engineering proceedings

MDPI

Proceeding Paper

Turning Waste into Soil Conditioner with a Sustainable Innovative Approach: Biochar †

Hakan Çelebi *, Tolga Bahadır, İsmail Şimşek and Şevket Tulun

Department of Environmental Engineering, Aksaray University, 68100 Aksaray, Turkey; tolgabahadir61@gmail.com (T.B.); ismailsimsek@aksaray.edu.tr (İ.Ş.); stulun@aksaray.edu.tr (Ş.T.)
* Correspondence: hakancelebi@aksaray.edu.tr; Tel.: +90-382-288-35-98
† Presented at the 4th International Electronic Conference on Applied Sciences, 27 October–10 November 2023; Available online: https://asec2023.sciforum.net/.

Abstract: Globally, the increase in population density, various epidemics (COVID-19, SARS, MERS, etc.), climate change, global warming, and the reduction of arable land have caused damage to the ecosystem. Quality soil is the most important factor that has a direct impact on safe food and a clean environment. Different pollutant loads, microbiological activities, climatic and topographic conditions, and current land use can change the properties of the soil. In recent years, fertile agricultural lands have been used in the construction industry. This situation explains the inadequacy between population growth and food supply. Both polluting parameters and non-purpose uses negatively affect soil quality, and alternative solutions are sought for this. One of these solutions is the application of various additives to the soil. Among these substances, biochar is a widely used additive in agricultural production, soil quality improvement, and pollutant treatment in water and soil environments. It is a carbon-rich product formed by the pyrolysis method of biochar, food, and agricultural wastes in an oxygen-free environment at ≥250 °C. In this study, current research is examined to explain the interaction of soil quality with biochar. The biochar materials used, the production conditions, and the three-step reaction in the soil were examined. This study summarizes the recent developments in the soil quality of biochar with a porous structure and high specific surface area.

Keywords: biochar; food waste; soil quality; soil conditioner

check for updates

Citation: Çelebi, H.; Bahadır, T.; Şimşek, İ.; Tulun, Ş. Turning Waste into Soil Conditioner with a Sustainable Innovative Approach: Biochar. *Eng. Proc.* **2023**, *56*, 149. https://doi.org/10.3390/ASEC2023-16356

Academic Editor: Nunzio Cennamo

Published: 27 November 2023

1. Introduction

In recent years, all countries of the world think that the ecosystem is under a heavy pollution load. In particular, the increase in population, sectoral developments, and the change in the waste structure with epidemics have led to a dynamic increase in environmental pollution. The ecosystem is dealing with numerous environmental pressures, including increased food and clean water demand, inadequacies in the supply chain, climate change, water scarcity, and soil degradation [1,2]. As a result of anthropogenic activities, constant changes in the environment and epidemics adversely affect the health of living things [3]. In particular, the increasing population and climate change have reduced agricultural areas and caused negativities in agricultural production and soil quality. Soil quality is integrated with the food chain and a clean ecosystem. Quality soil is the most important factor that has a direct impact on safe food and a clean environment. Different pollutant (heavy metals, paint, pesticides, etc.) loads, microbiological activities, climatic and topographic conditions, and current land use can change the properties of the soil. In recent years, fertile agricultural lands have been used in the construction sector. This situation explains the inadequacy between population growth and food supply. Both polluting parameters and non-purpose uses negatively affect soil quality, and alternative solutions are sought for this. One of these solutions is the application of various additives to the soil. Biochar, which is defined as "black gold," finds a wide application among these additives [4,5]. Lately, it is a widely used additive in agricultural production, soil quality improvement, and treatment of different pollutants in water and soil environments [6,7]. Biochar is based on the preparation of different organic raw materials by various techniques at ≥250 °C and under anoxic conditions [8]. In particular, the application of biochar is important in terms of the management and evaluation of food and agricultural wastes. With the industrial symbiosis approach and zero-waste planning, incorporating a waste as a raw material into the circular environmental process will eliminate waste minimization and waste-related pollution [9,10]. The main objective of this article is to perform a comprehensive review of current studies on biochar. The main criteria of this study are: (i) the production process of biochar, (ii) the composition of the biochar, (iii) effects of the biochar on soil quality, and (iv) environmental pros and cons of biochar.

2. Methodology

To find the articles to be used for this review, different databases (Science Direct, Springer, Wiley, Taylor and Francis, Scopus, PubMed, etc.) in the "Web of Science Core Collection" (Clarivate Analytics®, Boston, MA, USA) and "Google Scholar" (Googleplex, Mountain View, CA, USA) were scanned. For the study, 41 articles published in the last 5 years were investigated for evaluation.

