INNOVATIVE PYROLYSIS REACTOR DESIGN FOR ENHANCED PERFORMANCE AND SUPERIOR BIOCHAR QUALITY
/
REACTOR INOVATOR DE PIROLIZĂ PENTRU O PERFORMANȚĂ ȘI O CALITATE SUPERIOARĂ ÎMBUNĂTITĂ A BIOCHARULUI

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ABSTRACT
The three high-valuable products generated by the pyrolysis process are the biochar, the syngas, and the pyrolysis oil. The proportions of these products are influenced by several factors such as temperature, heating rate, and feedstock type. This research aimed to develop an innovative and improved pyrolysis reactor design, that can enhance both the quality and yield of biochar produced in thermochemical processes. The main objective was to enable the rapid conversion of various organic wastes, such as agricultural byproducts, wood chips, and other plant-based materials, into high-quality biochar. The experimental pyrolyzer model was designed with precise temperature control to optimize biochar properties and an intelligent process control system, which minimize emissions and maximize energy efficiency. This equipment not only contributes to sustainable waste management but also supports soil improvement by enhancing soil fertility and carbon sequestration in agricultural practices. The experimental results showed a high efficiency in obtaining a quality biochar within a short production time. Additionally, the biochar exhibited a water retention potential of up to 150% relative to the pre-treated biomass mass, while the energy consumption was estimated to be up to 15% lower compared to conventional methods.

REZUMAT
Cele trei produse de mare valoare generate de procesul de piroliză sunt biocharul, gazul de sinteză și uleiul de piroliză. Proporțiile acestor produse sunt influențate de mai mulți factori, cum ar fi temperatura, viteza de încălzire și tipul de materie primă. Prezenta cercetare a avut ca scop dezvoltarea unui proiect inovator de reactor de piroliză îmbunătățit, care poate îmbunătăți atât calitatea, cât și randamentul biocharului generat în procesele termochimice. Obiectivul principal a fost acela de a permite conversia rapidă a diferitelor deșeuri organice, cum ar fi produse secundare agricole, așchii de lemn și alte materiale pe bază de plante, în biochar de înaltă calitate. Modelul experimental de pirolizator este proiectat cu un control precis al temperaturii pentru a optimiza proprietățile biocharului și un sistem inteligent de control al procesului, care minimizează emisiile și maximizează eficiența energetică. Acest echipament nu numai că contribuie la gestionarea durabilă a deșeurilor, dar oferă și o îmbunătățire a solului, îmbunătățind fertilitatea solului și captarea carbonului în practicile agricole. Rezultatele experimentale au arătat o eficiență ridicată în obținerea unui biochar de calitate, într-un timp scurt de producție. Rezultatele experimentale au arătat o eficiență ridicată în obținerea unui biochar de calitate, cu un potențial de înmagazinare a apei de pana la 150% raportat la masa de tulpina înainte de tratare si un consum de energie estimat cu pana la 15% mai mic.

INTRODUCTION
Pyrolysis is a thermochemical process. It allows a controlled combustion of biomass in an oxygen-limited environment, generating both thermal energy and sterilized biochar (*Amalina et al. 2023; Nenciu et al., 2024*). Usually, upon completion of the thermochemical process, a significant amount of fixed carbon results in the form of biochar (between 10-20% of the initial mass), which can be used as an agricultural amendment. The gases generated during the process can be used to produce the thermal energy necessary to heat protected spaces or fruit dryers.

The industrial pyrolysis process offers a competitive alternative for the exploitation of numerous renewable energy sources, but also for the treatment and energy recovery of municipal, industrial or medical waste from various polluting industrial branches. The pyrolysis process is considered the most environmentally friendly thermochemical process, compared to combustion and incineration processes, because it has low emissions (*Farag et al., 2024*).

Biochar is an organic product resulting from the pyrolysis process of plant materials such as sawdust, straw or other agricultural waste. A common example of the use of pyrolysis is the conversion of plastic waste or biomass into liquid or gaseous fuels that can be used in various industrial or energy applications (*Tomczyk et al., 2020; Wang et al., 2021*). This process takes place at high temperatures, usually between 300 and 700 degrees Celsius, in an oxygen-limited environment (*Amalina et al., 2022; Sun et al., 2017; Buss W, 2021*). The resulting biochar has a porous structure and is considered a valuable soil amendment (*Salma et al., 2024*). Biochar contains approximately 98% carbon, which gives it chemical stability and the ability to retain nutrients in the soil. This composition makes it an effective amendment for improving soil quality (*Woolf et al., 2010; Yang et al., 2021; El-Naggar et al., 2019*).

