production and stresses (canopy expansion and stomatal closure) in the comparison between C3 and C4 crops under low irrigation regime (53 on the following page and 55 on page 116) and high irrigation regime(54 on page 115 and 56 on page 116).
The results highlights, also if the difference is not so big, that for C3 crops biochar could help more than for C4 crops.

11.5.4 Sandy soil

Analysis of the data shows that sandy soils treated with biochar resulted in a 6% increase in C3 biomass production under both irrigation regimes, confirming biochar's ability to provide greater benefits under conditions of limited water availability compared to higher water content. This trend is also observed for C4 crops, although the increase is more modest (+2% under the low regime and +3% under the high regime).
Canopy stress indicators show a reduction under the low irrigation regime, with a -3% decrease in canopy expansion stress and -4% in stomatal closure, while in high irrigation regime and -4% for both stresses in C3 crops.
Better results are seen for C4 crops, with a -4% reduction for both stress types in low irrigation regime. Even better results in the high irrigation regime with -6% for canopy expansion and -2% for stomatal closure.
These trends confirm biochar's effectiveness in supporting crop development during the growth phase and in enhancing yield. Regarding biomass production, the positive effect of biochar is more evident in C3 plants, whereas for stress mitigation, the benefits in sandy soils appear to be comparable for both C3 and C4 crops.

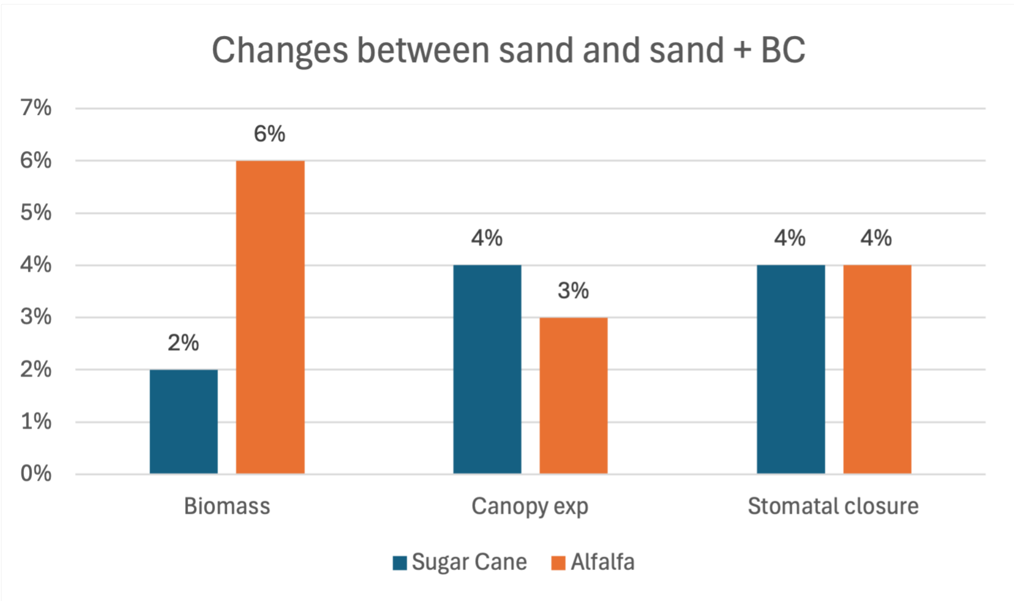

Figure 53: Differences between sand and sand + BC50 in biomass production and stresses with low irrigation regime for Sugar cane and Alfalfa