3. Biochar's Building Blocks

The majority of studies on biochar are carried out with agricultural (corn cob, rice straw, wheat straw, etc.) and food waste (walnut and peanut shells, fruit shells, tea waste, etc.) [11–14]. From a physicochemical point of view, the structure of biochar is related to the raw materials used and the preparation processes. Specific-quality biochar materials are obtained from different food and agricultural wastes. These differences are revealed by the proximate and ultimate analyses in Table 1. C, H, O, and N contents reveal the chemical effectiveness of biochar. In addition, biochar production methods and the geochemical cycle affect these contents [15]. The C content of biochar consists of inorganic and organic forms, and the H consists of aromatic and functional hydrogen. Under extremely hot conditions, N of biochar turns into a soluble form [4]. Compared to previous regions, the surface area of biochar was determined as 1.5–500 m^2/g [16]. The functional groups on the surface of biochar obtained from raw agricultural and food wastes consist of –OH, –COOH, –COOR, and –C=O [17,18]. These determine whether the biochar is hydrophilic or hydrophobic in different applications. In addition, the production temperature changes the increase (500–700 °C) and decrease (250–350 °C) of functional groups on the biochar surface [4]. The chemical composition of biochar is obtained with the raw material, and it varies depending on the production conditions, such as temperature, heating rate, residence time, and reactor type. For this reason, it is not possible to clearly define the chemical composition of biochar [19]. The cation exchange capacity affects the retention of soil nutrients and the fertilizer circulation of biochar. The pure CE value of biochar created with raw materials ranges from 14 to 17 cmol/kg [20].

Table 1. Physical and chemical properties of different biochar materials [4,10].

	Ultimate Analysis (%)			Proximate Analysis (%)	
Raw Material	**C**	**H**	**N**	**Ash Content**	**Moisture**
Sugar cane	73	0.9	1.1	49	1.5
Pine nut shell	79	3.76	0.89	2.51	5.20
Peanut shell	84	1.75	1.14	3.46	9.75
Soybean stover	82	4.29	1.88	2.64	5.86
Banana peel	36	0.25	1.94	9.28	12
Corn cob	62	7.5	1.02	2.30	12.8
Herb tea waste	45	5.91	2.61	13.4	7.26

Table 1. *Cont.*

	Ultimate Analysis (%)			Proximate Analysis (%)	
Raw Material	**C**	**H**	**N**	**Ash Content**	**Moisture**
Macadamia husk	52	5.77	0.33	1.53	6.90
Mango seed	46	5.54	0.89	1.38	4.97
Passion shell	42	5.47	0.62	1.46	3.15
Pistachio husk	48	5.32	0.34	5.61	7.83
Rice husk	42	6.34	1.85	15.1	10.9
Walnut shell	47	7.90	0.86	0.80	4.50
Tea waste	52	6.31	2.46	4.36	2.24
Spent coffee	57	7.70	2.74	2.06	36.2

3.1. Synthesis of Biochar

Biochar is a carbon-rich and dissolution-resistant material obtained as a result of thermal decomposition of organic material under anaerobic or low-oxygen conditions, and generally at low temperatures (200–900 °C). The origin of biochar is based on the black earth of the Amazon. Biochar obtained with different production methodologies has different properties in terms of both the functional and chemical structure due to differences in operating conditions. This difference causes the production of biochar in batch mode [21]. The conversion of agricultural and food wastes into biochar is possible with traditional (slow and fast pyrolysis) and innovative (hydrothermal carbonization and vacuum-sand/microwave radiation) thermochemical approaches [22,23]. The success of the chosen technique is affected by the type of waste and operating conditions [24]. Thermochemical conversion processes can be examined in two main parts, as dry and wet. Dry processes can be divided into four sections: fast pyrolysis, slow pyrolysis (carbonization), gasification, and partial pyrolysis (torrefaction). Hydrothermal carbonization can be used as an example for the wet thermochemical conversion process. General characteristics of the thermochemical conversion processes are presented in Table 2 [19]. The pyrolysis temperature used in thermochemical reactions in biochar production affects the biochar quality and the natural soil physical properties. In general, biochar produced at high temperatures has more moisture retention than that produced at low temperatures [19]. Biochar production methods are constantly being renewed [25,26]. When producing syngas via gasification, the main product is hydrogen. Biochar is a byproduct of gasification. Modern methods of producing biochar are hydrothermal carbonization and roasting [27]. Studies show that biochar production techniques are of great importance in terms of both the properties and the level of influence. The type and conditions of the biochar production process affect the quality of the product.