The role of Biochar is to maintain moisture and stimulate beneficial microorganisms in the soil. These microorganisms are essential for plant health, as they contribute to the decomposition of organic matter and the availability of nutrients (*Nidheesh et al., 2021*). Among the most used materials are wood waste *(Ahmad et al., 2017)*, agricultural residues (*Zhang et al., 2022, Voicea et al., 2024*), vegetable waste, manure (*Wang et al., 2021; Jang et al., 2022; Nenciu et al. 2023*), or industrial waste. Each of these raw materials has different characteristics that influence the final quality of the biochar produced. For example, the chemical composition and physical structure of biomass will determine the levels of fixed carbon and its ability to retain nutrients and water in the soil (*Feng et al., 2021; Issaka et al., 2022; Oprescu et al. 2022*).

The use of these raw materials not only helps create a valuable product such as biochar, but also contributes to the sustainable management of natural resources by recycling organic materials that might otherwise end up in landfills (*Neogi et al., 2022; Voicea et al., 2024*). The versatility of biochar highlights high potential in various industries, from agriculture and water treatment to animal husbandry. In a context where economic and commercial factors influence market dynamics, continuous innovation and research are essential to keep the biochar industry at the forefront of technological progress (*Nenciu et al., 2024; Popescu et al., 2022*).

Biochar has a complex porous network, which facilitates water absorption and retention, the size and distribution of the pores influence the water storage capacity, allowing it to retain moisture in the soil. It has many benefits such as: improving soil fertility (helps maintain moisture, which is essential for plant growth), reducing irrigation needs (by retaining water, biochar can reduce the frequency and amount of water needed for irrigation), stabilizing nutrients (preventing nutrient loss through leaching, thus maintaining a favorable environment for plants). Factors that influence the water storage potential are: the type of biomass used, pyrolysis conditions and interaction with the soil (*Liu et al., 2015; Lone et al., 2015*).

The objective of this work was to realize an improved design of a reactor for increasing the quality of biochar used in agricultural activities. After designing and building an Experimental Model of the equipment, it was tested for the treatment of plant waste from hemp and bamboo crops, in order to highlight the qualities of the obtained biochar and analyze the energy consumption.

MATERIAL AND METHODS

Experimental model design, customized for the pyrolysis of lignocellulosic biomass

This paper introduces an Experimental biochar production equipment designed and produced by the National Institute of Research - Development for Machines and Installations Designed for Agriculture and Food Industry - INMA Bucharest (Romania), distinguished by a series of innovative constructive elements. These advancements include enhancements in thermal efficiency, precise temperature control systems, and optimized batch management processes, all aimed at improving the quality and consistency of the resulting biochar. The equipment leverages smart control technologies for real-time monitoring and adjustment of critical parameters. This experimental setup is presented in figure 1.

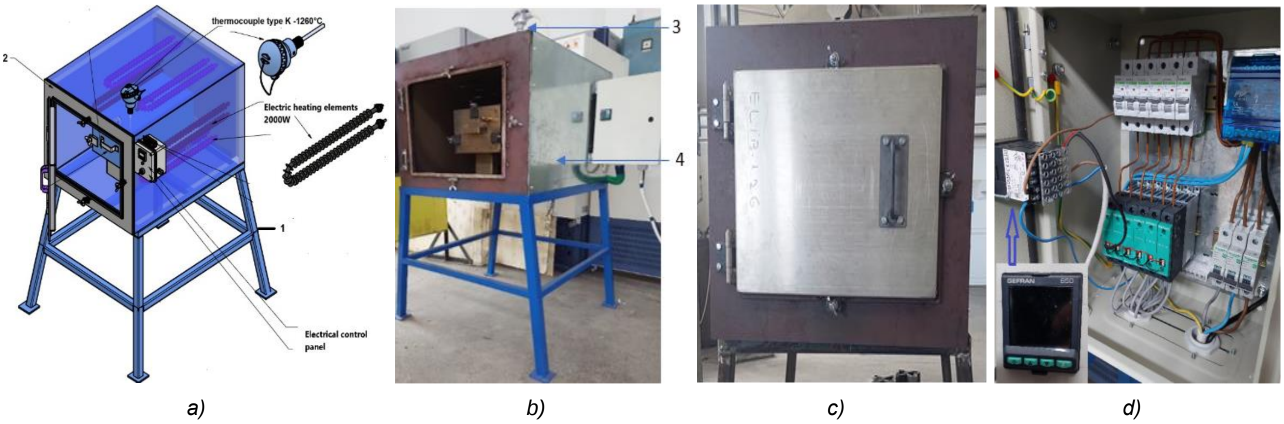

Fig. 1 – Experimental model for biochar production-general assembly

a) experimental model for biochar production; b) retort; c) equipment case; d) electrical control panel