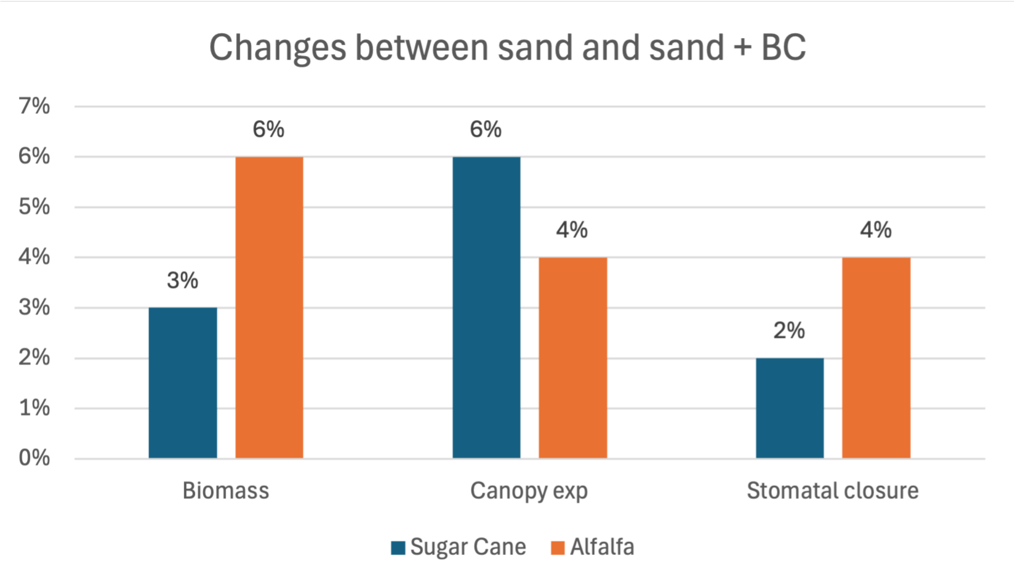

Figure 54: Differences between sand and sand + BC50 in biomass production and stresses with high irrigation regime for Sugar cane and Alfalfa

11.5.5 Loamy soil

In loamy soil for C3 crops results are a bit less evident than in sandy soil but the trend is the same: in low irrigation regime biomass production increase by 2%, canopy expansion stress reduce by 2% and stomatal closure stress reduce by 1%, while in high irrigation regime same effect as before except for stomatal closure stress that reduce only by 1%.
For C4 crops, there are not relevant improvements and this highlight the fact that for this type of crops biochar addition gave less benefit than for C3 crops. Results tells that in low irrigation regime biomass and stomatal closure stresses does not change, while canopy expansion even increase by 1%.

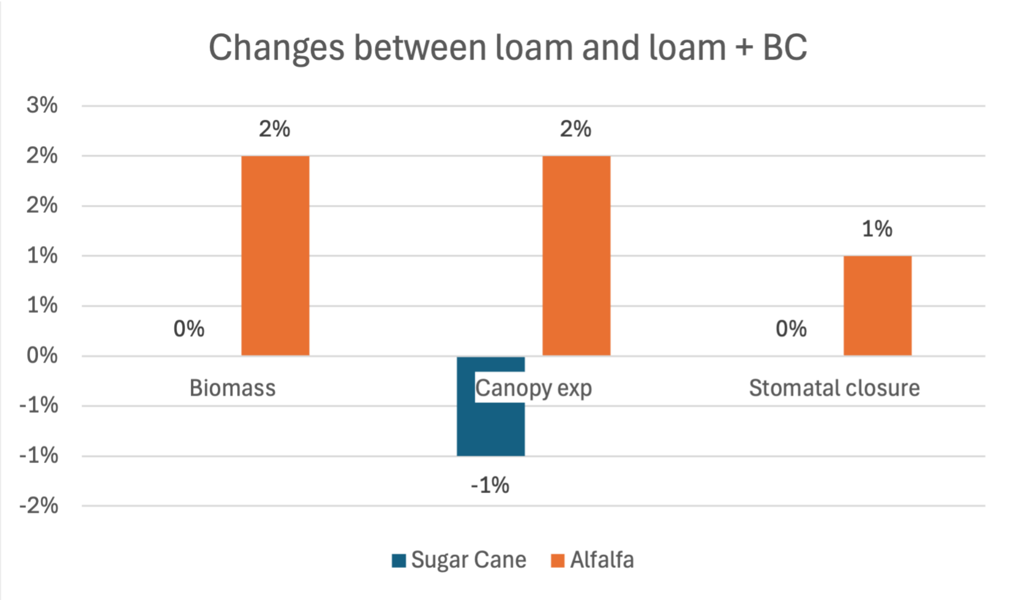

Figure 55: Differences between loam and loam + BC50 in biomass production and stresses with low irrigation regime for Sugar cane and Alfalfa

In high irrigation regime biomass production increase by 1%, canopy expansion stress does not change and stomatal closure stress reduce by 1%.