Table 2. Biochar production processes and standard conditions [19].

Parameter	**FP** [1]	**SP** [1]	**G** [1]	**PP** [1]	**HC** [1]
Heat	~500 °C	<400 °C	600–1800 °C	<300 °C	180–260 °C
Heating rate	1000 °C/min	<80 °C	-	-	5–10 °C
Reaction rime	A few seconds	A few hours or days	-	<2 h	5–720 min
Pressure	101.325 Pa	101.325 Pa or 1MPa	101.325 Pa/8 MPa	101.325 Pa	1–4.7 MPa
Environment	No oxygen	Limited oxygen	Limited oxygen	No oxygen	PW [1]
Bio-oil	75%	30%	5%	5%	5–25%
Synthesis gas	13%	35%	85%	15%	2–5%
Biochar	12%	35%	10%	80%	45–70%

[1] FP: fast pyrolysis, SP: slow pyrolysis, G: gasification, PP: partial pyrolysis, HC: hydrothermal carbonization, PW: pressure water.

3.2. Biochar as a Soil Ameliorator and Conditioner

As mentioned in Section 3, "Biochar's Building Blocks," biochar has many specific features. Its specific structure also offers many uses (renewable energy, nanotechnology, adsorbent, fertilizer, etc.). The power of biochar manifests itself in the water and soil ecosystem. In particular, interactions in the soil ecosystem are described in this study. Biochar is a practical soil amendment that can positively change agricultural activities, soil health, and development in terms of sustainability (see Figure 1) [28,29]. Microorganisms in the structure of the soil, which are the basic parts of the ecosystem, have a key role in the development of the soil [30,31]. Biochar provides population change in the soil biota to which it is added. In particular, the elemental composition and morphological functions (porosity and surface area) of biochar offer advantages for the growth of bacteria, fungi, and other microorganisms. Biochar, which is effective in water treatment, has an important position in the treatment of pollutants entering the soil ecosystem due to its adsorbent feature. Adding biochar, in terms of soil pollution and soil health, positively affects the physicochemical and microbiological properties of the soil [32]. It can also be a nutrient source for agricultural and other plant activities. Its content mainly depends on the raw materials used and the conditions of the pyrolysis process. Biochar can be applied to rehabilitate contaminated soils and mitigate climate change [10]. What makes biochar indispensable for soil is its relatively easy preparation and low cost [33]. One of the methods used for minimizing greenhouse gas (GHG) emissions is the addition of biochar to soil, as it is designed to capture and store carbon in the soil [34–36]. Biochar, when the C cycle is slow, provides carbon sequestration and CO_2 reduction. When biochar is added, the soil structure, aeration, water-holding capacity, and pore size can be positively affected, and soil improvement is achieved [37,38]. Thus, biochar can improve the soil's main structure in three stages (water-holding capacity, pore size, and microbial activity) [35,39,40].

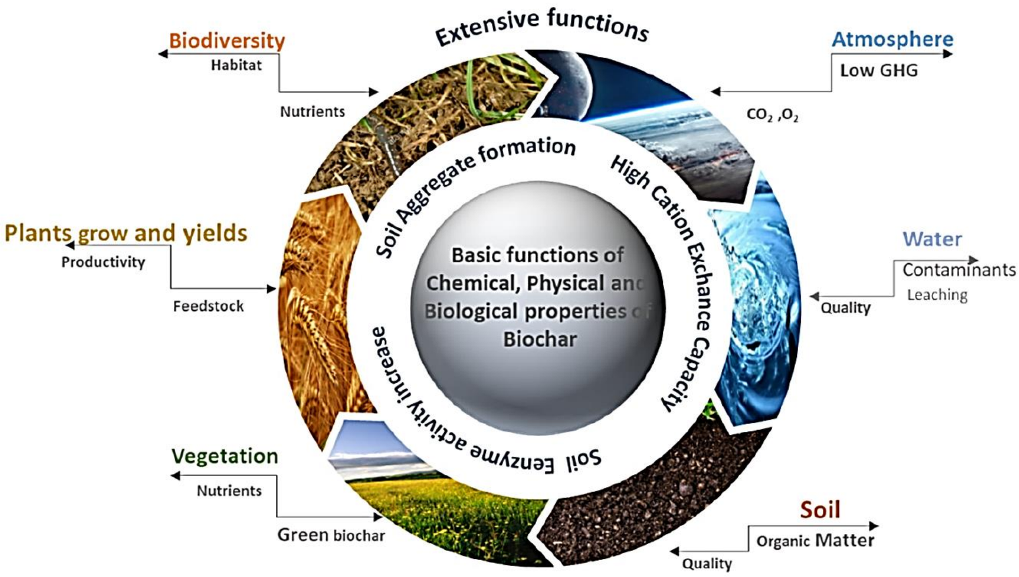

Figure 1. Biochar as a soil ameliorator and conditioner [41].