The experimental model (figure 1-a) is customized for processing vegetable waste, consisting of a support (1) that supports a housing (2) with the actuation and control elements. This equipment features an automated system for managing the thermal process within a low-oxygen environment. The system incorporates an advanced electrical control panel (figure 1 d) that precisely regulates the combustion process, significantly reducing the time required to produce the biochar. To further enhance efficiency, the design allows for rapid replacement of the retort after each batch. By utilizing the residual high temperature within the enclosure from the initial production cycle, the new retort minimize downtime between batches. The casing (figure 1-c) is made of two galvanized tanks, suitable for corrosive industrial environments. The two casings are mounted concentrically and are insulated from each other with a ceramic fiber resistant to very high temperatures (up to 1260°C), in order to eliminate thermal energy losses. On the casing bottom and ceiling there are six electric resistances mounted around the retort (2000 W each). An overpressure valve and a high temperature thermocouple (3) are also mounted on the casing. The working temperatures are 300-500 °C for straw and other vegetable residues and 600 °C for forestry residues. The retort, illustrated in figure 2 (a), is constructed from high-temperature-resistant stainless steel (17 255 CSN, AISI 310). This material ensures durability and performance under intense thermal conditions. The retort is equipped with a discharge opening, featuring a frame (figure 2 -b) that supports three eye bolts (figure 2 -a) for securely attaching the biochar lid. For ease of handling and transportation, a handle is mounted on both the upper casing and the lid. With a capacity of 19 liters, the retort is designed to accommodate significant quantities of raw material, enhancing batch efficiency and overall productivity. The electrical resistances are presented in figure 2 b, c.

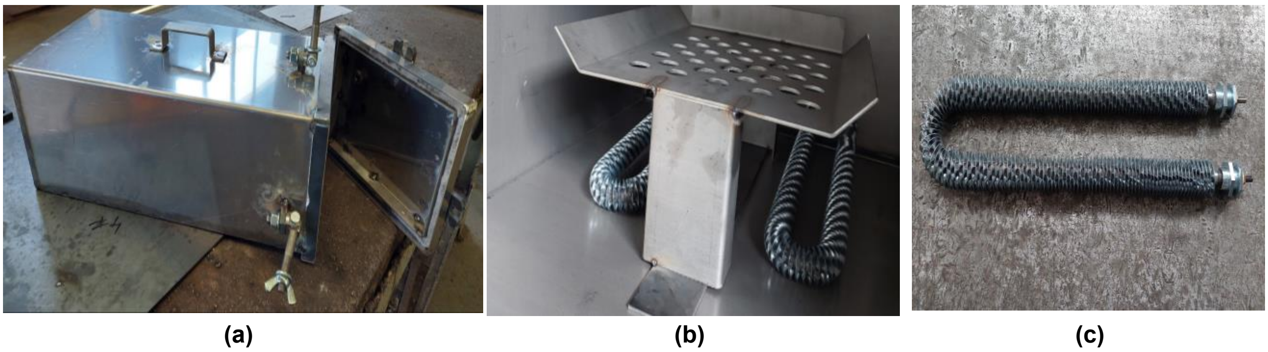

Fig. 2 - Heat treatment of organic material using a retort and electrical resistance

a) retort; b) retort support; c) electric resistances

The present experiment evaluated hemp and bamboo stems. Their high lignocellulosic content makes them well-suited for this process, yielding porous biochar with excellent water retention properties. Hemp and bamboo are fast-growing and renewable resources that may serve as sustainable feedstocks for biochar production. The stems were harvested in August, being sectioned at 1 meter in length and stored in a dry room, as can be seen in figure 3.

(a) (b)

Fig. 3 - Hemp and bamboo stems harvested for pyrolysis processing operations

(a) Hemp stalks and (b) bamboo stems

The stem pre-processing involved cutting the plants to a maximum length of 7 cm using a circular saw. The average moisture content of the bamboo and hemp was then determined using the oven-drying method. In this process, a sample was weighed (Figure 4a and b), dried in an oven at 105°C for 24 hours (Figure 4c), cooled in a desiccator, and then reweighed.

