

Article

The Impact of Pyrolysis Temperature on Biochar Properties and Its Effects on Soil Hydrological Properties

Mohammad Ghorbani ¹, Elnaz Amirahmadi ¹, Reinhard W. Neugschwandtner ², Petr Konvalina ¹, Marek Kopecký ^{1,*}, Jan Moudrý ¹, Kristýna Perná ¹ and Yves Theoneste Murindangabo ¹

¹ Department of Agroecosystems, Faculty of Agriculture and Technology, University of South Bohemia in Ceske Budejovice, Branišovská 1645/31A, 370 05 Ceske Budejovice, Czech Republic

² Institute of Agronomy, Department of Crop Sciences, University of Natural Resources and Life Sciences Vienna, Konrad-Lorenz-Straße 24, 3430 Tulln, Austria

* Correspondence: mkopeccky@fzt.jcu.cz

Abstract: Soil structure is a crucial constituent influencing soil organic richness, rooting systems, and soil moisture conservation. Adding biochar to the soil, which directly affects aggregation, can significantly alter the soil moisture status. The extent of this impact is influenced by the temperature at which pyrolysis biochar is formed. The impact of biochar derived from wheat straw made at 350, 450, 550, and 650 °C (B₃₅₀, B₄₅₀, B₅₅₀, B₆₅₀) on soil aggregation and moisture retention was evaluated in this study. Based on the results, B₅₅₀ had the largest mean weight diameter, most water-stable aggregates, and highest available water content compared to the control, with increases of 235%, 39% and 166% compared to the control. On the other hand, B₃₅₀ was identified as the weakest treatment, with no significant difference from the control. Using B₅₅₀ and B₆₅₀ significantly reduced the soil bulk density by 13% and 12% compared to the control. Therefore, the formation of micro-aggregates, the development of soil porosity, and the subsequent increase in soil available water are unavoidable during the addition of B₅₅₀. The change in the hydrophilic character of biochar and the attainment of an optimal oxygen/carbon ratio with pyrolysis degradations is a critical factor in soil hydrology issues.

Keywords: bulk density; clay particle; organic carbon; porosity; soil moisture



Citation: Ghorbani, M.; Amirahmadi, E.; Neugschwandtner, R.W.; Konvalina, P.; Kopecký, M.; Moudrý, J.; Perná, K.; Murindangabo, Y.T. The Impact of Pyrolysis Temperature on Biochar Properties and Its Effects on Soil Hydrological Properties. *Sustainability* **2022**, *14*, 14722. <https://doi.org/10.3390/su142214722>

Academic Editors: Peng Chen and Yi Liu

Received: 9 October 2022

Accepted: 7 November 2022

Published: 8 November 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Soil is a diverse natural ecosystem made up of minerals, organic matter, gases, liquids, and organisms that interact in a variety of ways [1]. The majority of terrestrial plants rely on soil for both quality and quantity, and hence healthy soil is crucial [2,3]. Many concepts deal with soil fertility, quality, and security [4]. For example, the “One Health” concept links human, animal and environmental health [5]. Lehmann et al. [6] pointed out that the designation of soil quality and soil health should not be confused. Soil quality is mainly related to ecosystem services concerning people. A lot of authors have already investigated ecosystem services, and this issue is relatively well described [1–3,7]. However, soil health goes beyond human health to broader sustainability goals, including the planet's health. Farming management must aim to support biological diversity, water quality, suitable climate, recreation, and human and planetary health [6]. According to Nannipieri et al. [8], healthy soils must fulfil many ecosystem services, including maintaining plant and animal productivity and biodiversity, maintaining or improving water and air quality, and promoting human health.

Severe hydrological extremes, such as long-term drought and extreme precipitation, have risen as a result of climate change [9]. This might cause an increase in global crop production instability [10]. Optimizing soil water content could encourage agroecosystems and soil microbial populations that rely on water to be more flexible [11]. Using ecological and pragmatic approaches to improve soil fertility is essential [12,13]. Biochar has been

recognized as a solution to the problematic soils [14]. This carbonaceous material produced by pyrolysis of biomass waste presents a profitable and effective strategy to increase soil fertility and simultaneously sequester soil carbon [15,16].

Biochar as a soil amendment can increase soil water availability [17], water holding capacity [18], soil aeration [19]. Feedstock, pyrolysis circumstance, and soil characteristics all influence these features. Among these parameters, pyrolysis temperature has the greatest influence on the final biochar product [20].

The surface area characteristics and mineral proportion of biochar are all affected by the pyrolysis temperature [21–23]. Regardless of the feedstock used, the formation of microstructure and an increase in the surface area of biochar has frequently been documented with increasing pyrolysis temperature [24–26]. An opening of the internal structure of willow biochar was observed when the pyrolysis temperature was ≥ 450 °C [27]. Some studies also reported that biochars produced in slow pyrolysis improved available water content (AWC) in both fine- and coarse-textured soils [28–30]. In practice, AWC is the most essential factor in irrigation schemes; for example, with a greater AWC, the interval of watering and the volume of irrigation water used may be minimized. The use of biochar has a positive impact on the moisture content of the soil [31,32]. Even when increasing the pyrolysis temperature to 600 and 800 °C, the total pore volume and phosphate absorption rate of biochar were shown to decrease [33]. The suggested mechanisms for this are the blockage and collapse of the pore structures by melting of the material during pyrolysis [34]. However, in three agricultural soils, biochars produced from straw and wood at varying temperatures had no beneficial impact on available water [35].

On the other hand, there are some factors that are directly affected by biochar amendment, and which play important roles in altering the water capacity in the soil, such as a decrease in the soil bulk density [36], an increase the total soil pore volume and alteration of the pore-size distribution [37], the expansion of the soil surface area, particularly in sandy clay soil [38], and the expansion of soil aggregation [39]. However, many of these proposed mechanisms have not been validated on the basis of direct evidence. Nevertheless, the role of soil aggregates in water retention cannot be ignored they affect the soil water retention through the pore structure. The capacity of a soil to store and fix organic carbon (OC) is strongly affected by aggregate stability [40]. Soil aggregate distribution is an important characteristic of soil structure that regulates soil moisture. Aggregates of different sizes have different effects on diffusion of gases, water, nutrients, and dissolved OC [41], and also on germination of seeds and plant growth. For instance, a fine seedbed with aggregates of less than 5 mm is good for crop establishment [42], while a soil with aggregates of 5 mm size is advantageous for plant growth [43]. A rougher aggregate structure could promote evaporation [44], decrease ion exchange activities [45], and reduce oxygen level in the inner portion of the aggregates owing to bioactivities [46]. Sustained aggregates demand a higher volume of linked pores in topsoil [31], which have the ability to speed up water ingress [32].

Various studies have looked into changes in soil structure and the effect of aggregation in water retention capacity. On the other hand, it appears that the use of biochar in the soil has a direct impact on the aggregation process due to its surface qualities. As a consequence, biochar-treated soils are considered to have a greater moisture potential than soils without biochar. It has been demonstrated that the feedstock and pyrolysis conditions have a significant impact on how effective biochar is in soil. To the best of our knowledge, the literature has not sufficiently investigated how the temperature of pyrolysis affects soil aggregation and moisture. Therefore, the focus of this research was on observing how changing pyrolysis temperature affected the moisture qualities of soil in terms of soil aggregation indices with a closer look into produced biochar structure. Furthermore, determining the proper pyrolysis conditions with which to achieve the best efficiency of wheat biochar with respect to water retention characteristics was an alternative objective.

2. Materials and Methods

2.1. Experimental Design

This study's soil came from a research location at the Faculty of Agriculture, University of Guilan in Rasht, Iran ($37^{\circ}11'59.3''$ N $49^{\circ}38'54.6''$ E). The soil has a clay texture (clay: 53%, silt: 29%, sand: 18%) and it is classified as Typic Hapludalfs. Biochars (B) derived from wheat straw were carbonized during 2 h at four pyrolysis temperatures (350, 450, 550, and 650 °C) in an electrical laboratory furnace equipped with a temperature controller with limited air access and the speed of the furnace heating was $10^{\circ}\text{C min}^{-1}$. After spending 1 day cooling down, the biochars were ground to a size smaller than 1 mm, following which they were ready to be added to the soil. Therefore, following treatments were used: C (control without biochar), B₃₅₀, B₄₅₀, B₅₅₀, and B₆₅₀. Three replications were performed. All treatments were applied at 3% by weight of biochar to soil and mixed well in plastic pots (21 cm width, 30 cm depth, and 3 kg soil capacity). The application rate of biochar was selected based on frequently used in conducted pot experiments [39,47,48]. The pots were then watered (field capacity plus 20%) and dried (permanent wilting point) in a controlled environment. The pots were placed in a greenhouse at 25 °C for 7 days to check the moisture level. The incubation time was 5 months. After that, two undisturbed and disturbed soil samples collected from each pot for analysis of soil physical and chemical characteristics.