4. Results

Biochar has been described as environmentally friendly by researchers. However, some of its features and its surface structure may adversely affect the soil ecosystem and other environments. The functional groups and some elemental components of biochar can be transformed into harmful components by chemical reactions in the soil and released. The investigations performed here revealed that biochar can take an active role in soil improvement due to factors such as its active pore distribution, organic functional groups, adsorbing capacity, and high stability. One of the most important advantages of adding biochar is minimizing the effect of pollutants by affecting the soil biota. Biochar's long carbon sink capacity is expected to increase carbon storage in the soil structure and, thus, reduce greenhouse gas emissions.

Author Contributions: Conceptualization, methodology, formal analysis, investigation, resources, writing—original draft preparation, writing—review and editing, visualization, H.Ç., T.B., İ.Ş. and Ş.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: This study was carried out at the Aksaray University Central Library and Engineering Faculty Environmental Engineering Department.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Marczak, D.; Lejcus, K.; Lejcu's, I.; Misiewicz, J. Sustainable innovation: Turning waste into soil additives. *Materials* **2023**, *16*, 2900. [CrossRef] [PubMed]
2. Kim, H.B.; Kim, J.G.; Kim, T.; Alessi, D.S.; Baek, K. Interaction of biochar stability and abiotic aging: Influences of pyrolysis reaction medium and temperature. *Chem. Eng. J.* **2021**, *411*, 128441. [CrossRef]
3. Xiong, Y.; Shi, Q.; Sy, N.D.; Dennis, N.M.; Schlenk, D.; Gan, J. Influence of methylation and demethylation on plant uptake of emerging contaminants. *Environ. Int.* **2022**, *170*, 107612. [CrossRef] [PubMed]
4. Zhang, Y.; Wang, J.; Feng, Y. The effects of biochar addition on soil physicochemical properties: A review. *Catena* **2021**, *202*, 105284. [CrossRef]
5. Joseph, S.; Cowie, A.L.; Zwieten, L.V.; Bolan, N.; Budai, A.; Buss, W.; Cayuela, M.L.; Graber, E.R.; Ippolito, J.A.; Kuzyakov, Y.; et al. How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. *GCB-Bioenergy* **2021**, *13*, 1731–1764. [CrossRef]
6. Babla, M.; Karwal, U.; Yong, M.T.; Jahandari, S.; Rahme, M.; Chen, Z.H.; Tao, Z. Value-added products as soil conditioners for sustainable agriculture. *Resour. Conserv. Recycl.* **2022**, *178*, 106079. [CrossRef]
7. Wang, L.; Ok, Y.S.; Tsang, D.C.W.; Alessi, D.S.; Rinklebe, J.; Masek, O.; Bolan, N.S.; Hou, D. Biochar composites: Emerging trends, field successes and sustainability implications. *Soil Use Manag.* **2022**, *38*, 14–38. [CrossRef]