(a) (b) (c)

Fig. 4 - Raw material processing

a) hemp; b) bamboo; c) drying of the raw material

Thermochemical processing method of plant materials using pyrolysis

The processing method involves opening the upper lid of the retort and loading the shredded raw material, which was shredded to a length of approximately 7 cm, for a faster processing. Once the material is loaded, the electric resistance is activated in order to initiate heating. The thermic process begins for a period that varies depending on the granulation and moisture content of the raw material, typically ranging from 30 to 120 minutes. This approach ensures efficient pyrolysis tailored to the characteristics of the raw input material. To prevent biochar oxidation, the retort was cooled by immersion in cold water for 30 minutes, then extracted and temporarily stored in a desiccator to maintain its stability until further experimental analysis.

Assessing the Water Retention Capacity of Biochar

Biochar derived from different biomass sources exhibits varying water retention properties. To evaluate these characteristics, the water storage capacity of biochar produced from bamboo and hemp was analyzed. The biochar samples were placed in a vessel, weighed (Fig.5), and then immersed in water for 2 minutes. After this interval, the excess water was drained, and the samples were weighed again. This procedure was repeated five times to ensure accuracy, for 24 hours. This approach provided a comprehensive understanding of the water retention capabilities of biochar over different timeframes.

Fig. 5 - Different phases during the experiments to evaluate the water storage potential in biochar

In order to determine the dry biochar density, a 1000 ml vessel was filled with bamboo biochar and then weighed. This process was repeated 10 times for each type of material to ensure accuracy and account for potential variations in particle arrangement and compaction. The average values were then calculated to provide a more reliable density measurement, using equation (1).

$$\rho = \frac{m}{v} \qquad (1)$$

where ρ is the density (kg/L), m is the biochar mass (Kg) and v is the biochar volume (L)

RESULTS

Given that the moisture content of hemp and bamboo varies along the stem length, three representative sections were analyzed for each feedstock: the lower, middle, and upper parts of the stem. Table 1 presents the moisture content of bamboo and hemp stems, from different plant parts, after being stored for three months following harvest.

Table 1

Feedstocks moisture content

Plant part	Stem moisture average content %	
	Bamboo plant	Hemp plant
Lower part of the stem	17	21
Middle part of the stem	18	23
Upper part of the stem	15	22

The temperature during the pyrolysis process was carefully adjusted to minimize the loss of organic matter through gasification. This controlled approach aimed to optimize the conversion efficiency, ensuring a higher yield of biochar while preserving key carbon fractions. Figure 6 illustrates the temperature increase rate during the experiment, using the pyrolysis experimental model. This evaluation was particularly useful for equipment calibration when using organic materials that present different densities.

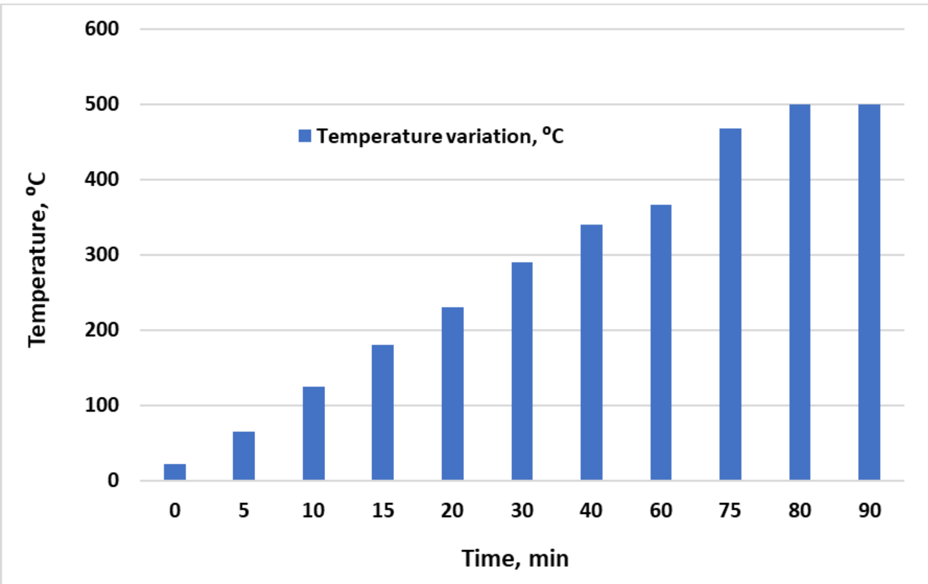

Fig. 6 - Temperature variation over time during pyrolysis equipment operation

The evaluation of biochar density after the completion of the process revealed a density for bamboo biochar of 0.2315 kg/L, while the density of hemp biochar was 0.0985 kg/L.