2.2. Biochar Characteristics

The analyses of biochar properties are shown in Table 1. The pH was determined using a 1:20 (*w/v*) biochar to water ratio [49]. An elemental analyzer was used to detect total carbon, hydrogen, and nitrogen (Perkin Elmer 2400 II). The ammonium acetate technique was used to determine CEC and exchangeable cations [50]. The Brunner, Emmett, and Teller (BET) approach was used to calculate the specific surface area [51]. To look into the effects of varying the pyrolysis temperature on the microstructure of biochar more thoroughly, scanning electron microscope (SEM) was used (Hitachi-TM3030, Japan). Figure 1 shows the results of SEM with high magnification. The functional groups in the produced biochars used in this study were analyzed using a Fourier transform infrared (FTIR) spectrophotometer in the mid-infrared region, from 4000 cm^{-1} to 400 cm^{-1} . The resulting FTIR spectra are shown in Figure 2.

Table 1. Characteristics of biochar (B) made from wheat straw at four different pyrolysis temperatures (350, 450, 550 and 650 °C).

Property	B ₃₅₀	B ₄₅₀	B ₅₅₀	B ₆₅₀
* SSA ($\text{m}^2\text{ g}^{-1}$)	40.1 ± 2.53	51.3 ± 2.16	85.8 ± 3.18	70.4 ± 2.13
pH	7.7 ± 0.02	8.5 ± 0.03	8.9 ± 0.02	11.7 ± 0.02
CEC (cmolc kg^{-1})	15.3 ± 1.21	19.5 ± 1.56	43.4 ± 2.15	37.2 ± 2.82
C (%)	30.1 ± 1.09	42.1 ± 1.68	52.4 ± 2.24	57.6 ± 1.97
H (%)	3.56 ± 0.03	3.22 ± 0.02	2.51 ± 0.02	1.94 ± 0.01
O (%)	14.8 ± 0.92	13.6 ± 0.67	12.9 ± 0.38	12.4 ± 0.49
N (%)	1.39 ± 0.01	1.25 ± 0.01	1.64 ± 0.02	1.53 ± 0.02
O/C ratio	0.49 ± 0.01	0.32 ± 0.01	0.24 ± 0.01	0.21 ± 0.01
Biochar yield (%)	26.2 ± 1.54	37.4 ± 2.81	45.3 ± 2.93	16.8 ± 0.97

* SSA: Specific surface area; CEC: cation exchange capacity, C: carbon, H: hydrogen, O: oxygen, N: nitrogen.

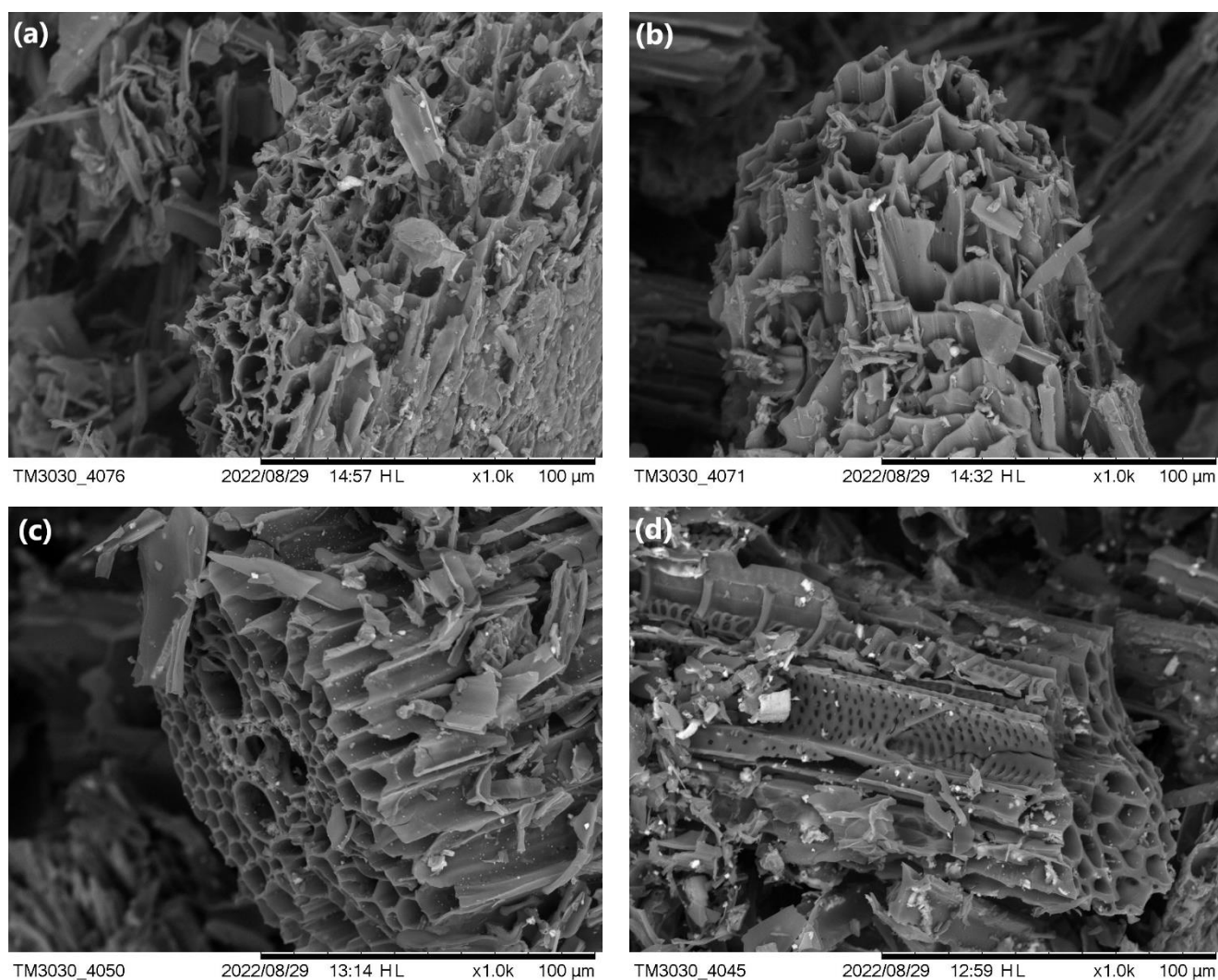


Figure 1. Scanning electron microscopy (SEM) images of biochar produced at (a) 350 °C, (b) 450 °C, (c) 550 °C, and (d) 650 °C.

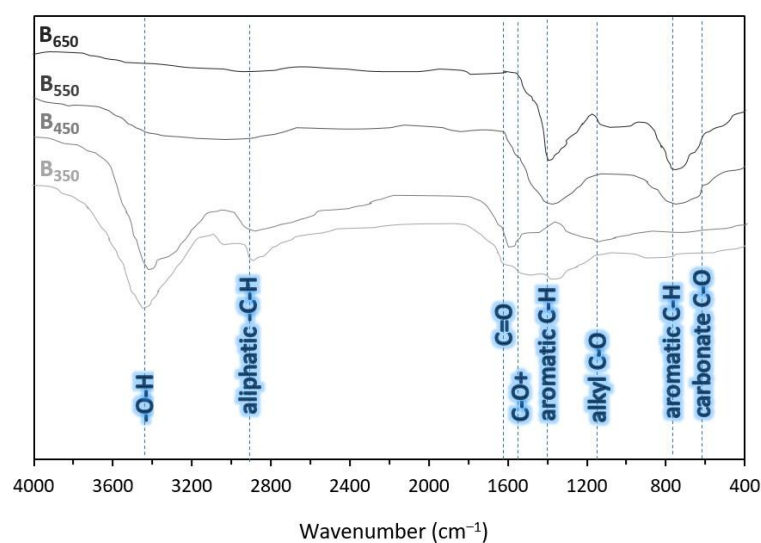


Figure 2. Fourier transform infrared (FTIR) spectra of four different biochar.