8. Nguyen, V.T.; Nguyen, T.B.; Chen, C.W.; Hung, C.M.; Vo, T.D.H.; Chang, J.H.; Dong, C.D. Influence of pyrolysis temperature on polycyclic aromatic hydrocarbons production and tetracycline adsorption behavior of biochar derived from spent coffee ground. *Bioresour. Technol.* **2019**, *284*, 197–203. [CrossRef]
9. Chojnacka, K.; Moustakas, K.; Witek-Krowiak, A. Bio-based fertilizers: A practical approach towards circular economy. *Bioresour. Technol.* **2020**, *295*, 122223. [CrossRef]
10. Samoraj, M.; Mironiuk, M.; Witek-Krowiak, A.; Izydorczyk, G.; Skrzypczak, D.; Mikula, K.; Basladynska, S.; Moustakas, K.; Chojnacka, K. Biochar in environmental friendly fertilizers-Prospects of development products and technologies. *Chemosphere* **2022**, *296*, 133975. [CrossRef]
11. Dandamudi, K.P.R.; Murdock, T.; Lammers, P.J.; Deng, S.; Fini, E.H. Production of functionalized carbon from synergistic hydrothermal liquefaction of microalgae and swine manure. *Resour. Conserv. Recycl.* **2021**, *170*, 105564. [CrossRef]
12. Yaman, E.; Ulusal, A.; Uzun, B.B. Co-pyrolysis of lignite and rapeseed cake: A comparative study on the thermal decomposition behavior and pyrolysis kinetics. *SN Appl. Sci.* **2021**, *3*, 97. [CrossRef]
13. Lin, Y.L.; Zheng, N.Y. Biowaste-to-biochar through microwave-assisted wet cotorrefaction of blending mango seed and passion shell with optoelectronic sludge. *Energy* **2021**, *225*, 120213. [CrossRef]
14. Yousaf, B.; Liu, G.; Ubaid Ali, M.; Abbas, Q.; Liu, Y.; Ullah, H.; Imtiyaz Cheema, A. Decisive role of vacuum-assisted carbonization in valorization of ligninenriched (Juglans regia-shell) biowaste. *Bioresour. Technol.* **2021**, *323*, 124541. [CrossRef] [PubMed]
15. El-Naggar, A.; El-Naggar, A.H.; Shaheen, S.M.; Sarkar, B.; Chang, S.X.; Tsang, D.C.W.; Rinklebe, J.; Ok, Y.S. Biochar composition-dependent impacts on soil nutrient release, carbon mineralization, and potential environmental risk: A review. *J. Environ. Manag.* **2019**, *241*, 458–467. [CrossRef]
16. Ngo, D.N.G.; Chuang, X.Y.; Huang, C.P.; Hua, L.C. Compositional characterization of nine agricultural waste biochars: The relations between alkaline metals and cation exchange capacity with ammonium adsorption capability. *J. Environ. Chem. Eng.* **2023**, *11*, 110003. [CrossRef]
17. Janu, R.; Mrlik, V.; Ribitsch, D.; Hofman, J.; Soja, G. Biochar surface functional groups as affected by biomass feedstock, biochar composition and pyrolysis temperature. *Carbon Resour. Conv.* **2021**, *4*, 36–46. [CrossRef]
18. Wei, S.Y.; Zhu, M.; Fan, X.; Song, J.; Peng, P.; Li, K.; Jia, W.; Song, H. Influence of pyrolysis temperature and feedstock on carbon fractions of biochar produced from pyrolysis of rice straw, pine wood, pig manure and sewage sludge. *Chemosphere* **2019**, *218*, 624–631. [CrossRef]
19. Altıkat, A.; Alma, M.H. Biochar and soil physical properties. *J. Inst. Sci. Technol.* **2021**, *11*, 2599–2612.