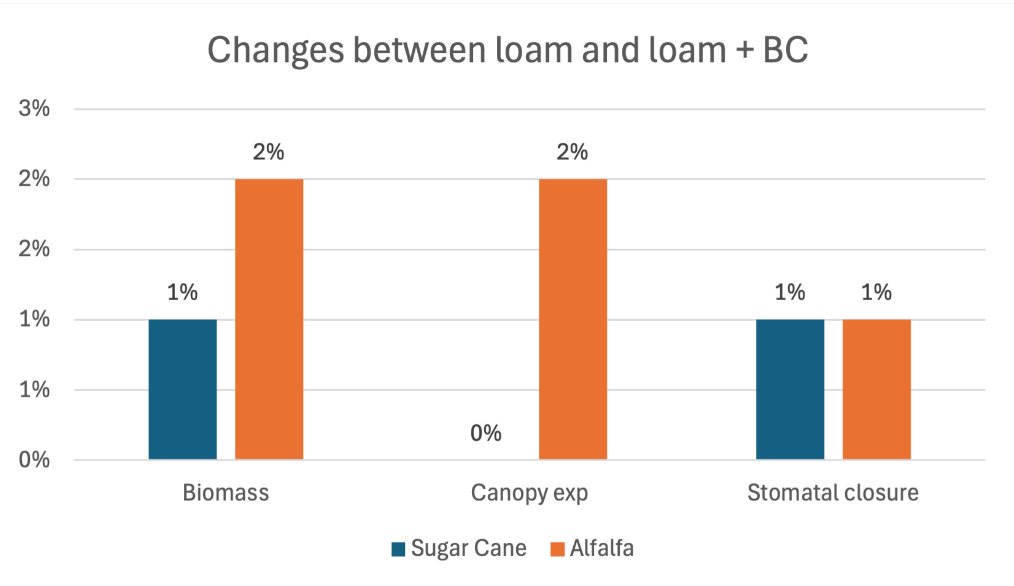

Figure 56: Differences between loam and loam + BC50 in biomass production and stresses with high irrigation regime for Sugar cane and Alfalfa

The results confirm the potential of biochar for C3 crops and sandy soils. Its positive effects are especially evident under water stress conditions, improving crop productivity and reducing physiological stress. For C4 crops in loamy soil biochar addition does not bring relevant results, while in sandy soil gives more benefits.

12 Conclusions

This work aimed to explore the world of biochar, with a focus on its technological, economic, and application aspects within the context of sustainable agriculture.
The first objective was to assess the feasibility for farmers to effectively integrate biochar into agronomic practices, considering the current economic and regulatory constraints. The business analysis highlights two contrasting aspects: on one hand, the opportunity offered by carbon offsetting to generate revenue; on the other, the high production costs of biochar, mainly due to the initial investment in equipment and the transportation costs, which significantly increases the final price for the customer and often makes its use economically unfeasible.
A critical issue is the lack of synergy between environmental benefits and economic return: most producers do not benefit financially from the ecological advantages that biochar provides and, consequently, adoption remains low, especially in Europe.
Unless used under very favorable conditions or supported by incentives, biochar alone is not always economically sustainable for farmers. This situation is exacerbated by the complexity of the regulatory frameworks and the strict requirements imposed by law. Moreover, participation in the carbon offset market requires compliance with additional standards, which are often more restrictive than existing regulations and further limit operational freedom.
Currently, generating revenue solely from biochar sales is challenging, though not impossible, with Northern Europe serving as a positive example. At the moment, a crucial role is played by wood distillate, which remains essential for the Italian biochar industry to achieve economic viability. Encouragingly, market analyses report steady growth, with a 3-year CAGR of 54%, indicating increasing competitiveness in the carbon sequestration sector, alongside reduced waste generation and disposal needs.
Among non-agricultural applications, promising uses of biochar have emerged in construction materials and asphalt. These are traditionally high polluting sectors where biochar can significantly reduce environmental impact by storing carbon without compromising material quality or stability. Additionally, these applications allow for the use of lower quality feedstock, as the biochar is encapsulated within the final product, minimizing environmental interaction. Once again, the development of this market niche could be supported by a regulatory framework that recognizes biochar as a construction material, with clearly defined rules, which are currently lacking.
Surely, a key driver for the future will be the inclusion of biochar in the regulated carbon credit market, which would substantially boost demand. To contextualize, the regulated carbon market generated 152 billion € over the last decade, compared to only 2 billion € from voluntary markets. This integration can be achieved only through continued demonstration of biochar's carbon sequestration potential, waste reduction capabilities, and benefits in both agricultural and non-agricultural contexts. This highlights the strategic importance of associations such as IBI and ICHAR, which are pivotal to the future of the biochar industry.