2.3. Soil Characteristics

The wet-sieving process was used to examine the wet aggregate size distribution. After open sun-drying, the soils were moistened with tap water for roughly 24 h. The soil was then soaked in a bucket of tap water and sieved at 35 oscillations per min (with a 35 mm amplitude) for 10 min on a set of sieves with apertures 2, 1, 0.5, 0.25, and 0.053 mm in diameter. After wet-shaking, the remaining material in every sieve removed carefully and dried at 105 °C. The weight ratio of aggregates from each sieve on the total weight of aggregates was computed to determine the aggregate size distribution. Using wet sieving results, the mean weight diameter (MWD) of the soil aggregates was calculated as follows [52]:

$$\text{MWD} = \sum_{i=1}^n \bar{X}_i W_i, \quad (1)$$

where $\bar{X}$ denotes the average diameter of the aggregates left on each sieve, W_i denotes the weight ratio of aggregates per sieve to the total weight of the soil, n denotes the number of sieves used.

To evaluate water-stable aggregates, 4 g of 1–2 mm air-dried aggregates were loaded into a 0.26 mm sieve, pre-wetted with water for 24 h, and then shaken 35 times min^{-1} vertically approximately 1.5 cm for 3 min using a single-sieve wet-sieving technique [52]. After drying, the weight of unstable and stable aggregates was calculated. The water-stable aggregates (WSA) index is computed as follows:

$$\text{WSA} = \frac{W_a - W_c}{W_o - W_c} \times 100, \quad (2)$$

where W_a denotes the weight of material on the sieve after wet sieving, W_c denotes the weight of sand material, W_o denotes the weight of aggregates placed on the sieve prior wet sieving.

The soil bulk density (BD) was measured by the clod method, and then the soil porosity was calculated using BD values [53]. Spectrophotometry (PerkinElmer Optima 7300 V) was used to estimate the quantity of soluble base cations (Ca^{2+} and Mg^{2+}), and the flame photometer was used to calculate Na^+ (M410 Sherwood). The sodium absorption ratio (SAR) was then computed using the following formula:

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{\frac{\text{Ca}^{2+} + \text{Mg}^{2+}}{2}}} \times 100, \quad (3)$$

2.4. Water Retention Capacity

Using porous plate funnels and pressure plate equipment, the soil water content curves were calculated [54]. The imposed tensions were 0, −10, −33, −100, −300, −500, and −1500 kPa which are equals to 0, 2, 2.5, 3, 3.5, 3.7, and 4.2 pF (log matric potential). The field capacity (FC) and the permanent wilting point (PWP) were determined to be −33 and −1500 kPa, respectively. Three replications were performed. The difference between FC and PWP was used to compute the available water content (AWC).

2.5. Data Analysis

One-way analysis of variance (ANOVA) was performed to examine the significance of differences in soil parameters among treatments. Lowercase letters in the figures indicate statistically significant differences after the least significant difference (LSD) test at $p < 0.05$. To analyzing existing correlation between pyrolysis temperature and soil properties, linear regression was performed as follows: (a) mean of predicted values and residuals, (b) normality of unstandardized residues values ($p > 0.05$) by Shapiro–Wilk test, (c) the existence of potential outliers by Cook–Weisberg test, (d) the presence of autocorrelation between regression variables by Durbin–Watson test and (e) the significant of regression model by Fisher–Snedecor test significance. SPSS 26.0 was used to analyze the data, and Excel 2020 was used to create all of the figures.

3. Results

3.1. Changes in Soil Characteristics

Applying B₄₅₀, B₅₅₀, and B₆₅₀ treatments significantly affected MWD and WSA ($p < 0.05$) (Figure 3). The highest MWD and WSA were attained with B₅₅₀, with an increase of 235% and 39% compared to the control. The second highest values for both MWD and WSA were obtained with B₆₅₀ with an increase of 157% and 28% compared to the control. MWD and WSA of B₆₅₀ did not significantly differ from B₄₅₀, and the control and B₃₅₀.

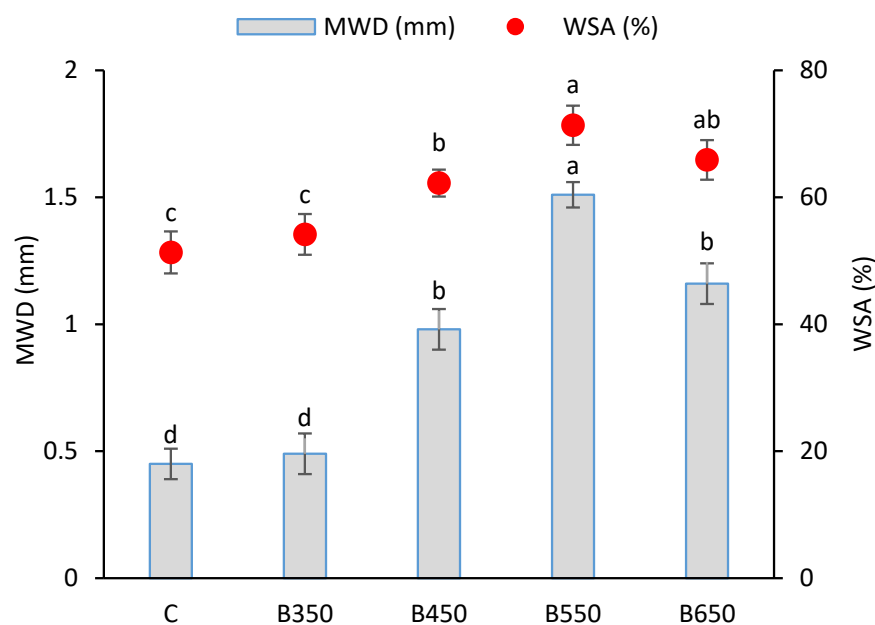


Figure 3. Effect of biochar (B) treatments on (a) mean weight diameter (MWD) and water-stable aggregates (WSA). Different lowercase letters indicate differences ($p < 0.05$). Bars represent standard errors ($n = 3$).

The quantity of micro-aggregates in the soil was affected by the biochar treatments ($p < 0.05$) (Figure 4). B₅₅₀ significantly increased the percentage of micro-aggregates in the soil from 43% (control) to 55%. Additionally, B₃₅₀ and B₄₅₀ were jointly in second place, without a significant difference between them but they were significantly lower than B₅₅₀. Using B₆₅₀, on the other hand, did not result in a significant change from the control. On the other hand, the value of SAR showed a significant increase compared to the control, except for B₅₅₀, which did not significantly differ from the control. The highest SAR resulted from the application of B₆₅₀, with an increase of 129% compared to the control.

Biochar treatments had a significant impact on soil BD and porosity ($p < 0.05$) (Figure 5). Applying B₅₅₀ and B₆₅₀ significantly increased the porosity by 15% and 14% compared to the control, respectively, but decreased the BD by 13% and 12% compared to the control, respectively. The B₃₅₀ treatment had the worst results, since neither the porosity nor the BD differed from the control. B₄₅₀ showed values intermediate between the control and B₅₅₀ and B₆₅₀ for both parameters.

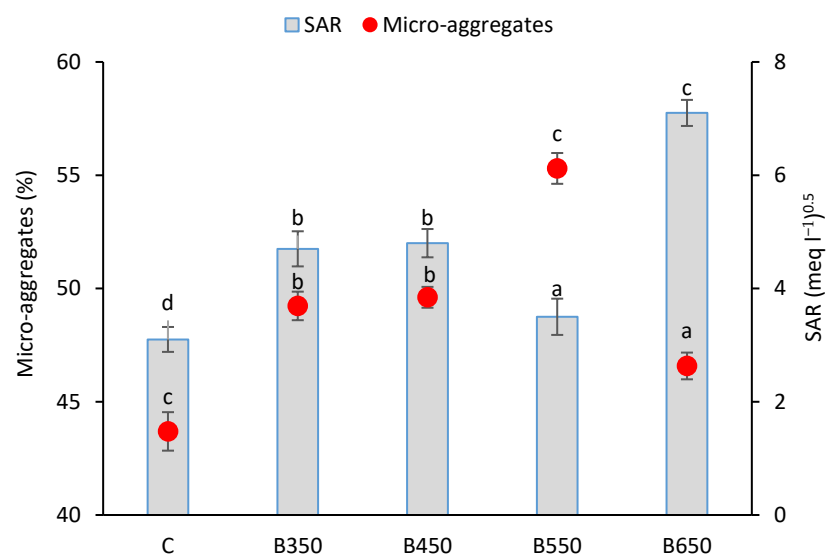


Figure 4. Effect of biochar (B) treatments on sodium absorption ratio (SAR) and percentage of micro-aggregates. Different lowercase letters indicate differences ($p < 0.05$). Bars represent standard errors ($n = 3$).