20. Kharel, G.; Sacko, O.; Feng, X.; Morris, J.R.; Phillips, C.L.; Trippe, K.; Kumar, S.; Lee, J.W. Biochar surface oxygenation by ozonization for super high cation exchange capacity. *ACS Sustain. Chem. Eng.* **2019**, *7*, 16410–16418. [CrossRef]
21. Praveen, S.; Jegan, J.; Pushpa, T.B.; Gokulan, R.; Bulgariu, L. Biochar for removal of dyes in contaminated water: An overview. *Biochar* **2022**, *4*, 10. [CrossRef]
22. Alvarez, M.L.; Gasco, G.; Palacios, T.; Paz-Ferreiro, J.; Mendez, A. Fe oxidesbiochar composites produced by hydrothermal carbonization and pyrolysis of biomass waste. *J. Anal. Appl. Pyrol.* **2020**, *151*, 104893. [CrossRef]
23. Lin, J.; Sun, S.; Xu, D.; Cui, C.; Ma, R.; Luo, J.; Fang, L.; Li, H. Microwave directional pyrolysis and heat transfer mechanisms based on multiphysics field stimulation: Design porous biochar structure via controlling hotspots formation. *Chem. Eng. J.* **2022**, *429*, 132195. [CrossRef]
24. Yaashikaa, P.R.; Kumar, P.S.; Varjani, S.; Saravanan, A. A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy. *Biotechnol. Rep.* **2020**, *28*, e00570. [CrossRef]
25. Tagade, A.; Kirti, N.; Sawarkar, A.N. Pyrolysis of agricultural crop residues: An overview of researches by Indian scientific community. *Bioresour. Technol. Rep.* **2021**, *15*, 100761. [CrossRef]
26. Sahoo, S.S.; Vijay, V.K.; Chandra, R.; Kumar, H. Production and characterization of biochar produced from slow pyrolysis of pigeon pea stalk and bamboo. *Clean. Eng. Technol.* **2021**, *3*, 100101. [CrossRef]
27. Krysanova, K.; Krylova, A.; Zaichenko, V. Properties of biochar obtained by hydrothermal carbonization and torrefaction of peat. *Fuel* **2019**, *256*, 115929. [CrossRef]
28. Hamidzadeh, Z.; Ghorbannezhad, P.; Ketabchi, M.R.; Yeganeh, B. Biomass-derived biochar and its application in agriculture. *Fuel* **2023**, *341*, 127701. [CrossRef]
29. Layek, J.; Narzari, R.; Hazarika, S.; Das, A.; Rangappa, K.; Devi, S.; Balusamy, A.; Saha, S.; Mandal, S.; Idapuganti, R.G.; et al. Prospects of biochar for sustainable agriculture and carbon sequestration: An overview for eastern himalayas. *Sustainability* **2022**, *14*, 6684. [CrossRef]
30. Enaime, G.; Lübken, M. Agricultural waste-based biochar for agronomic applications. *Appl. Sci.* **2021**, *11*, 8914. [CrossRef]
31. Zhao, Y.; Li, Y.L.; Yang, Y.L. A state-of-the-art review on modeling the biochar effect: Guidelines for beginners. *Sci. Total Environ.* **2022**, *802*, 149861. [CrossRef] [PubMed]
32. Kochanek, J.; Soo, R.M.; Martinez, G.; Dakuidreketi, A.; Mudge, A.M. Biochar for intensification of plant-related industries to meet productivity, sustainability and economic goals: A review. *Resour. Conserv. Recycl.* **2022**, *179*, 106109. [CrossRef]
33. Kumar, A.; Singh, E.; Mishra, R.; Kumar, S. Biochar as environmental armour and its diverse role towards protecting soil, water and air. *Sci. Total Environ.* **2022**, *806*, 150444. [CrossRef] [PubMed]
34. Matustík, J.; Pohrelý, M.; Kocí, V. Is application of biochar to soil really carbon negative? The effect of methodological decisions in life cycle assessment. *Sci. Total Environ.* **2021**, *807*, 151058. [CrossRef] [PubMed]
35. O'Connor, J.; Hoang, S.A.; Bradney, L.; Dutta, S.; Xiong, X.; Tsang, D.C. A review on the valorisation of food waste as a nutrient source and soil amendment. *Environ. Pollut.* **2021**, *272*, 115985. [CrossRef] [PubMed]
36. Mustafa, A.; Brtnicky, M.; Hammerschmiedt, T.; Kucerik, J.; Kintl, A.; Chorazy, T.; Naveed, M.; Skarpa, P.; Baltazar, T.; Malicek, O.; et al. Food and agricultural wastesderived biochars in combination with mineral fertilizer as sustainable soil amendments to enhance soil microbiological activity, nutrient cycling and crop production. *Front. Plant Sci.* **2022**, *13*, 1028101. [CrossRef] [PubMed]
37. Khalid, S.; Shahid, M.; Murtaza, B.; Bibi, I.; Natasha; Naeem, M.A.; Niazi, N.K. A critical review of different factors governing the fate of pesticides in soil under biochar application. *Sci. Total Environ.* **2020**, *711*, 134645. [CrossRef]
38. Simanski, V.; Horak, J.; Bordoloi, S. Improving the soil physical properties and relationships between soil properties in arable soils of contrasting texture enhancement using biochar substrates: Case study in Slovakia. *Geoderma Reg.* **2022**, *28*, e00443. [CrossRef]
39. Kamali, M.; Sweygers, N.; Al-Salem, S.; Appels, L.; Aminabhavi, T.M.; Dewil, R. Biochar for soil applications-sustainability aspects, challenges and future prospects. *Chem. Eng. J.* **2022**, *428*, 131189. [CrossRef]
40. Lehmann, J.; Cowie, A.; Masiello, C.A.; Kammann, C.; Woolf, D.; Amonette, J.E.; Cayuela, M.; Camps-Arbestain, M.; Wihitman, T. Biochar in climate change mitigation. *Nature Geosci.* **2021**, *14*, 883–892. [CrossRef]
41. Cara, I.G.; Topa, D.; Puiu, I.; Jitareanu, G. Biochar a promising strategy for pesticide-contaminated soils. *Agriculture* **2022**, *12*, 1579. [CrossRef]