The cooled biochar was then weighed to evaluate the loss of material through gasification of organic material. It can be observed that the biochar obtained from bamboo lost 68.89% of its weight and the biochar obtained from hemp lost 81.96% of its weight. Hemp and bamboo stems were selected due to the shape of the stem, which has an inner hole that has a larger contact surface and allows a faster absorption of water (table 2).

Table 2

Feedstocks mass variation induced by the biochar production process

No.	Feedstocks for biochar production	Unprocessed material (kg)	Processed material (biochar) (kg)	Difference (%)
1	Bamboo biochar	0.8045	0.2503	68.89
2	Hemp biochar	0.4496	0.0811	81.96

Energy consumption per unit of time

In 1.4 hours needed to fully process the stems through pyrolysis, energy consumption reached 16.8 kWh. Based on average energy costs in Romania, this corresponds to approximately 4.1 EUR per batch. However, due to differences in plant density, the biochar yield per batch was 0.400 kg for hemp and 0.900 kg for bamboo.

Daily Productivity Calculation of Equipment

Considering that the equipment is fitted with two retorts (allowing for continuous operation without interruptions), the maximum productivity per hour is 0.29 kg/h for hemp and 0.64 kg/h for bamboo. Over an 8-hour workday, the total output reaches 2.29 kg for hemp and 5.12 kg for bamboo. Figure 7 illustrates the water storage capacity of the biochar mass, after it was immersed in water for 24 hours. The aim of the experiment was to evaluate the maximum water storage capacity within the biochar structure, simulating moisture retention in the soil.

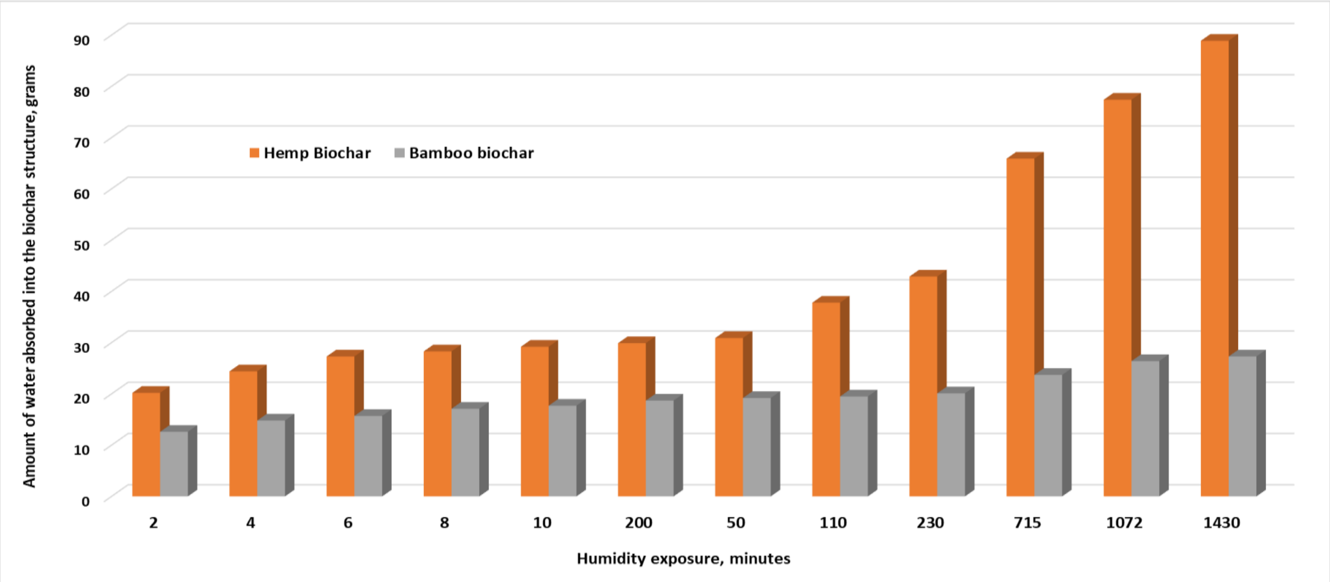

Fig. 7 - Water storage potential in biochar depending on water soaking time

Table 3 shows the water storage potential over time, the bamboo biochar stored a quantity of 27.3 grams in the 1430 min, that is 47.80%, and the hemp biochar stored a quantity of 88.9 grams, that is 150.17%.