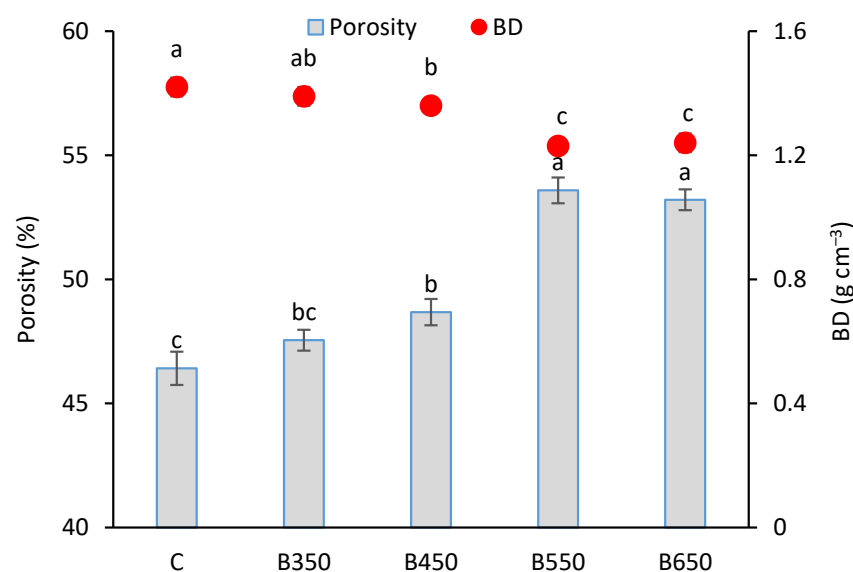


Figure 5. Effect of biochar treatments on total soil porosity and bulk density. Different lowercase letters indicate differences between the treatments ($p < 0.05$). Bars represent standard errors ($n = 3$).

3.2. Water Retention

The use of biochar had a considerable impact on FC, PWP, and AWC (Figure 6). The FC significantly increased with B₄₅₀ and B₅₅₀ by 14% and 17% compared to the control, respectively. Meanwhile, the FC with B₃₅₀ and B₆₅₀ as lower compared to B₄₅₀ and B₅₅₀ and did not differ compared to the control ($p < 0.05$). The three treatments B₄₅₀, B₅₅₀ and B₆₅₀ significantly decreased the PWP by 20%, 23% and 21% compared to the control, respectively. There was no noticeable difference between B₃₅₀ and the control. The highest AWC was attained when applying B₄₅₀ and B₅₅₀ with an increase in 146% and 166% compared to the control, respectively. Additionally, B₆₅₀ increased the AWC by 89% compared to the control. The control and B₃₅₀, on the other hand, showed no significant difference.

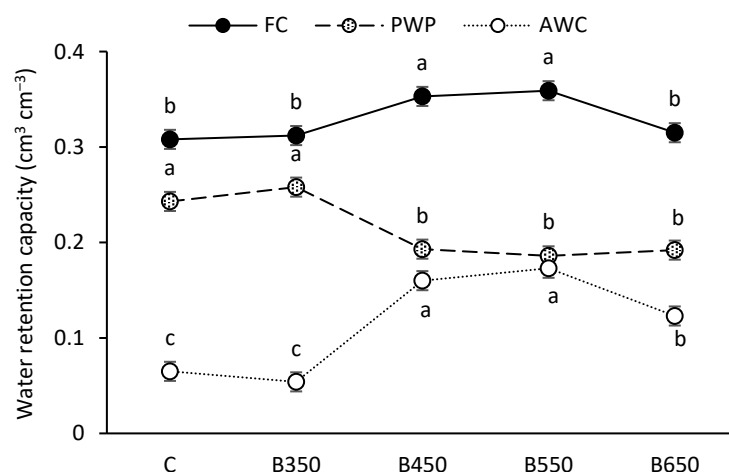


Figure 6. Effect of biochar treatments on field capacity (FC), permanent wilting point (PWP) and available water content (AWC). Different lowercase letters indicate differences between the treatments ($p < 0.05$). Bars represent standard errors ($n = 3$).

The statistical characteristics of the regressions between pyrolysis temperature and soil properties are presented in Table 2. The residuals of all models passed heteroscedasticity for the existence of potential outliers using the Cook–Weisberg test. The results of the Shapiro–Wilk test significantly showed that residuals had a normal distribution due to their having a sig. value of greater than 0.05. The Durbin–Watson statistic ranged from 0 to 4, with a value of 2.0 indicating no autocorrelation. Values close to 0 mean that there is a positive autocorrelation and values close to 4.0 indicate negative autocorrelation. In this study, autocorrelation between residuals was not observed on the basis of the Durbin–Watson test. The regression model was significant according to the Fisher–Snedecor model significance test. Because the mean of the residuals was close to zero, the residual distribution was close to a normal distribution, and therefore the model was better fitted. As can be observed from Figure 7, the results show that there is positive relationship between soil characteristics and pyrolysis temperature, such that coefficients of determined were obtained for them as follows: $R^2 = 0.61$ for MWD, $R^2 = 0.53$ for WSA, $R^2 = 0.46$ for micro-aggregates, $R^2 = 0.51$ for SAR, $R^2 = 0.53$ for porosity, and $R^2 = 0.65$ for BD.

Table 2. The statistical characteristics of the dependence variables.

Constant Variable	Dependent Variable	<i>n</i>	R	R^2	F Test (Sig.)	S-W Test (Sig.)	D-W Test	Mean of Predicted Values	Mean of Residual
* Pyrolysis temp.	MWD	12	0.78	0.61	191.9 (0.000)	0.71	1.814	10.87	0.000
Pyrolysis temp.	WSA	12	0.73	0.53	459.6 (0.000)	0.62	1.731	56.43	0.000
Pyrolysis temp.	Micro-agg	12	0.69	0.46	419.2 (0.000)	0.36	1.839	50.21	0.000
Pyrolysis temp.	SAR	12	0.71	0.51	205.8 (0.000)	0.55	1.667	6.121	0.000
Pyrolysis temp.	Porosity	12	0.73	0.53	457.4 (0.000)	0.48	1.968	54.73	0.000
Pyrolysis temp.	BD	12	0.81	0.65	116.3 (0.000)	0.79	2.109	4.986	0.000

* temp.: temperature, MWD: mean weight diameter, WSA: water stable aggregate; Micro-agg: micro-aggregate, SAR: sodium absorption ratio, BD: bulk density, *n*: observations, R: coefficient of correlation, R^2 : coefficient of determination, F: Fisher–Snedecor test, S-W: Shapiro–Wilk test, and D-W: Durbin–Watson test.