A key selling point for practical application is its ability to reduce nutrient leaching, lowering costs for farmers and minimizing pollution, as discussed in Section 9.4.1 ("A General Overview on Urea and Biochar").
Overall, the future of the biochar market appears highly promising, provided there is increased confidence in carbon credits and strong collaboration among stakeholders to simplify participation and reduce bureaucratic burdens.
Focusing on agricultural applications, biochar proves to be a powerful tool for sustainable agriculture, particularly in environments with poor soil fertility or unfavorable conditions. As shown in the meta-analyses, real world agricultural experiments indicate yield increases of 13–16% and water availability improvements of 8–15%, results that are partially confirmed by AquaCrop simulations.
In particular, the most significant yield improvement was observed in table 39 on page 109, with a +12% increase in biomass production on sandy soils with biochar addition. Other yield improvements were more modest, typically ranging from 5–8%, especially under less limiting conditions (simulations 2 to 5).
Sandy soils showed the best results, followed by loamy soils (yield increase of 2–5%), while clay soils showed negligible benefits. This trend is consistent with findings from the literature, which also highlight the stronger effect of biochar on coarse-textured soils.
Regarding water retention and increased water availability, expectations were confirmed only for sandy soils. As shown in table 24 on page 98, biochar applied at 50 cm depth increased water availability in the root zone by 11,4%, and by 7,5% when applied within the top 30 cm. Loamy soils showed modest increases (3–4%), while improvements in clay soils were negligible. Figure 44 on page 103 visually confirms biochar's ability to retain more water by altering soil structure and physical properties.
Deep percolation analysis (38 on page 109 and 39 on page 109) further supports biochar's effectiveness in water conservation, particularly in sandy soils, where up to 12% of irrigation water can be saved, contributing to reduced agricultural environmental pressure. Water productivity also improved with biochar use, as shown in table 31 on page 102, with gains of 13,7% in sandy soils, 7,3% in loamy soils, and 4,2% in clay soils.
These outcomes are closely related to one of the most innovative aspects of this work: the analysis of reduced water stress due to biochar. As shown in figure 37 on page 107, biochar addition increased water margin over the leaf expansion threshold by 57,3% in sandy soils and 23,2% in loamy soils, demonstrating its capacity to support crop growth under stress conditions.
Another way to observe biochar's ability to support crops during drought periods is shown in figures 47 on page 108 and 48 on page 108, where the buffering effect of biochar is demonstrated by the fact that the water margin exceeding Wr(exp) is consistently higher in treated soils compared to untreated ones. In general, simulations indicate that biochar led to a stress reduction of up to 4%.
Lastly, the analysis of C3 and C4 crops provides numerical support to the findings of Stephen Joseph et al. (2024), confirming biochar's greater positive impact on C3 crops. In sandy soils, biomass production increased by 6% for

C3 crops and 2% for C4 crops, with water stress reductions of 4% and 3–4%, respectively 53 on page 114 and 12 on page 65.
Some deviations from theoretical expectations can be explained by the nature of the AquaCrop model, which is based on hydrological processes and does not account for other biochar-related benefits, such as enhanced nutrient cycling, pH modulation, root biomass increase, microbial biodiversity, or resistance to disease stresses.
For this reason, future developments should include simulation tools that go beyond hydrology to fully capture the complexity of agricultural systems developing a more comprehensive simulation tool.
Institutions like FAO, IBI, or EBC should take the lead in promoting and funding the creation of such tools, potentially integrating carbon credit valuation and modeling the economic balance, taking into account increased yields, reduced input costs, and revenues from carbon offsets. Biochar can only fulfill its potential within a circular economy framework if supported by technological innovation and a coordinated effort across economic, political, and technical sectors.
Such synergy is essential to transform its environmental benefits into real-world impact.

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