An important indicator to consider is the percentage of water that each type of heat-treated material can retain relative to its own mass.

The stem fiber used to produce the biochar was found to play a crucial role in water storage capacity. Table 3 presents the water storage rate relative to the initial mass of each experimental plant. This analysis helps identify which structure offers the most effective storage solution.

Table 3

Water storage rate relative to the initial plant-mass

No.	Biochar type	Dry mass of biochar (gram)	Water storage potential as a percentage of biochar dry mass (%)									
			2 min	4 min	6 min	8 min	10 min	20 min	50 min	110 min	230 min	1430 min
1	Bamboo biochar	132.6	34.12	41.22	46.11	47.80	49.32	50.51	52.20	63.85	72.47	150.17
2	Hemp biochar	59.2	10.86	13.11	14.68	15.22	15.70	16.08	16.61	20.32	23.06	47.80

Discussions

Following the process of pyrolysis the material in the retort for biochar production, a significant difference was observed in the weight losses of the materials used. After cooling the biochar obtained from bamboo, it showed a weight loss of 68.89%, indicating that a considerable proportion of the original material was transformed into gases and vapors during the pyrolysis process. On the other hand, the biochar obtained from hemp had an even higher loss of 81.96%, thus suggesting that the gasification process was more pronounced for the latter. These results underline not only the efficiency of different biomasses in biochar generation, but also their high potential in the context of biochar production from organic waste. Analyzing these processes can provide valuable information for the optimization of biochar production and the efficient use of available resources.

Hemp biochar demonstrated a significantly higher water storage capacity compared to the bamboo biochar, having a better water storing potential (150.17% calculated in relation to the initial processed mass). These results suggest that hemp biochar could be more effective in improving soil water retention, which could be beneficial for agriculture, especially in arid conditions.

CONCLUSIONS

- The equipment allows a very fine adjustment of the temperatures, depending on the vegetable material, in order to customize the pyrolysis processes according to the structure of the vegetable waste. Thus, pyrolysis is improved for treating a variety of vegetable materials, keeping the high characteristics of biochar and avoiding overheating.

- The equipment consumes little energy compared to other equipment. On the one hand, this energy saving results from the advanced temperature regulation system (PLC and sensors) and on the other hand, due to the very good insulation of the thermal chamber-reactor. The circular arrangement of the electrical resistances also helps in efficient heating of the material.

- The retort type system helps to maintain a larger amount of biochar in the solid phase at the expense of gases and oils. Therefore, it is a better constructive design for the management of vegetable waste, for the purpose of use in agriculture. Constructive variants that maximize biogas and oils are more efficient for energy and industrial applications, but the proposed objective was to obtain a larger amount of biochar.

- All the adjustment of the equipment manages to increase the porosity, so that the biochar managed to store up to 150% water for bamboo (relative to the mass of the stem before treatment) and 47% water for hemp.

- The reduction in mass by 68.89% for bamboo stalks and 81.96% for hemp stalks is important because it reduces the costs of transporting the biochar from the farm to the agricultural land where it is applied.

- *The obtained biochar offers multiple benefits in agriculture and for the environment, such as:*

• Improving soil fertility: Biochar can retain nutrients and water in the soil, which improves soil fertility. It can also reduce nutrient loss through runoff.

• Reduction of carbon emissions: The production process of biochar involves the capture and storage of carbon from organic materials, due to its chemical stability, biochar can store long-term carbon in the soil.

• Improving soil structure: Biochar can improve soil structure, favoring the development of plant roots and improving its drainage.

• Remediation of degraded soils: Biochar can be used to remediate degraded soils, such as those that are saline or those affected by pollution.

• Promoting sustainability in agriculture: The use of biochar in agricultural practices can contribute to greater sustainability of agricultural systems, reducing reliance on chemical fertilizers and pesticides.

• Improving water retention: Biochar has the ability to retain water in the soil, which can be beneficial in water-scarce areas or during periods of drought. Adding biochar to sandy soils reduces irrigation requirements by up to 40%.

• Reduction of greenhouse gas emissions: By sequestering carbon in the soil and reducing methane and nitrous oxide emissions, biochar can help reduce greenhouse gas emissions from the soil.

• Improved plant health: Soils treated with biochar can support healthier crops that are more resistant to diseases and pests.

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