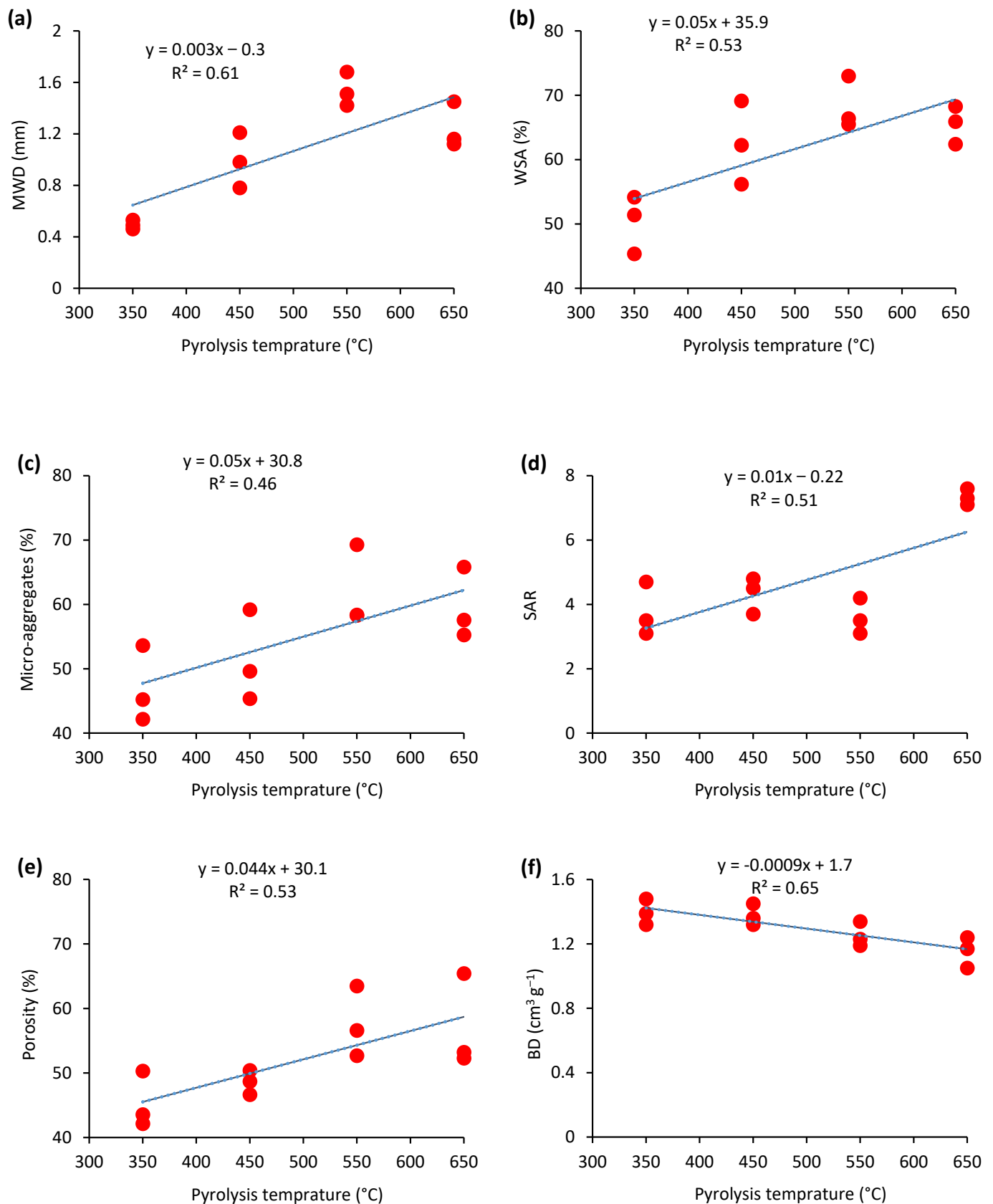


Figure 7. Regression relationships between the pyrolysis temperature of wheat biochar for (a) mean weight diameter (MWD), (b) water-stable aggregate (WSA), (c) micro-aggregates, (d) sodium absorption ratio, (e) porosity, and (f) soil bulk density (BD). The values on each graph represent the total number of treatments and replicates.

4. Discussion

In this study, adjusting the biochars' pyrolysis temperature resulted in appreciable changes in the soil's porosity and bulk density, and, consequently, its hydrological characteristics (Figure 5). These changes can be interpreted on the basis of the occurrence of several mechanisms that are interrelated. Firstly, the change in the hydrophilic nature of biochar with pyrolysis degradations is a key factor in this regard. The O/C ratio is a practical indicator for the determination of the level of the conversion of biomass to biochar, and also the rate of carbonization [55]. When the pyrolysis temperature increases, the O content falls during the decarboxylation reaction, lowering the O/C ratio [56,57]. Higher loss of O indicates higher carbonization of the feedstock, formation of more fused aromatic rings, and stronger C structure of the biochar [58]. The polarity of biochars is determined by the O/C molar ratio [22]. Nevertheless, the values of 0.2 and 0.4 as lower and upper limits of the O/C ratio, respectively, are accepted for the characterization and differentiation of biochar from soot and biomass [55]. A higher O/C ratio means less change in the feedstock and better biomass features in the carbonized product [58]. Overall, a O/C ratio between 0.2 and 0.4 means more carbon skeletons and oxygenated functional groups. As shown in Table 1, the lowest and highest O/C ratio obtained from B₆₅₀ and B₃₅₀, respectively, which would be a reasonable justification for that assertion. Therefore, B₃₅₀ having the worst performance can be explaining by there being less alteration during the pyrolysis process, and the fact that it retains its feedstock characteristics at the end of production, as B₆₅₀, which has a much higher loss of O, possesses characteristics outside the range of biochar and has become a soot. Raising the pyrolysis temperature to above 550 °C appears to lessen biochar polarization, making the biochar surface less hydrophilic. Moreover, it was observed that when the pyrolysis temperature rose to above 500 °C, the yield of biochar synthesis decreased by 10% for every 100 °C increase [59]. For this reason, B₄₅₀ and B₅₅₀ exhibit more benefits compares to the two other treatments. This means that B₄₅₀ and B₅₅₀ had a sufficiently porous C structure and oxygenated functional groups in their structure to provide room to contain more moisture [26]. The development of an arranged carbon skeleton with an increase in pyrolysis temperature is clearly visible from the microscopic images of the produced biochars (Figure 1). Therefore, this stable C structure can be considered an effective factor for improving soil AWC. A notable distance between FC and PWP moisture points in the water retention curve after the application biochar produced at high temperature can therefore be inferred (Figure 6). Low temperatures (<550 °C) have been shown to produce biochars with more oxygen-containing functional groups, resulting in an amorphous C matrix that increases nutritional availability [38]. According to the FTIR test in the current study, the sharp peaks present in B₃₅₀ and B₄₅₀ at wavenumbers of 3430 and 1620 cm⁻¹, which can be attributed to functional hydroxyl and carboxyl groups, can support that claim (Figure 2). However, the hydrophobicity is increased as a negative property [60]. Maize stalk biochar generated at 650 °C was shown to have no effect on aggregate stability due to the lack of oxygen-containing functional groups [26]. Throughout, the best pyrolysis temperature range to generate optimal biochar with low hydrophobicity was found to be between 400 and 600 °C [21]. Additionally, because of the prevalence of non-polar aliphatic and aromatic groups in organic compounds, the relatively low pyrolysis temperature (450 °C) induces increased water repellent activity. This hydrophobic situation provides negative capillary pressure, keeping water from entering the pores [61]. Furthermore, higher temperatures resulted in a loss of hydrogen (H) owing to the increased carbonization and a loss of nitrogen (N) due to the evaporation of N-containing compounds. It has been demonstrated that at temperatures above 400 °C, a significant proportion of N is lost as N₂O, NO, and NO₂ [62]. When we increased the temperature from 350 to 650 °C in our experiment, biochar yield decreased progressively. This is most likely due to the loss of volatile organic molecules at high temperature, resulting in the formation of tiny pores, while primary organizational structures such as cellulose are preserved [59]. These tiny pores are clearly visible in the SEM image of B₆₅₀ (Figure 1). This process created a well-developed microporous structure in the biochar and resulted in low weight,

low density, and multiple micro-pores [36–38]. Gradual increase in soil porosity, as well as the decrease in bulk density with increasing pyrolysis temperature, demonstrate the effectiveness of changes in weight and volume of biochars. This is confirmed by the fact that porosity has a positive connection with pyrolysis temperature and BD has a negative relation with pyrolysis temperature.

The second important factor that plays a key role in improving the water content in soil is the interface between biochar particles and soil aggregation [25], as the positive correlation of MWD and WSA versus pyrolysis temperature confirms (Figure 7). The distribution of micro-aggregates (<250 μm) in soil is a key feature of soil structure, and it is considered to influence soil water retention [63]. These micro-aggregates are made up of a variety of mineral, organic, and biotic components that are linked together with biochemical functions throughout soil formation. Stable micro-aggregates have the capability of increasing flux and impacting unsaturated water conductivity by providing a higher number of linked pores [11,26]. MWD and WSA significantly changed with different pyrolysis conditions, with B₅₅₀ showing the highest values for both parameters (Figure 3). This can be attributed to the proper pyrolysis conditions exhibited by B₅₅₀, and thus the higher organo-mineral component in the soil. The most critical parameters for improving AWC were features such as specific surface area and adequate soil OC [29]. It has been proven that increasing pyrolysis temperature to values higher than 550 °C, regardless of the type and rate of feedstock, significantly decreases the OC, basal soil respiration, and, consequently, aggregate stability indices [63]. Therefore, the biggest increase in micro-aggregates being recorded for B₅₅₀ could be related to the greater OC value in the B₅₅₀. This is important, because biochar providing OC and linking to the soil particles results in the formation of stable organo-minerals that are less vulnerable to degradation. According to certain studies, a considerable proportion of OC in biochar generated above 650 °C is recalcitrant OC, but the proportion of recalcitrant and labile OC in biochar produced at temperatures below 550 °C is about equal [30,63]. Therefore, the presence of more labile OC using biochar in the soil indicates the improvement of aggregation due to the creation of organo-mineral bridges between soil particles. This is supported by the positive correlation between micro-aggregates and pyrolysis temperature. Additionally, the lower percentage of micro-aggregates in B₆₅₀ than B₅₅₀ is related to their alkaline characteristics. B₆₅₀ has much higher pH compared to the other treatments (Table 1), which indicates an increase in the percentages of alkaline cations (e.g., Na⁺, K⁺, Ca²⁺, and Mg²⁺) [26,64,65]. In addition, the increased sodium adsorption ratio (SAR) in B₆₅₀ indicates that significant Na⁺ has been added to the soil (Figure 4). As a consequence, when Na⁺ is available in exchangeable form in the soil, it substitutes Ca²⁺ and Mg²⁺ adsorbed on the soil clays, causing soil particle distribution. Since the flocculation of clay particles is one of the basic conditions for the formation of micro-aggregates, this dispersion results in breakdown of soil micro-aggregates. For this reason, a decrease in micro-aggregates occurred with increasing SAR could be observed in B₆₅₀. This argument is backed up by the fact that SAR and pyrolysis temperature have a positive relationship. Figure 8 summarizes the percentage of changes in soil characteristics affected by different pyrolysis temperatures in this study.

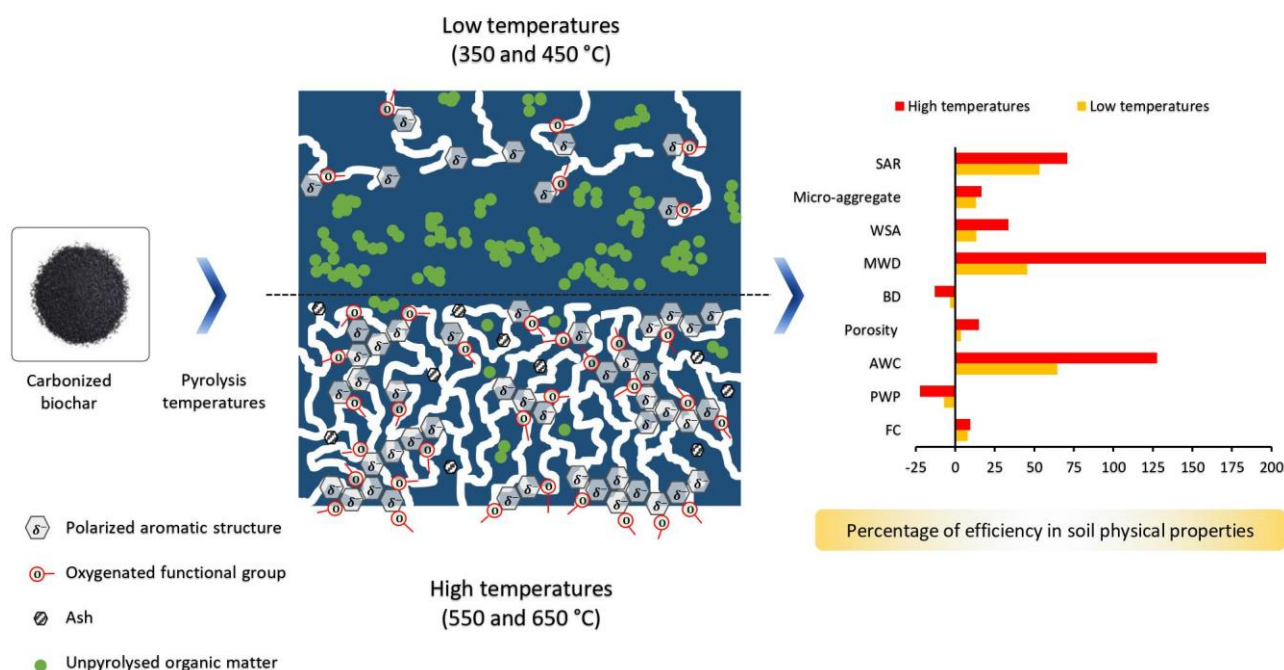


Figure 8. Summary of changes in soil characteristics affected by different pyrolysis temperature.

5. Conclusions

To investigate the impact of biochar on aggregate function in terms of boosting soil moisture capacity, an experiment was performed in which four wheat biochar samples that had been pyrolyzed at various temperatures were compared. The results showed that increasing pyrolysis temperature to more than 550 °C notably boosted the hydrophobicity in biochar structure due to the much higher loss of O content. Additionally, biochar produced at a temperature of 450 to 550 °C boosted organo–mineral complexes and improved the soil structure due to its possessing a robust carbon skeleton, increased specific surface area, and more cations ready to bind to soil particles. Overall, B₅₅₀ was recognized as being the most efficient treatment, which has an obvious impact on soil mean weight diameter, water stable aggregate, porosity, and soil available water content, which exhibited 235%, 39%, 15% and 166% increases, respectively, compared to the control. Therefore, changes in the chemical and surface characteristics of biochar are seen as a function of temperature, and therefore understanding the ideal temperature will have a big influence on the structure of soil modified with biochar. The importance of this issue becomes clearer when the physiological differences between different feedstocks are considered, such as resistance and degradability at pyrolysis temperatures. Therefore, in order to improve biochar efficiency with respect to soil hydrological concerns, the appropriate temperature for various feedstocks must be determined based on the region's agricultural waste management strategy.

Author Contributions: Conceptualization, M.G.; methodology, M.G.; software, M.G. and E.A.; validation, M.G., P.K., J.M., R.W.N. and M.K.; formal analysis, M.G. and E.A.; investigation, M.G. and E.A.; resources, P.K., J.M.; data curation, M.G., E.A., R.W.N., K.P. and Y.T.M.; writing—original draft preparation, M.G. and E.A.; writing—review and editing, M.G., E.A., P.K., R.W.N. and M.K.; visualization, M.G.; supervision, M.G.; project administration, E.A.; funding acquisition, P.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by University of South Bohemia in České Budějovice (GAJU 085/2022/Z).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors gratefully acknowledge the University of Guilan, Iran for providing the site for the experiment and laboratory measurements.

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

References

1. Wall, D.H.; Nielsen, U.N.; Six, J. Soil Biodiversity and Human Health. *Nature* **2015**, *528*, 69–76. [[CrossRef](#)] [[PubMed](#)]
2. Krasilnikov, P.; Taboada, M.A. Amanullah Fertilizer Use, Soil Health and Agricultural Sustainability. *Agriculture* **2022**, *12*, 462. [[CrossRef](#)]
3. Salomon, M.J.; Cavagnaro, T.R. Healthy Soils: The Backbone of Productive, Safe and Sustainable Urban Agriculture. *J. Clean. Prod.* **2022**, *341*, 130808. [[CrossRef](#)]
4. Bünemann, E.K.; Bongiorno, G.; Bai, Z.; Creamer, R.E.; De Deyn, G.; de Goede, R.; Fleskens, L.; Geissen, V.; Kuyper, T.W.; Mäder, P.; et al. Soil Quality—A Critical Review. *Soil Biol. Biochem.* **2018**, *120*, 105–125. [[CrossRef](#)]
5. Keith, A.M.; Schmidt, O.; McMahon, B.J. Soil Stewardship as a Nexus between Ecosystem Services and One Health. *Ecosyst. Serv.* **2016**, *17*, 40–42. [[CrossRef](#)]
6. Lehmann, J.; Bossio, D.A.; Kögel-Knabner, I.; Rillig, M.C. The Concept and Future Prospects of Soil Health. *Nat. Rev. Earth Environ.* **2020**, *1*, 544–553. [[CrossRef](#)]
7. Ghaley, B.B.; Porter, J.R.; Sandhu, H.S. Soil-Based Ecosystem Services: A Synthesis of Nutrient Cycling and Carbon Sequestration Assessment Methods. *Int. J. Biodivers. Sci. Ecosyst. Serv. Manag.* **2014**, *10*, 177–186. [[CrossRef](#)]
8. Nannipieri, P.; Ascher, J.; Ceccherini, M.T.; Landi, L.; Pietramellara, G.; Renella, G. Microbial Diversity and Soil Functions. *Eur. J. Soil Sci.* **2003**, *54*, 655–670. [[CrossRef](#)]
9. Tabari, H. Climate Change Impact on Flood and Extreme Precipitation Increases with Water Availability. *Sci. Rep.* **2020**, *10*, 13768. [[CrossRef](#)]
10. Hänsel, S. Changes in the Characteristics of Dry and Wet Periods in Europe (1851–2015). *Atmosphere* **2020**, *11*, 1080. [[CrossRef](#)]
11. Bertola, M.; Ferrarini, A.; Visioli, G. Improvement of Soil Microbial Diversity through Sustainable Agricultural Practices and Its Evaluation by -Omics Approaches: A Perspective for the Environment, Food Quality and Human Safety. *Microorganisms* **2021**, *9*, 1400. [[CrossRef](#)]
12. Inyang, M.I.; Gao, B.; Yao, Y.; Xue, Y.; Zimmerman, A.; Mosa, A.; Pullammanappallil, P.; Ok, Y.S.; Cao, X. A Review of Biochar as a Low-Cost Adsorbent for Aqueous Heavy Metal Removal. *Crit. Rev. Environ. Sci. Technol.* **2016**, *46*, 406–433. [[CrossRef](#)]
13. Ok, Y.S.; Chang, S.X.; Gao, B.; Chung, H.-J. SMART Biochar Technology—A Shifting Paradigm towards Advanced Materials and Healthcare Research. *Environ. Technol. Innov.* **2015**, *4*, 206–209. [[CrossRef](#)]
14. Yu, H.; Zou, W.; Chen, J.; Chen, H.; Yu, Z.; Huang, J.; Tang, H.; Wei, X.; Gao, B. Biochar Amendment Improves Crop Production in Problem Soils: A Review. *J. Environ. Manag.* **2019**, *232*, 8–21. [[CrossRef](#)]
15. Ahmad, M.; Ok, Y.S.; Kim, B.-Y.; Ahn, J.-H.; Lee, Y.H.; Zhang, M.; Moon, D.H.; Al-Wabel, M.I.; Lee, S.S. Impact of Soybean Stover- and Pine Needle-Derived Biochars on Pb and As Mobility, Microbial Community, and Carbon Stability in a Contaminated Agricultural Soil. *J. Environ. Manag.* **2016**, *166*, 131–139. [[CrossRef](#)]
16. Smith, P. Soil Carbon Sequestration and Biochar as Negative Emission Technologies. *Glob. Chang. Biol.* **2016**, *22*, 1315–1324. [[CrossRef](#)]
17. Ahmad Bhat, S.; Kuriqi, A.; Dar, M.U.D.; Bhat, O.; Sammen, S.S.; Towfiqul Islam, A.R.M.; Elbeltagi, A.; Shah, O.; Al-Ansari, N.; Ali, R.; et al. Application of Biochar for Improving Physical, Chemical, and Hydrological Soil Properties: A Systematic Review. *Sustainability* **2022**, *14*, 11104. [[CrossRef](#)]
18. Mohamed, B.A.; Ellis, N.; Kim, C.S.; Bi, X.; Emam, A.E. Engineered Biochar from Microwave-Assisted Catalytic Pyrolysis of Switchgrass for Increasing Water-Holding Capacity and Fertility of Sandy Soil. *Sci. Total Environ.* **2016**, *566–567*, 387–397. [[CrossRef](#)]
19. Cayuela, M.L.; Sánchez-Monedero, M.A.; Roig, A.; Hanley, K.; Enders, A.; Lehmann, J. Biochar and Denitrification in Soils: When, How Much and Why Does Biochar Reduce N₂O Emissions? *Sci. Rep.* **2013**, *3*, 1732. [[CrossRef](#)]
20. Ippolito, J.A.; Cui, L.; Kammann, C.; Wrage-Mönnig, N.; Estavillo, J.M.; Fuertes-Mendizabal, T.; Cayuela, M.L.; Sigua, G.; Novak, J.; Spokas, K.; et al. Feedstock Choice, Pyrolysis Temperature and Type Influence Biochar Characteristics: A Comprehensive Meta-Data Analysis Review. *Biochar* **2020**, *2*, 421–438. [[CrossRef](#)]
21. Tomczyk, A.; Sokołowska, Z.; Boguta, P. Biochar Physicochemical Properties: Pyrolysis Temperature and Feedstock Kind Effects. *Rev. Environ. Sci. Bio/Technol.* **2020**, *19*, 191–215. [[CrossRef](#)]
22. Hassan, M.; Liu, Y.; Naidu, R.; Parikh, S.J.; Du, J.; Qi, F.; Willett, I.R. Influences of Feedstock Sources and Pyrolysis Temperature on the Properties of Biochar and Functionality as Adsorbents: A Meta-Analysis. *Sci. Total Environ.* **2020**, *744*, 140714. [[CrossRef](#)] [[PubMed](#)]
23. Sun, Y.; Zhang, Z.; Sun, Y.; Yang, G. One-Pot Pyrolysis Route to Fe–N-Doped Carbon Nanosheets with Outstanding Electrochemical Performance as Cathode Materials for Microbial Fuel Cell. *Int. J. Agric. Biol. Eng.* **2020**, *13*, 207–214. [[CrossRef](#)]

24. Elnour, A.Y.; Alghyamah, A.A.; Shaikh, H.M.; Poulouse, A.M.; Al-Zahrani, S.M.; Anis, A.; Al-Wabel, M.I. Effect of Pyrolysis Temperature on Biochar Microstructural Evolution, Physicochemical Characteristics, and Its Influence on Biochar/Polypropylene Composites. *Appl. Sci.* **2019**, *9*, 1149. [\[CrossRef\]](#)
25. Chatterjee, R.; Sajjadi, B.; Chen, W.-Y.; Mattern, D.L.; Hammer, N.; Raman, V.; Dorris, A. Effect of Pyrolysis Temperature on Physicochemical Properties and Acoustic-Based Amination of Biochar for Efficient CO₂ Adsorption. *Front. Energy Res.* **2020**, *8*, 85. [\[CrossRef\]](#)
26. Wang, M.; Tafti, N.D.; Wang, J.J.; Wang, X. Effect of Pyrolysis Temperature on Si Release of Alkali-Enhanced Si-Rich Biochar and Plant Response. *Biochar* **2021**, *3*, 469–484. [\[CrossRef\]](#)
27. Budai, A.; Rasse, D.P.; Lagomarsino, A.; Lerch, T.Z.; Paruch, L. Biochar Persistence, Priming and Microbial Responses to Pyrolysis Temperature Series. *Biol. Fertil. Soils* **2016**, *52*, 749–761. [\[CrossRef\]](#)
28. Günal, E.; Erdem, H.; Çelik, İ. Effects of Three Different Biochars Amendment on Water Retention of Silty Loam and Loamy Soils. *Agric. Water Manag.* **2018**, *208*, 232–244. [\[CrossRef\]](#)
29. Ayaz, M.; Feizienė, D.; Tilvikienė, V.; Akhtar, K.; Stulpinaitė, U.; Iqbal, R. Biochar Role in the Sustainability of Agriculture and Environment. *Sustainability* **2021**, *13*, 1330. [\[CrossRef\]](#)
30. Kalu, S.; Simojoki, A.; Karhu, K.; Tammeorg, P. Long-Term Effects of Softwood Biochar on Soil Physical Properties, Greenhouse Gas Emissions and Crop Nutrient Uptake in Two Contrasting Boreal Soils. *Agric. Ecosyst. Environ.* **2021**, *316*, 107454. [\[CrossRef\]](#)
31. Wang, D.; Li, C.; Parikh, S.J.; Scow, K.M. Impact of Biochar on Water Retention of Two Agricultural Soils—A Multi-Scale Analysis. *Geoderma* **2019**, *340*, 185–191. [\[CrossRef\]](#)
32. Li, L.; Zhang, Y.-J.; Novak, A.; Yang, Y.; Wang, J. Role of Biochar in Improving Sandy Soil Water Retention and Resilience to Drought. *Water* **2021**, *13*, 407. [\[CrossRef\]](#)
33. Jung, K.-W.; Jeong, T.-U.; Kang, H.-J.; Ahn, K.-H. Characteristics of Biochar Derived from Marine Macroalgae and Fabrication of Granular Biochar by Entrapment in Calcium-Alginate Beads for Phosphate Removal from Aqueous Solution. *Bioresour. Technol.* **2016**, *211*, 108–116. [\[CrossRef\]](#)
34. Leng, L.; Xiong, Q.; Yang, L.; Li, H.; Zhou, Y.; Zhang, W.; Jiang, S.; Li, H.; Huang, H. An Overview on Engineering the Surface Area and Porosity of Biochar. *Sci. Total Environ.* **2021**, *763*, 144204. [\[CrossRef\]](#)
35. Burrell, L.D.; Zehetner, F.; Rampazzo, N.; Wimmer, B.; Soja, G. Long-Term Effects of Biochar on Soil Physical Properties. *Geoderma* **2016**, *282*, 96–102. [\[CrossRef\]](#)
36. Toková, L.; Igaz, D.; Horák, J.; Aydin, E. Effect of Biochar Application and Re-Application on Soil Bulk Density, Porosity, Saturated Hydraulic Conductivity, Water Content and Soil Water Availability in a Silty Loam Haplic Luvisol. *Agronomy* **2020**, *10*, 1005. [\[CrossRef\]](#)
37. de Jesus Duarte, S.; Glaser, B.; Pellegrino Cerri, C. Effect of Biochar Particle Size on Physical, Hydrological and Chemical Properties of Loamy and Sandy Tropical Soils. *Agronomy* **2019**, *9*, 165. [\[CrossRef\]](#)
38. Saha, R.; Galagedara, L.; Thomas, R.; Nadeem, M.; Hawboldt, K. Investigating the Influence of Biochar Amendment on the Physicochemical Properties of Podzolic Soil. *Agriculture* **2020**, *10*, 471. [\[CrossRef\]](#)
39. Ghorbani, M.; Asadi, H.; Abrishamkesh, S. Effects of Rice Husk Biochar on Selected Soil Properties and Nitrate Leaching in Loamy Sand and Clay Soil. *Int. Soil Water Conserv. Res.* **2019**, *7*, 258–265. [\[CrossRef\]](#)
40. Islam, M.U.; Jiang, F.; Guo, Z.; Peng, X. Does Biochar Application Improve Soil Aggregation? A Meta-Analysis. *Soil Tillage Res.* **2021**, *209*, 104926. [\[CrossRef\]](#)
41. Xiao, S.; Zhang, W.; Ye, Y.; Zhao, J.; Wang, K. Soil Aggregate Mediates the Impacts of Land Uses on Organic Carbon, Total Nitrogen, and Microbial Activity in a Karst Ecosystem. *Sci. Rep.* **2017**, *7*, 41402. [\[CrossRef\]](#) [\[PubMed\]](#)
42. Lamichhane, J.R.; Boizard, H.; Dürr, C.; Richard, G.; Boiffin, J. Effect of Cropping Systems and Climate on Soil Physical Characteristics, Field Crop Emergence and Yield: A Dataset from a 19-Year Field Experiment. *Data Brief* **2021**, *39*, 107581. [\[CrossRef\]](#) [\[PubMed\]](#)
43. Zhou, M.; Liu, C.; Wang, J.; Meng, Q.; Yuan, Y.; Ma, X.; Liu, X.; Zhu, Y.; Ding, G.; Zhang, J.; et al. Soil Aggregates Stability and Storage of Soil Organic Carbon Respond to Cropping Systems on Black Soils of Northeast China. *Sci. Rep.* **2020**, *10*, 265. [\[CrossRef\]](#) [\[PubMed\]](#)
44. Ma, L.; Shao, M.; Li, T. Characteristics of Soil Moisture and Evaporation under the Activities of Earthworms in Typical Anthrosols in China. *Sustainability* **2020**, *12*, 6603. [\[CrossRef\]](#)
45. Bedel, L.; Legout, A.; Poszwa, A.; van der Heijden, G.; Court, M.; Goutal-Pousse, N.; Montarges-Pelletier, E.; Ranger, J. Soil Aggregation May Be a Relevant Indicator of Nutrient Cation Availability. *Ann. For. Sci.* **2018**, *75*, 103. [\[CrossRef\]](#)
46. Schlüter, S.; Henjes, S.; Zawallich, J.; Bergaust, L.; Horn, M.; Ippisch, O.; Vogel, H.-J.; Dörsch, P. Denitrification in Soil Aggregate Analogues-Effect of Aggregate Size and Oxygen Diffusion. *Front. Environ. Sci.* **2018**, *6*, 17. [\[CrossRef\]](#)
47. Amirahmadi, E.; Mohammad Hojjati, S.; Kammann, C.; Ghorbani, M.; Biparva, P. The Potential Effectiveness of Biochar Application to Reduce Soil Cd Bioavailability and Encourage Oak Seedling Growth. *Appl. Sci.* **2020**, *10*, 3410. [\[CrossRef\]](#)
48. Grafmüller, J.; Schmidt, H.-P.; Kray, D.; Hagemann, N. Root-Zone Amendments of Biochar-Based Fertilizers: Yield Increases of White Cabbage in Temperate Climate. *Horticulturae* **2022**, *8*, 307. [\[CrossRef\]](#)
49. Rajkovich, S.; Enders, A.; Hanley, K.; Hyland, C.; Zimmerman, A.R.; Lehmann, J. Corn Growth and Nitrogen Nutrition after Additions of Biochars with Varying Properties to a Temperate Soil. *Biol. Fertil. Soils* **2012**, *48*, 271–284. [\[CrossRef\]](#)

50. Munera-Echeverri, J.L.; Martinsen, V.; Strand, L.T.; Zivanovic, V.; Cornelissen, G.; Mulder, J. Cation Exchange Capacity of Biochar: An Urgent Method Modification. *Sci. Total Environ.* **2018**, *642*, 190–197. [\[CrossRef\]](#)
51. Subedi, R.; Taupe, N.; Pelissetti, S.; Petruzzelli, L.; Bertora, C.; Leahy, J.J.; Grignani, C. Greenhouse Gas Emissions and Soil Properties Following Amendment with Manure-Derived Biochars: Influence of Pyrolysis Temperature and Feedstock Type. *J. Environ. Manag.* **2016**, *166*, 73–83. [\[CrossRef\]](#)
52. Besalatpour, A.A.; Ayoubi, S.; Hajabbasi, M.A.; Mosaddeghi, M.R.; Schulin, R. Estimating Wet Soil Aggregate Stability from Easily Available Properties in a Highly Mountainous Watershed. *Catena* **2013**, *111*, 72–79. [\[CrossRef\]](#)
53. Xu, L.; He, N.; Yu, G. Methods of Evaluating Soil Bulk Density: Impact on Estimating Large Scale Soil Organic Carbon Storage. *Catena* **2016**, *144*, 94–101. [\[CrossRef\]](#)
54. Robertson, B.B.; Gillespie, J.D.; Carrick, S.T.; Almond, P.C.; Payne, J.; Chau, H.W.; Smith, C.M.S. Measuring the Water Retention Curve of Rock Fragments: A Novel Repacked Core Methodology. *Eur. J. Soil Sci.* **2022**, *73*, e13181. [\[CrossRef\]](#)
55. 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. [\[CrossRef\]](#)
56. Ghorbani, M.; Amirahmadi, E.; Zamanian, K. In-situ Biochar Production Associated with Paddies: Direct Involvement of Farmers in Greenhouse Gases Reduction Policies besides Increasing Nutrients Availability and Rice Production. *Land Degrad. Dev.* **2021**, *32*, 3893–3904. [\[CrossRef\]](#)
57. Asadi, H.; Ghorbani, M.; Rezaei-Rashti, M.; Abrishamkesh, S.; Amirahmadi, E.; Chengrong, C.; Gorji, M. Application of Rice Husk Biochar for Achieving Sustainable Agriculture and Environment. *Rice Sci.* **2021**, *28*, 325–343. [\[CrossRef\]](#)
58. Spokas, K.A. Review of the Stability of Biochar in Soils: Predictability of O:C Molar Ratios. *Carbon Manag.* **2010**, *1*, 289–303. [\[CrossRef\]](#)
59. Chen, X.; Cui, Z.; Fan, M.; Vitousek, P.; Zhao, M.; Ma, W.; Wang, Z.; Zhang, W.; Yan, X.; Yang, J.; et al. Producing More Grain with Lower Environmental Costs. *Nature* **2014**, *514*, 486–489. [\[CrossRef\]](#)
60. Lü, H.; Chen, X.-H.; Mo, C.-H.; Huang, Y.-H.; He, M.-Y.; Li, Y.-W.; Feng, N.-X.; Katsoyiannis, A.; Cai, Q.-Y. Occurrence and Dissipation Mechanism of Organic Pollutants during the Composting of Sewage Sludge: A Critical Review. *Bioresour. Technol.* **2021**, *328*, 124847. [\[CrossRef\]](#)
61. Baveye, P.C.; Schnee, L.S.; Boivin, P.; Laba, M.; Radulovich, R. Soil Organic Matter Research and Climate Change: Merely Re-Storing Carbon Versus Restoring Soil Functions. *Front. Environ. Sci.* **2020**, *8*, 579904. [\[CrossRef\]](#)
62. Yang, C.; Liu, J.; Lu, S. Pyrolysis Temperature Affects Pore Characteristics of Rice Straw and Canola Stalk Biochars and Biochar-Amended Soils. *Geoderma* **2021**, *397*, 115097. [\[CrossRef\]](#)
63. Saffari, N.; Hajabbasi, M.A.; Shirani, H.; Mosaddeghi, M.R.; Mamedov, A.I. Biochar Type and Pyrolysis Temperature Effects on Soil Quality Indicators and Structural Stability. *J. Environ. Manag.* **2020**, *261*, 110190. [\[CrossRef\]](#)
64. Cely, P.; Gascó, G.; Paz-Ferreiro, J.; Méndez, A. Agronomic Properties of Biochars from Different Manure Wastes. *J. Anal. Appl. Pyrolysis* **2015**, *111*, 173–182. [\[CrossRef\]](#)
65. Zhao, S.-X.; Ta, N.; Wang, X.-D. Effect of Temperature on the Structural and Physicochemical Properties of Biochar with Apple Tree Branches as Feedstock Material. *Energies* **2017**, *10*, 1293. [\[CrossRef\]](#)